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(54) **Title**: MICROFABRICATED CALORIMETER FOR RF POWER MEASUREMENT

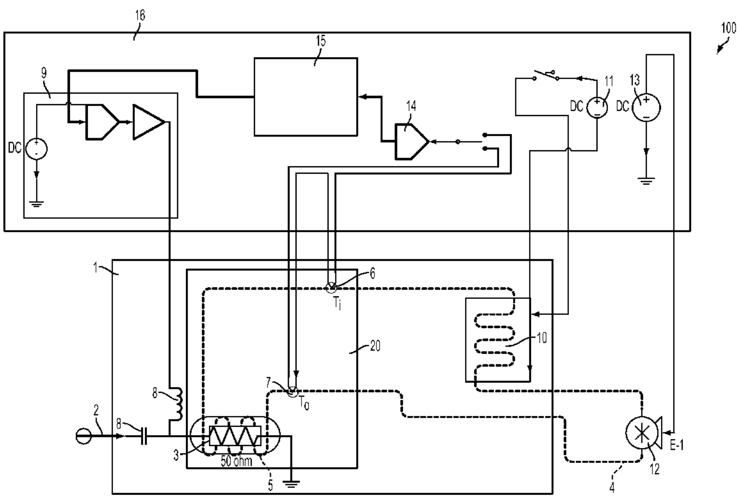

FIG. 2

(57) **Abstract**: Disclosed is a radio frequency (RF) power calorimeter having a load electrically coupled to a RF input, a variable low-frequency power source electrically coupled to the load and configured to apply low-frequency bias to the load. The RF power calorimeter includes a thermal medium thermally coupled to the load. Additionally, the RF power calorimeter includes an outlet temperature sensor thermally coupled to the thermal medium, the outlet temperature sensor being positioned to measure the temperature of the thermal medium due to heating by the load. The RF power calorimeter also has circuitry configured to use temperature measurements of the thermal medium in thermal contact with an RF load in combination with the low-frequency bias to measure average power of an RF source electrically coupled to the RF input. Also disclosed in a method of measuring RF power using the RF power calorimeter.

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MICROFABRICATED CALORIMETER FOR RF POWER MEASUREMENT

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application Serial No. 61/767,872 filed February 22, 2013 and entitled "MICROFABRICATED CALORIMETER FOR RF POWER MEASUREMENT", which is herein incorporated by reference in its entirety.

FIELD OF THE INVENTION

[0002] This invention relates generally to radio frequency (RF) power measurement. In particular, it relates to a microfabricated DC substitution calorimeter for RF power measurement and a method of using the calorimeter.

BACKGROUND OF THE INVENTION

[0003] RF power is a frequently measured quantity because other RF electrical quantities like current, voltage, and impedance are difficult to measure and quantify in RF equipment. At low frequencies, power measurement is made by interpretation of voltage and current across a known impedance. However, at higher frequencies, such as RF frequencies, the impedance changes significantly and therefore direct measurement of power is not feasible.

[0004] Traditionally, handheld RF power meters have directly measured RF power by directly transducing high frequency RF power into a DC signal, such as by using a Schottky or Gallium-Arsenide diode, and measuring the DC signal. However, the accuracy of meters using these traditional direct measurement techniques are sensitive to the measured RF signal's frequency and waveform.

[0005] Accordingly, a need exists for a handheld RF power meter that is insensitive to an RF signal's frequency or waveform.

BRIEF SUMMARY OF THE INVENTION

[0006] According to one aspect of the present invention, a radio frequency (RF) power calorimeter is provided. The RF power calorimeter having a load electrically coupled to a RF input, the RF input configured to be electrically coupled to an RF power source; a variable low-frequency power source electrically coupled to the load and configured to apply low-frequency power to the load; a thermal medium thermally coupled to the load; an outlet temperature sensor thermally coupled to the thermal medium, the outlet temperature sensor being positioned to measure the temperature of the thermal medium due to heating by the load; circuitry configured to calculate power of the RF source electrically coupled to the RF input by: determining an average power of the RF source based on temperature measurements of the thermal medium using a variable bias from the low-frequency power source.

[0007] In another aspect of the invention, determining an average power of the RF source includes: applying a known low-frequency input to the load, the known low-frequency input having a predetermined power value; measuring a first output temperature of the thermal medium after application of the low-frequency input to the load; applying the RF source to the load during application of the known low-frequency input; measuring a second output temperature of the thermal medium during application of the known low-frequency input and the RF source; reducing the power value of the known low-frequency input while measuring the output temperature of the thermal medium until the output temperature is substantially equal to the first output temperature; determining a power value of the known low-frequency input when the output temperature is substantially equal to the first output temperature; and calculating power of the RF source based on the difference between the predetermined value of the known low-frequency input and the power value of the known low-frequency input when the output temperature is substantially equal to the first output temperature.

[0008] In another aspect of the invention, the variable low-frequency power source is an alternating current voltage source.

[0009] In another aspect of the invention the variable low-frequency power source is a direct current voltage source.

[0010] In another aspect of the invention, the thermal medium is a fluid circulated through thermal medium channels.

[0011] In another aspect of the invention, a flowrate of the thermal medium fluid through the thermal medium channels is variable.

[0012] In another aspect of the invention, a fluid channel path array comprised of multiple fluid channels is configured to vary the flowrate of the thermal medium fluid through the thermal medium channels.

[0013] In another aspect of the invention, the fluid channel path array is comprised of a fluid switch in fluid communication with multiple fluid channels, each fluid channel of the fluid channel path array having a different length and/or hydraulic diameter.

[0014] In another aspect of the invention, each fluid channel of the fluid channel path array has a thermal medium pump.

[0015] In another aspect of the invention, the thermal medium is a substrate thermally coupled to a heat exchanger.

[0016] In another aspect of the invention, the outlet temperature sensor is a Wheatstone bridge.

[0017] In another aspect of the invention, the power calorimeter is configured to measure power between about 100 μW and 100mW.

[0018] In another aspect of the invention, the power calorimeter is configured to measure power at frequencies down to 0 Hz and well above 12 GHz.

[0019] In another aspect of the invention, the power calorimeter is configured to measure power at frequencies between about 0 Hz and about 12 GHz.

[0020] In another aspect of the invention, the RF power calorimeter is further comprised of a non-conductive substrate; wherein the load and output sensor are microfabricated on the non-conductive substrate.

[0021] In a further aspect of the invention, the RF power calorimeter is a microfabricated calorimeter having a thermal medium and a low frequency power source; the power calorimeter is configured to determine an average power of an RF source based on temperature measurements of the thermal medium using a variable bias from the low-frequency power source.

[0022] According to another aspect of the invention, a method of measuring RF power is provided. The method of measuring RF power includes: providing a load electrically coupled to a RF input; providing a thermal medium thermally coupled to the load; applying a known low-frequency input to the load, the known low-frequency input having a predetermined power value; measuring a first output temperature of the thermal medium after application of the known low-frequency input to the load; applying an unknown RF input to the load during application of the known low-frequency input; measuring a second output temperature of the thermal medium during application of the known low-frequency input and the unknown RF input; reducing the known low-frequency input while measuring the output temperature of the thermal medium until the output temperature is substantially equal to the first output temperature; determining a value of the known low-frequency input when the output temperature is substantially equal to the first output temperature; and calculating power of the RF input based on the difference between the predetermined value of the known low-frequency input and the value of the known low-frequency input when the output temperature is substantially equal to the first output temperature.

[0023] In another aspect of the invention, the method is carried out using a microfabricated RF power calorimeter.

[0024] In another aspect of the invention, the variable low-frequency input is an alternating current voltage source.

[0025] In another aspect of the invention, the variable low-frequency input is a direct current voltage source.

[0026] In another aspect of the invention, the thermal medium is a fluid circulated through thermal medium channels.

[0027] In another aspect of the invention, a flowrate of the thermal medium fluid through the thermal medium channels is variable.

[0028] In another aspect of the invention, a fluid channel path array comprised of multiple fluid channels is configured to vary the flowrate of the thermal medium fluid through the thermal medium channels.

[0029] In another aspect of the invention, the fluid channel path array is comprised of a fluid switch in fluid communication with multiple fluid channels, each fluid channel of the fluid channel path array having a different length and/or hydraulic diameter.

[0030] In another aspect of the invention, each fluid channel of the fluid channel path array has a thermal medium pump.

[0031]

[0032] In another aspect of the invention, the thermal medium is a substrate thermally coupled to a heat exchanger.

[0033] In another aspect of the invention, the output temperature is obtained with a Wheatstone bridge temperature sensor.

[0034] In another aspect of the invention, the power calorimeter is configured to measure power between about 100 μW and 100mW.

[0035] In another aspect of the invention, the power calorimeter is configured to measure power at frequencies down to 0 Hz and well above 12 GHz.

[0036] In another aspect of the invention, the power calorimeter is configured to measure power at frequencies between about 0 Hz and about 12 GHz.

[0037] In another aspect of the invention, the RF power calorimeter is further comprised of a non-conductive substrate; wherein the load and output sensor are microfabricated on the non-conductive substrate.

[0038] According to another aspect of the invention, a method of measuring radio frequency power comprises: using temperature measurements of fluid moving over an RF load in combination with a DC bias to measure average power.

[0039] According to another aspect of the invention, a method of measuring radio frequency power comprises using temperature measurements of a thermal medium in thermal contact with an RF load in combination with a DC bias to measure average power.

[0040] According to another aspect of the invention, a radio frequency (RF) power calorimeter comprises: a load electrically coupled to a RF input; a variable low-frequency power source electrically coupled to the load and configured to apply low-frequency bias to the load; a thermal medium thermally coupled to the load; an outlet temperature sensor thermally coupled to the thermal medium, the outlet temperature sensor being positioned to measure the temperature of the thermal medium due to heating by the load; and circuitry configured to use temperature measurements of the thermal medium in thermal contact with an RF load in combination with the low-frequency bias to measure average power of an RF source electrically coupled to the RF input.

[0041] Advantages of the present invention will become more apparent to those skilled in the art from the following description of the embodiments of the invention which have been shown and described by way of illustration. As will be realized, the invention is capable of other and different embodiments, and its details are capable of modification in various respects.

BRIEF DESCRIPTION OF SEVERAL VIEWS OF THE DRAWINGS

[0042] These and other features of the present invention, and their advantages, are illustrated specifically in embodiments of the invention now to be described, by way of example, with reference to the accompanying diagrammatic drawings, in which:

[0043] FIG. 1 is a block diagram of a conventional RF absolute flow calorimeter;

[0044] FIG. 2 is a block diagram of a microfabricated RF power measurement calorimeter in accordance with an embodiment of this invention;

[0045] FIG. 3 is a layout of a first substrate of a microfabricated RF power measurement calorimeter in accordance with an embodiment of this invention;

[0046] FIG. 4a-b are depictions of a first substrate and a second substrate of a microfabricated RF power measurement calorimeter in accordance with an embodiment of this invention;

[0047] FIG. 5 is a depiction of a first substrate and a second substrate of a microfabricated RF power measurement calorimeter in accordance with an embodiment of this invention;

[0048] FIG. 6 is a close-up of a section of a first substrate of a microfabricated RF power measurement calorimeter in accordance with an embodiment of this invention;

[0049] FIG. 7 is a close-up of a section of a first substrate of a microfabricated RF power measurement calorimeter in accordance with an embodiment of this invention;

[0050] FIG. 8 is a plot of the measured voltage vs. time at different DC powers for a microfabricated RF power measurement calorimeter in accordance with an embodiment of this invention;

[0051] FIG. 9 is a plot of the measured voltage vs. applied DC power at a plurality of flow rates for a microfabricated RF power measurement calorimeter in accordance with an embodiment of this invention;

[0052] FIG. 10 is a block diagram of a microfabricated RF power measurement calorimeter in accordance with an embodiment of this invention;

[0053] FIG. 11 is a block diagram of a microfabricated RF power measurement calorimeter in accordance with another embodiment of this invention;

[0054] FIG. 12 is a flow chart of a method of measuring power using a microfabricated RF power measurement calorimeter in accordance with an embodiment of this invention;

[0055] FIG. 13 is a flow chart of another method of measuring power using a microfabricated RF power measurement calorimeter in accordance with an embodiment of this invention;

[0056] FIG. 14 is a flow chart of an additional method of measuring power using a microfabricated RF power measurement calorimeter in accordance with an embodiment of this invention;

[0057] FIG. 15 is a block diagram of a microfabricated RF power measurement calorimeter in accordance with an embodiment of this invention; and

[0058] FIG. 16 is a block diagram of a microfabricated RF power measurement calorimeter in accordance with an embodiment of this invention.

[0059] It should be noted that all the drawings are diagrammatic and not drawn to scale. Relative dimensions and proportions of parts of these figures have been shown exaggerated or reduced in size for the sake of clarity and convenience in the drawings. The same reference numbers are generally used to refer to corresponding or similar features in the different embodiments. Accordingly, the drawing(s) and description are to be regarded as illustrative in nature and not as restrictive.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0060] Approximating language, as used herein throughout the specification and claims, may be applied to modify any quantitative representation that could permissibly vary without resulting in a change in the basic function to which it is related. Accordingly, a value modified by a term or terms, such as "about", is not limited to the precise value specified. In at least some instances, the approximating language may correspond to the precision of an instrument for measuring the value. Range limitations may be combined and/or interchanged, and such ranges are identified and include all the sub-ranges stated herein unless context or language indicates otherwise. Other than in the operating examples or where otherwise indicated, all numbers or expressions referring to quantities of ingredients, reaction conditions and the like, used in the specification and the claims, are to be understood as modified in all instances by the term "about".

[0061] "Optional" or "optionally" means that the subsequently described event or circumstance may or may not occur, or that the subsequently identified material may or may not be present, and that the description includes instances where the event or circumstance occurs or where the material is present, and instances where the event or circumstance does not occur or the material is not present.

[0062] As used herein, the terms "comprises", "comprising", "includes", "including", "has", "having", or any other variation thereof, are intended to cover a non-exclusive inclusion. For example, a process, method, article or apparatus that comprises a list of elements is not necessarily limited to only those elements, but may include other elements not expressly listed or inherent to such process, method, article, or apparatus.

[0063] The singular forms "a", "an", and "the" include plural referents unless the context clearly dictates otherwise.

[0064] The basic principle behind microwave RF power measurement is the transducing of high frequency power into a DC signal and measuring the resulting DC signal. RF power measurement calorimeters, such as the absolute flow RF power measurement calorimeter depicted in FIG. 1, have been investigated and have shown to be an acceptable method for the measurement of RF power in certain situations.

[0065] A system level block diagram of a conventional RF absolute flow calorimeter is shown in FIG 1. RF power is passed to the internal load resistor. The load resistor is hollow and has the working fluid flow through it. A pump is used to circulate the fluid from the reservoir to the load and then back to the reservoir after removing the heat by passing it through a heat exchanger. The reservoir is large enough to stabilize the working fluid and keep the average temperature constant. Temperature sensors are used to measure the temperature difference between the fluid before passing through the load and after. The sensors are mostly thermistors due to their fast response and sensitivity. A flow sensor is used to determine the mass flow rate of the fluid through the load. By thermodynamic first principles, the RF power can be determined from the temperature difference, mass flow rate, and specific heat of the fluid.

[0066] Absolute flow calorimeters, such as the one depicted in FIG. 1, are too large to be placed in a handheld package, require the use of a flowmeter which increases uncertainty and decreases accuracy, and have a large thermal mass, which results in a lengthy equilibrium period and measurement acquisition time when employing the DC substitution method.

[0067] However, the microfabricated RF power measurement calorimeter 100 shown in FIG. 2 is capable of measuring signals having an average power of 100 μW to 100mW. The measured signals can range from a low frequency signal to a signal in excess of 12 GHz. Further, calorimeter 100 of FIG. 2 does not use a flowmeter, which allows for power measurement accuracies to less than 0.2% of reading in a hand-held device form factor.

[0068] Turning to FIG. 2, the embodiment of the microfabricated RF power calorimeter 100 shown has a first substrate 1, printed circuit board assembly 16, and RF input 2. Printed circuit board assembly 16 contains variable low frequency power source 9, control and processing electronics 15, temperature measurement electronics 14, heat exchanger power source 11, and pump power source 13. In some embodiments, printed circuit board assembly 16 also contains pump 12. However, in other embodiments, pump 12 is not mounted on printed circuit board assembly 16. First substrate 1 is constructed of glass and provides a base for the following fabricated components: load 3, thermal medium 4, thermal medium channels 5, inlet temperature sensor 6, outlet temperature sensor 7, bias tee 8, and heat exchanger 10. It is contemplated that first substrate 10 could also be constructed of other materials including, but not limited to, quartz, ceramic, silicon, or gallium arsenide (GaAs).

[0069] In one exemplary embodiment, RF input 2 can be configured as a transmission line of copper that provides an electrical path to load 3 and current return path 17 from load 3. It is contemplated that the transmission line of RF input 2 could also be constructed of other materials including, but not limited to, aluminum, gold, or platinum. Load 3 is a resistor made of tantalum nitride (TaN) that absorbs electrical energy and converts the electrical energy to heat. It is contemplated that load 3 could also be constructed of other materials including, but not limited to, tantalum, nichrome (NiCr), or rhenium trioxide (ReO_3).

[0070] In the embodiment of FIG. 2, thermal medium 4 is a mineral oil cooling fluid in thermal medium channels 5 that contacts load 3, inlet temperature sensor 6, outlet temperature sensor 7, and heat exchanger 10. Thermal medium cooling fluid 4 is moved through thermal medium channels 5 by pump 12. The thermal medium cooling fluid 4 receives heat from load 3 and carries the heat to outlet temperature sensor 7. It is contemplated that the thermal medium cooling fluid 4 could also be another material including, but not limited to, water, mineral oil, benzene, methanol, or refrigerant.

[0071] Inlet temperature sensor 6 measures the temperature of the thermal medium cooling fluid 4 in thermal medium channels 5 before the cooling fluid passes over and receives heat from load 3. Inlet temperature sensor 6 is used to maintain thermal medium 4 at a constant temperature at inlet temperature sensor 6 when only power from variable low frequency power source 9 is applied to load 3, and when power from both variable low frequency power source 9 and power from RF input 2 are applied to load 3. In this embodiment, inlet temperature sensor 6 is constructed of platinum. However, it is contemplated that the inlet temperature sensor 6 could be constructed of other materials having a high temperature coefficient of resistance (TCR) including, but not limited to, polysilicon or aluminum.

[0072] Outlet temperature sensor 7 measures the temperature of the thermal medium cooling fluid 4 in thermal medium channels 5 after the cooling fluid passes over and receives heat from load 3. Outlet temperature sensor 7 is used to ascertain the thermal medium cooling fluid temperature 4 at outlet temperature sensor 7 when only power from variable low frequency power source 9 is applied to load, and also ascertain the thermal medium cooling fluid temperature 4 at outlet temperature sensor 7 when power from RF input 2 is applied to load 3 as power from variable low frequency power source 9 is proportionally removed from load 3, in an effort to determine when the power removed from load 3 by variable low frequency power source 9 is equal to the power applied to load 3 by RF input 2. In this embodiment, outlet temperature sensor 7 is constructed of platinum. However, it is contemplated that the outlet temperature sensor 7 could be constructed of other materials having a high temperature coefficient of resistance (TCR) including, but not limited to, polysilicon or aluminum.

[0073] Bias tee 8 is comprised of a discrete capacitor and inductor. Power from variable low frequency power source 9 is applied to load 3 through bias tee 8. Variable low frequency power source 9 is a precision variable DC voltage source or a precision low-frequency AC voltage source.

[0074] Heat exchanger 10 is an active or passive heat exchanger that maintains thermal medium cooling fluid 4 at thermal equilibrium through cooling thermal medium 4. When heat exchanger 10 is an active heat exchanger, heat exchanger power source 11 is present and provides power to heat exchanger 10. Further thermal medium pump 12 powered by thermal medium pump power source 13 circulates thermal medium cooling fluid 4 through thermal medium channels 5. In one embodiment, thermal medium pump 12 is a piezoelectric pump, however it is contemplated that a person having ordinary skill in the art can choose to use another suitable type of pump.

[0075] Temperature measurement electronics 14 convert electrical signals from inlet temperature sensor 6 and outlet temperature sensor 7 into a voltage or numeric value through the use of an analog to digital converter for further manipulation by control and processing electronics 15. Control and processing electronics 15 read the temperatures of inlet temperature sensor 6 and outlet temperature sensor 7. Further, control and processing electronics 15 also controls the amount of power applied to load 3 by variable low frequency voltage power source 9. Control and processing electronics 15 also have a processor and memory for storing and retrieving the program executed by processor and for processing the temperature measurements of inlet temperature sensor 6 and outlet temperature sensor 7.

[0076] As can be seen, microfabricated RF power calorimeter 100 of FIG. 2 is comprised of a thin non-conductive first substrate 1 onto which an absorptive load 3 is mounted. Load 3 is resistive and is comprised of a film deposited on first substrate 1. The shape and size of load 3 are determined such that lowest amount of reflected RF energy is achieved based on the electrical impedance of the RF input (transmission line) 2 connected to microfabricated RF power calorimeter 100. Conductive material is deposited on first substrate 1 around load 3 on the same side of first substrate 1 and functions as the return path for the current to RF input (transmission line) 2. Two temperature sensors, inlet temperature sensor 6 and outlet temperature sensor 7, are deposited near load 3 on first substrate 1, but do not touch load 3. In some embodiments, bias tee 8 is also microfabricated on first substrate 1.

[0077] An insulating layer of silicon dioxide is applied over the entire top surface 1a of first substrate 1 covering the aforementioned layers. The bottom surface (not shown) of first substrate 1 is devoid of any deposited material. A second substrate 20 constructed from polydimethylsiloxane (PDMS) is constructed with thermal medium channels 5 to contain a thermal medium cooling fluid 4. The second substrate 20 is bonded to the first substrate 1 such that the thermal medium cooling fluid 4 flowing through thermal medium channels 5 is in contact with and thermally coupled to load 3, inlet temperature sensor 6, and outlet temperature sensor 7.

[0078] More specifically, the microfabrication of components on first substrate 1 is performed by first spincoating a positive photoresist (Shipley 1818) on first substrate 1. First substrate 1 is then patterned using a conventional UV photolithography method. Then, aluminum is deposited with E-Beam evaporation. Another layer of Shipley 1818 positive photoresist is applied to cover all patterns and exposed to create the load 3, inlet temperature sensor 6, and outlet temperature sensor 7 pattern. Tantalum nitride is filled into the photoresist mold through DC sputtering, and acetone is used for lift-off.

[0079] Next, polydimethylsiloxane (PDMS) is used for creating the second substrate 20 containing microfluidic thermal medium channels 5 and inlet connection 21 and outlet connection 22 for pump 12 and heat exchanger 10. Second substrate 20 is created by spin coating a layer of negative photoresist (MicroChem, SU-8 2050) and patterning on a silicon wafer. The width of the microfluidic thermal medium channels 5 is 100 μm. After developing the UV exposed photoresist, a soft mold is formed. Then, PDMS mixture is poured over the soft mold, followed by curing at 80°C for half an hour. Finally, a PDMS replica is punched to form the inlet connection 21 and outlet connection 22. Second substrate 20 is then positioned on and bonded to first substrate 1 by O_2 plasma treatment for 20 seconds. The fabricated second substrate 20 is shown in FIGS. 4a-b. A heat exchanger 10 is affixed to the second substrate 20 on top of the thermal medium channels 5. An micro thermal medium pump 12 drives the thermal medium fluid 4 through thermal medium channels 5 and heat exchanger 10. In some embodiments, micro thermal medium pump 12 is mounted on PCBA 16.

[0080] FIGS. 3 and 4a-b depict the layout of load 3, return current path 17, inlet temperature sensor 6, and outlet temperature sensor 7 microfabricated on first substrate 1. Further depicted are thermal medium channels 5, microfluidic inlet 21, and microfluidic outlet 22 microfabricated on second substrate 20 in accordance with an embodiment of RF power measurement calorimeter 100. FIG. 5 shows second substrate 20 mounted on first substrate 1. Further, FIG. 5 also depicts RF input 2 connected to load 3 and return current path 17 of substrate 1. FIG. 6 is a close up view of inlet temperature sensor 6, outlet temperature 7, load 3, and current return path 17 of first substrate 1 in accordance with an embodiment of RF power measurement calorimeter 100. FIG. 7 is a close up view of load 3 and current return path 17 of first substrate 1, and microfluidic thermal medium channels 5 of second substrate 20 in accordance with an embodiment of RF power measurement calorimeter 100. It is contemplated that in some embodiments of first substrate 1, load 3 and RF input 2 can have conductive material used for current return path 17 deposited on the same side as load 3, on the opposite side of load 3 and RF input 2, or a combination of on the same side and on the opposite side of load 3 and RF input 2 (e.g. suspended co-planer waveguide, grounded microstrip or grounded co-planer waveguide).

[0081] As can be seen in FIGS. 3 and 4a-b, in some embodiments, inlet temperature sensor 6 is located in an inlet temperature sensor Wheatstone bridge 18, and outlet temperature sensor 7 is located in an outlet temperature sensor Wheatstone bridge 19 fabricated symmetrically on first substrate 1. The Wheatstone bridges 18 and 19 allow inlet temperature sensor 6 and outlet temperature sensor 7 to detect temperature changes of thermal medium 4 more accurately. Additionally, even though second substrate 20 is not shown in FIG. 3, for ease of understanding, thermal medium channels 5, microfluidic inlet 21, and microfluidic outlet 22 are also depicted in relation to load 3, inlet temperature sensor 6, and outlet temperature sensor 7.

[0082] In operation, one pair of the pads on each Wheatstone bridge 18 and 19 are used to apply a DC voltage ($V_{in} = 0.5$ V) and the other pair of pads is used to measure the output voltage. The following equation represents the relation between V_{out}, V_{in} and R_{sensor}

$$V_{out} = \left(\frac{R_{sensor}}{R_3+R_{sensor}} - \frac{R_2}{R_1+R_2} \right) * V_{in}$$

[0083] Turning to Wheatstone bridge 19, an applied power on the load 3 generates a heat that is transferred from load 3 to thermal medium 4. Once the heated thermal medium 4 reaches outlet temperature sensor 7, the resistance of outlet temperature sensor 7 will increase, therefore causing V_{out} of Wheatstone bridge 19 to increase accordingly. Further, the resistance of outlet temperature sensor 7 decreases when the temperature of thermal medium 4 flowing over outlet temperature sensor 7 decreases, causing V_{out} of Wheatstone bridge 19 to decrease accordingly. Along the same lines, the resistance of inlet temperature sensor 6 decreases when the temperature of thermal medium 4 flowing over inlet temperature sensor 6 decreases, causing V_{out} of Wheatstone bridge 18 to decrease accordingly. Further, the resistance of inlet temperature sensor 6 increases when the temperature of thermal medium 4 flowing over inlet temperature sensor 6 increases, causing V_{out} of Wheatstone bridge 18 to increase accordingly.

[0084] FIG. 8 shows V_{out} as a function of time for outlet temperature sensor Wheatstone bridge 19 and applied power at different flow rates. As can be seen, five different DC power values were applied to load 3 in FIG. 8.

[0085] Further, FIG. 8 also shows that a higher flow rate of thermal medium 4 can transfer more heat from load 3 to outlet temperature sensor 7. This is confirmed in FIG. 9, which demonstrates that a higher flowrate produces a sharper V_{out} vs. applied power slope when a given DC power value is applied to load 3.

[0086] FIG. 10 shows an alternative embodiment of RF power measurement calorimeter 100 in which bias tee 8 is eliminated and replaced with a DC load 23 located in close proximity to load 3. In embodiments having a load for RF power received through RF input 2 and a separate load for power received from the variable low frequency power source 9, the load 3 receiving RF power is called is called RF load 3, and the load 23 receiving the variable low frequency power is called DC load 23. During DC substitution, DC load 23 acts as the secondary power source that is used to compare the heating difference between variable low frequency power source 9 and the unknown RF power source received through RF input 2. When RF switch 25 is closed, power is delivered to RF load 3 from unknown RF power source received through RF input 2. RF switch 25 is a single pole single throw switch that is controlled by control and processing electronics 15.

[0087] FIG. 11 shows a further embodiment of RF power measurement calorimeter 100 in which fluid is not used as thermal medium 4. Instead, first substrate 1 acts as thermal medium 4 and is used to provide a temperature reference. Additionally, a means for maintaining the first substrate 1 at a constant temperature (e.g. a regulated cooling means) is included in the embodiment. Further, it is contemplated that in some embodiments of RF power measurement calorimeter 100, the means for maintaining the first substrate 1 at a constant temperature is an active or passive heat exchanger 10 mounted integral to first substrate 1.

[0088] In FIG. 11, first substrate 1 is constructed of glass and provides a base for the following fabricated components: RF load 3, DC load 23, inlet temperature sensor 6, outlet temperature sensor 7, and heat exchanger 10. It is contemplated that the first substrate 1 could also be constructed of other materials including, but not limited to, quartz, ceramic, silicon, or gallium arsenide (GaAs).

[0089] In one exemplary embodiment, RF input 2 can be configured as a transmission line of copper that provides an electrical path to RF load 3 and current return path 17 from RF load 3. It is contemplated that the transmission line of RF input 2 could also be constructed of other materials including, but not limited to, aluminum, gold, or platinum. RF load 3 is a resistor made of tantalum nitride (TaN) that absorbs electrical energy and converts the electrical energy to heat. It is contemplated that RF load 3 could also be constructed of other materials including, but not limited to, tantalum, nichrome (NiCr), or rhenium trioxide (ReO_3).

[0090] DC load 23 is a resistor made of tantalum nitride (TaN) that absorbs electrical energy and converts the electrical energy to heat. It is contemplated that DC load 23 could also be constructed of other materials including, but not limited to, tantalum, nichrome (NiCr), or rhenium trioxide (ReO_3). During DC substitution, DC load 23 acts as the secondary power source that is used to compare the heating difference between variable low frequency power source 9 and the unknown RF power source received through RF input 2. Temperature sensors 6 and 7 measure the temperature of first substrate 1 to determine thermal equilibrium. Further, heat exchanger 10 cools the first substrate 1 and maintains the first substrate 1 at a fixed temperature value. Temperature measurement electronics 14 convert electrical signals from the temperature sensors 6 and 7 into a voltage or numeric value. Control and processing electronics 15 read the temperature of temperature sensors 6 and 7, control variable low frequency power source 9, and process the temperature measurements of sensors 6 and 7.

[0091] Further, variable low frequency power source 9 applies a precision variable DC or low frequency voltage to DC load 23. After thermal equilibrium of first substrate 1 is reached, the reduction of power to DC load 23 is used to determine the RF power present on RF load 3.

[0092] As is noted above, RF power measurement calorimeter 100 uses DC substitution to measure the RF power delivered to load 3 through RF input 2. DC substitution uses a secondary precision power source, such as variable low frequency power source 9, and compares the heating difference between the power applied to load 3 by variable low frequency power source 9 and the unknown RF power delivered to load 3 through RF input 2.

[0093] DC substitution uses a precision, low-frequency power source to compare the heating difference between the low-frequency power source having a known output power value and an RF power source having an unknown output power value. The amount of power by which the low-frequency source must be reduced to maintain thermal equilibrium is used to determine the power of the unknown RF source. Power from a low-frequency voltage source can be determined to a much higher level of accuracy then direct measurement of high-frequency power, such as RF or microwave power.

[0094] It is contemplated that in some embodiments of RF power measurement calorimeter 100, the flowrate of thermal medium cooling fluid 4 presented to load 3, inlet temperature sensor 6, and outlet temperature sensor 7 can be selectable or variable in order to improve the power measurement range of RF power measurement calorimeter 100. Variation of the flow rate of thermal medium cooling fluid 4 along thermal medium channels 5 to load 3, inlet temperature sensor 6, and outlet temperature sensor 7 helps to maintain maximum temperature sensitivity over varying power loads. For example, for lower power measurements, lower flowrates can be used to increase sensitivity, while higher power measurements benefit from higher flowrates to reduce load failure. Any change in flowrate of thermal medium cooling fluid 4 along thermal medium channels 5 requires the flowrate to be stabilized and a unique DC calibration, such as those discussed and shown in FIGS. 12-14, prior to any power measurement.

[0095] Turning to FIG. 15, some embodiments of RF power measurement calorimeter 100 have a fluid channel path array 30 that can be used to change the flowrate of thermal medium cooling fluid 4 travelling along thermal medium channels 5. In the embodiment shown in FIG. 15, the fluid channel path array 30 is located between outlet temperature sensor 7 and thermal medium pump 12, however, it is contemplated that a person having ordinary skill in the art can choose to place fluid channel path array 30 at another location along thermal medium channel 5.

[0096] Fluid channel path array 30 has an upstream fluid switch 31, a downstream fluid switch 33, and multiple fluid channels 32a-n, with "n" being the letter in the alphabet corresponding to the number of fluid channels 32. Upstream fluid switch 31 and downstream fluid switch 33 are fluidly connected to and configured to switch the flow of thermal medium cooling fluid 4 between fluid channels 32a-n, thereby directing thermal medium cooling fluid 4 along only one of the multiple fluid channels 32a-n at a given time; such as when upstream fluid switch 31 is configured to direct thermal medium cooling fluid 4 along fluid channel 32a, downstream fluid switch 33 will be configured to receive thermal medium cooling fluid 4 from fluid channel 32a and direct the thermal medium cooling fluid 4 from fluid channel 32a downstream through thermal medium channel 5. Each of the multiple fluid channels 32a-n is uniquely modified in its length and/or hydraulic diameter, thereby presenting different pressure drops to thermal medium pump 12.

[0097] It is contemplated that one or both of upstream fluid switch 31 and downstream fluid switch 33 can be a valve and/or manifold. It is contemplated that fluid channel path array 30 can be directly integrated onto first substrate 1, or externally mounted. Further, it is contemplated that any of upstream fluid switch 31, fluid channels 32a-n, and/or downstream fluid switch 33 can be directly integrated onto first substrate 1, or externally mounted. It is contemplated that in some embodiments, upstream fluid switch 31 and downstream fluid switch 33 are manually switched. In other embodiments, the switching of upstream fluid switch 31 and downstream fluid switch 33 are controlled by control and processing electronics 15.

[0098] Turning to FIG. 16, other some embodiments of RF power measurement calorimeter 100 have a fluid channel path array 30 having an upstream fluid switch 31 and multiple fluid channels 32a-n. Each of the multiple fluid channels 32a-n has a thermal medium pump 12a-n. In some embodiments, thermal medium pumps 12a-n share a single thermal medium pump power source 13 that is capable of powering one thermal medium pump 12a-n at a given time. In other embodiments, each thermal medium pump 12a-n is individually powered by a corresponding thermal medium pump power source 13a-n. Upstream fluid switch 31, multiple fluid channels 32a-n, and thermal medium pumps 12a-n are fluidly connected and configured to switch the flow of thermal medium cooling fluid 4 between fluid channels 32a-n, thereby directing thermal medium cooling fluid along only one of the multiple fluid channels 32a-n at a given time; such as when upstream fluid switch 31 is configured to direct thermal medium cooling fluid 4 along fluid channel 32a, the corresponding thermal medium power source 13 will power the corresponding thermal medium pump 12a.

[0099] It is contemplated that any of fluid channel path array 30, thermal medium pump 12a-n, and/or thermal medium pump power source 13a-n can be directly integrated onto first substrate 1, or externally mounted. Further, it is contemplated that any of upstream fluid switch 31, fluid channels 32a-n, and/or downstream fluid switch 33 can be directly integrated onto first substrate 1, or externally mounted. It is contemplated that in some embodiments, upstream fluid switch 31 and thermal medium power source 13 are manually switched. In other embodiments, the switching of upstream fluid switch 31 and thermal medium power source 13 are controlled by control and processing electronics 15.

[00100] Further, it is also contemplated that in some embodiments of RF power measurement calorimeter 100, thermal medium pump power source 13 of thermal medium pump 12 is configured to be reduced or modulated to vary the flowrate of thermal medium cooling fluid 4 along thermal medium channel 5. It is contemplated that in some embodiments, the reduction or modulation of thermal medium pump power source 13 of thermal medium pump 12 is manually performed. In other embodiments, it is contemplated that the reduction or modulation of thermal medium pump power source 13 of thermal medium pump 12 is controlled by control and processing electronics 15. It is contemplated that any one or more of the methods and structures for varying the flowrate of thermal medium cooling fluid 4 along thermal medium channel 5 discussed and/or shown in this application can be used alone or in combination in an embodiment of RF power measurement calorimeter 100.

[00101] FIG. 12 shows one method of DC substitution that can be used in conjunction with an embodiment of RF power measurement calorimeter 100. In step 301, A known, fixed level of power from variable low frequency power source 9 is applied to the load 3 via the bias tee 8: ***Pref***. The value of this initial, fixed power is $\mathbf{P_{eq} = (V_{eq})^2/R_{load}}$.

[00102] In step 305, the thermal medium 4 is allowed to heat while the active or passive heat exchanger 10 simultaneously maintains the thermal medium 4 at thermal equilibrium. This equilibrium is determined by the inlet temperature sensor 6 as ***Tin***. The temperature of the thermal medium 4 (exiting fluid or of the first substrate 1) is monitored by the outlet temperature sensor 7 also at equilibrium: ***Tout.*** These initial temperatures, $\mathbf{T_{ineq}}$ & $\mathbf{T_{outeq}}$, are monitored by measurement electronics 14.

[00103] In step 310, an unknown RF power ***P*** is now applied to the load 3 via the RF input 2. This unknown RF power must be equal to or less than $\mathbf{P_{eq}}$. The total power applied to the load 3 will be the sum of the known & unknown powers: ***Pref + P***.

[00104] In step 315, initially this sum is greater than $\mathbf{P_{eq}}$ and the fluid or substrate temperature of thermal medium 4 will rise. The known power from the variable low frequency power source 9 is proportionately reduced by control electronics 15 until thermal medium 4 attains starting equilibrium as determined when ***Tout*** = $\mathbf{T_{outeq}}$. Let this reduced power be $\mathbf{P_{meas}}$. The inlet temperature ***Tin*** must also be maintained at ***Tin*** = $\mathbf{T_{ineq}}$ by the heat exchanger 10.

[00105] In step 320, when these conditions are met, the unknown RF power can be determined by the amount the known power source had to be proportionately reduced: ***P*** = $\mathbf{P_{eq}} - \mathbf{P_{meas}}$.

[00106] It is understood that if the unknown power is zero, then $\mathbf{P_{meas}} = \mathbf{P_{eq}}$.

[00107] One advantage of this measurement technique is power from a low-frequency voltage source ***Pref*** can be determined to a much higher level of accuracy then direct measurement of high-frequency (e.g. RF) power.

[00108] Turning to FIG. 13, shown is another embodiment of determining an average power of the RF source. In step 401, a known low-frequency input from variable low frequency power source 9 is applied to the load 3. The known low-frequency input has a predetermined power value. In step 405, a first output temperature of thermal medium 4 is measured by outlet temperature sensor 7 after application of the low-frequency input to load 3.

[00109] In step 410, an RF source having an unknown power is applied to load 3 during application of the known low-frequency input. In step 415, a second output temperature of the thermal medium 4 is measured by outlet temperature sensor 7 during application of the known low-frequency input and the RF source having an unknown power value.

[00110] In step 420, the power value of the known low-frequency input is reduced while measuring the output temperature of thermal medium 4 using outlet temperature sensor 7 until the output temperature is substantially equal to the first output temperature. In step 425, a power value of the known low-frequency input is determined when the output temperature measured by outlet temperature sensor 7 in step 420 is substantially equal to the first output temperature measured by outlet temperature sensor 7 in step 401.

[00111] In step 430, a value for the unknown power of the RF source is calculated based on the difference between the predetermined power value of the known low-frequency input in step 401 and the power value of the known low-frequency input when the output temperature is substantially equal to the first output temperature at the end of step 420.

[00112] Turning to FIG. 14, also disclosed is a method of measuring RF power. In step 501, a load 3 electrically coupled to a RF input 2 is provided. In step 505, a thermal medium 4 thermally coupled to the load 3 is provided. In step 510, a known low-frequency input from variable low frequency power source 9 is applied to the load 3. The known low-frequency input has a predetermined power value.

[00113] In step 515, a first output temperature of the thermal medium 4 is measured after application of the known low-frequency input to the load 3. In step 520, an RF input having an unknown power is applied to the load 3 during application of the known low-frequency input.

[00114] In step 525, a second output temperature of the thermal medium 4 is measured during application of the known low-frequency input and the unknown RF input. In step 530, the known low-frequency input is reduced while measuring the output temperature of the thermal medium 4 until the output temperature is substantially equal to the first output temperature.

[00115] In step 535, a value of the known low-frequency input is determined when the output temperature is substantially equal to the first output temperature. In step 540, a value for the known power of the RF input is calculated based on the difference between the predetermined power value of the known low-frequency input and the power value of the known low-frequency input when the output temperature is substantially equal to the first output temperature.

[00116] While this invention has been described in conjunction with the specific embodiments described above, it is evident that many alternatives, combinations, modifications and variations are apparent to those skilled in the art. Accordingly, the preferred embodiments of this invention, as set forth above are intended to be illustrative only, and not in a limiting sense. Various changes can be made without departing from the spirit and scope of this invention. Combinations of the above embodiments and other embodiments will be apparent to those of skill in the art upon studying the above description and are intended to be embraced therein. Therefore, the scope of the present invention is defined by the appended claims, and all devices, processes, and methods that come within the meaning of the claims, either literally or by equivalence, are intended to be embraced therein.

[00117] What is claimed is:

CLAIMS

1. A radio frequency (RF) power calorimeter comprising:

a load electrically coupled to a RF input, the RF input configured to be electrically coupled to an RF power source;

a variable low-frequency power source electrically coupled to the load and configured to apply low-frequency power to the load;

a thermal medium thermally coupled to the load;

an outlet temperature sensor thermally coupled to the thermal medium, the outlet temperature sensor being positioned to measure the temperature of the thermal medium due to heating by the load;

circuitry configured to calculate power of the RF source electrically coupled to the RF input by:

determining an average power of the RF source based on temperature measurements of the thermal medium using a variable bias from the low-frequency power source.

2. The RF power calorimeter of claim 1, wherein determining an average power of the RF source includes:

applying a known low-frequency input to the load, the known low-frequency input having a predetermined power value;

measuring a first output temperature of the thermal medium after application of the low-frequency input to the load;

applying the RF source to the load during application of the known low-frequency input;

measuring a second output temperature of the thermal medium during application of the known low-frequency input and the RF source;

reducing the power value of the known low-frequency input while measuring the output temperature of the thermal medium until the output temperature is substantially equal to the first output temperature;

determining a power value of the known low-frequency input when the output temperature is substantially equal to the first output temperature; and

calculating power of the RF source based on the difference between the predetermined value of the known low-frequency input and the power value of the known low-frequency input when the output temperature is substantially equal to the first output temperature.

3. An RF power calorimeter as set forth in claim 1 or 2, wherein said variable low-frequency power source is an alternating current voltage source.

4. An RF power calorimeter as set forth in claim 1 or 2, wherein said variable low-frequency power source is a direct current voltage source.

5. An RF power calorimeter as set forth in any one of the preceding claims, wherein said thermal medium is a fluid circulated through thermal medium channels.

6. The RF power calorimeter of claim 5, wherein a flowrate of said thermal medium fluid through said thermal medium channels is variable.

7. The RF power calorimeter of claim 6 further comprising a fluid channel path array comprised of multiple fluid channels configured to vary said flowrate of said thermal medium fluid through said thermal medium channels.

8. The RF power calorimeter of claim 7, wherein said fluid channel path array is comprised of a fluid switch in fluid communication with multiple fluid channels, each fluid channel of said fluid channel path array having a different length and/or hydraulic diameter.

9. The RF power calorimeter of claim 8, wherein each fluid channel of said fluid channel path array has a thermal medium pump.

10. An RF power calorimeter as set forth in any one of claims 1-4, wherein said thermal medium is a substrate thermally coupled to a heat exchanger.

11. An RF power calorimeter as set forth in any one of the preceding claims, wherein said outlet temperature sensor is a Wheatstone bridge.

12. An RF power calorimeter as set forth in any one of the preceding claims, wherein said power calorimeter is configured to measure power between about 100 μW and 100mW.

13. An RF power calorimeter as set forth in any one of the preceding claims, wherein said power calorimeter is configured to measure power at frequencies down to 0 Hz and well above 12 GHz.

14. An RF power calorimeter as set forth in any one of the preceding claims, wherein said RF power calorimeter is further comprised of a non-conductive substrate; wherein said load and output sensor are microfabricated on said non-conductive substrate.

15. An RF power calorimeter comprised of a microfabricated calorimeter having a thermal medium and a low frequency power source; said power calorimeter is configured to determine an average power of an RF source based on temperature measurements of said thermal medium using a variable bias from the low-frequency power source.

16. A method of measuring radio frequency (RF) power, the method comprising:

providing a load electrically coupled to a RF input;

providing a thermal medium thermally coupled to the load;

applying a known low-frequency input to the load, the known low-frequency input having a predetermined power value;

measuring a first output temperature of the thermal medium after application of the known low-frequency input to the load;

applying an unknown RF input to the load during application of the known low-frequency input;

measuring a second output temperature of the thermal medium during application of the known low-frequency input and the unknown RF input;

reducing the known low-frequency input while measuring the output temperature of the thermal medium until the output temperature is substantially equal to the first output temperature;

determining a value of the known low-frequency input when the output temperature is substantially equal to the first output temperature; and

calculating power of the RF input based on the difference between the predetermined value of the known low-frequency input and the value of the known low-frequency input when the output temperature is substantially equal to the first output temperature.

17. The method of claim 16, wherein said method is carried out using a microfabricated RF power calorimeter.

18. The method of claim 17, wherein said variable low-frequency input is an alternating current voltage source.

19. The method as set forth in any one of claims 17 or 18, wherein said variable low-frequency input is a direct current voltage source.

20. The method as set forth in any one of claims 17-19, wherein said thermal medium is a fluid circulated through thermal medium channels.

21. The RF power calorimeter of claim 20, wherein a flowrate of said thermal medium fluid through said thermal medium channels is variable.

22. The RF power calorimeter of claim 21 further comprising a fluid channel path array comprised of multiple fluid channels configured to vary said flowrate of said thermal medium fluid through said thermal medium channels.

23. The RF power calorimeter of claim 22, wherein said fluid channel path array is comprised of a fluid switch in fluid communication with multiple fluid channels, each fluid channel of said fluid channel path array having a different length and/or hydraulic diameter.

24. The RF power calorimeter of claim 23, wherein each fluid channel of said fluid channel path array has a thermal medium pump.

25. The method as set forth in any one of claims 17-20, wherein said thermal medium is a substrate thermally coupled to a heat exchanger.

26. The method as set forth in any one of claims 17-25, wherein said output temperature is obtained with a Wheatstone bridge temperature sensor.

27. The method as set forth in any one of claims 17-26, wherein said power calorimeter is configured to measure power between about 100 μW and 100mW.

28. The method as set forth in any one of claims 17-27, wherein said power calorimeter is configured to measure power at frequencies down to 0 Hz and well above 12 GHz.

29. The method as set forth in any one of claims 17-28, wherein said RF power calorimeter is further comprised of a non-conductive substrate; wherein said load and output sensor are microfabricated on said non-conductive substrate.

30. A method of measuring radio frequency power, the method comprising:

using temperature measurements of a thermal medium in thermal contact with an RF load in combination with a DC bias to measure average power.

31. The method of measuring radio frequency power of claim 30, wherein said method comprises:

using temperature measurements of fluid moving over an RF load in combination with a DC bias to measure average power.

32. A radio frequency (RF) power calorimeter comprising:

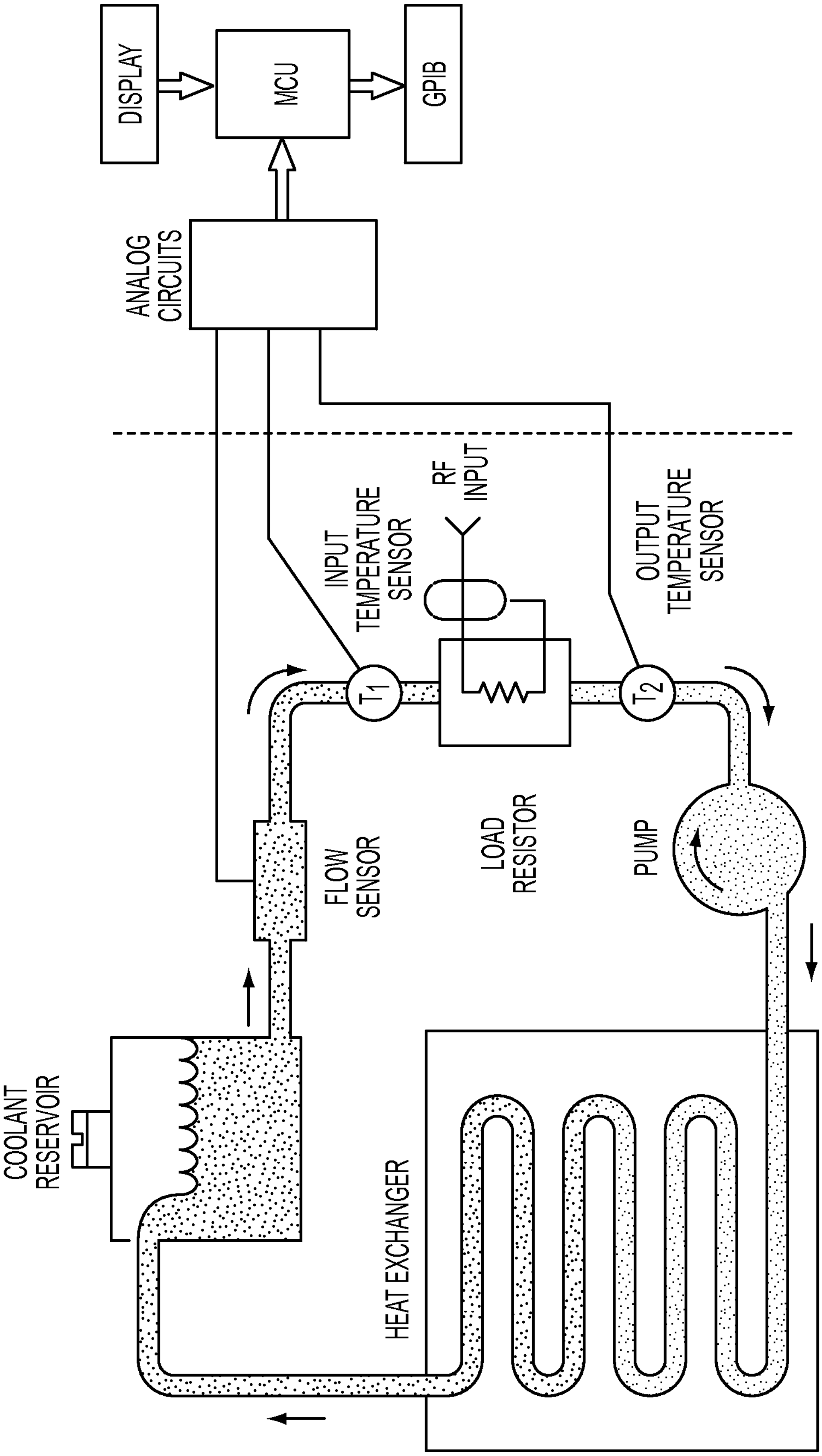
a load electrically coupled to a RF input;

a variable low-frequency power source electrically coupled to the load and configured to apply low-frequency bias to the load;

a thermal medium thermally coupled to the load;

an outlet temperature sensor thermally coupled to the thermal medium, the outlet temperature sensor being positioned to measure the temperature of the thermal medium due to heating by the load;

circuitry configured to use temperature measurements of the thermal medium in thermal contact with an RF load in combination with the low-frequency bias to measure average power of an RF source electrically coupled to the RF input.



DISPLAY
MCU
GPIB
ANALOG CIRCUITS
INPUT TEMPERATURE SENSOR
RF INPUT
OUTPUT TEMPERATURE SENSOR
T_1
T_2
FLOW SENSOR
LOAD RESISTOR
PUMP
COOLANT RESERVOIR
HEAT EXCHANGER

FIG. 1

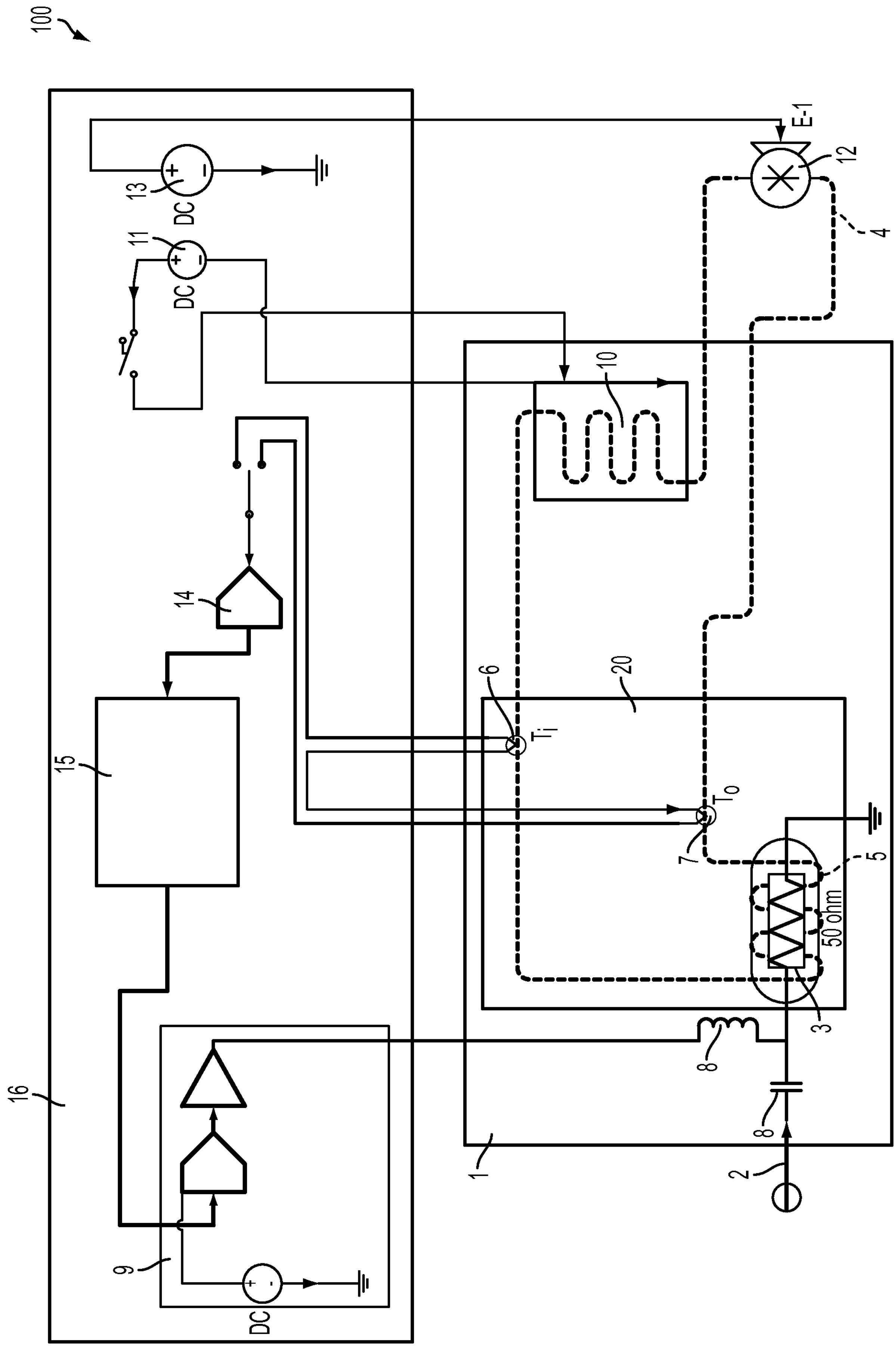


FIG. 2

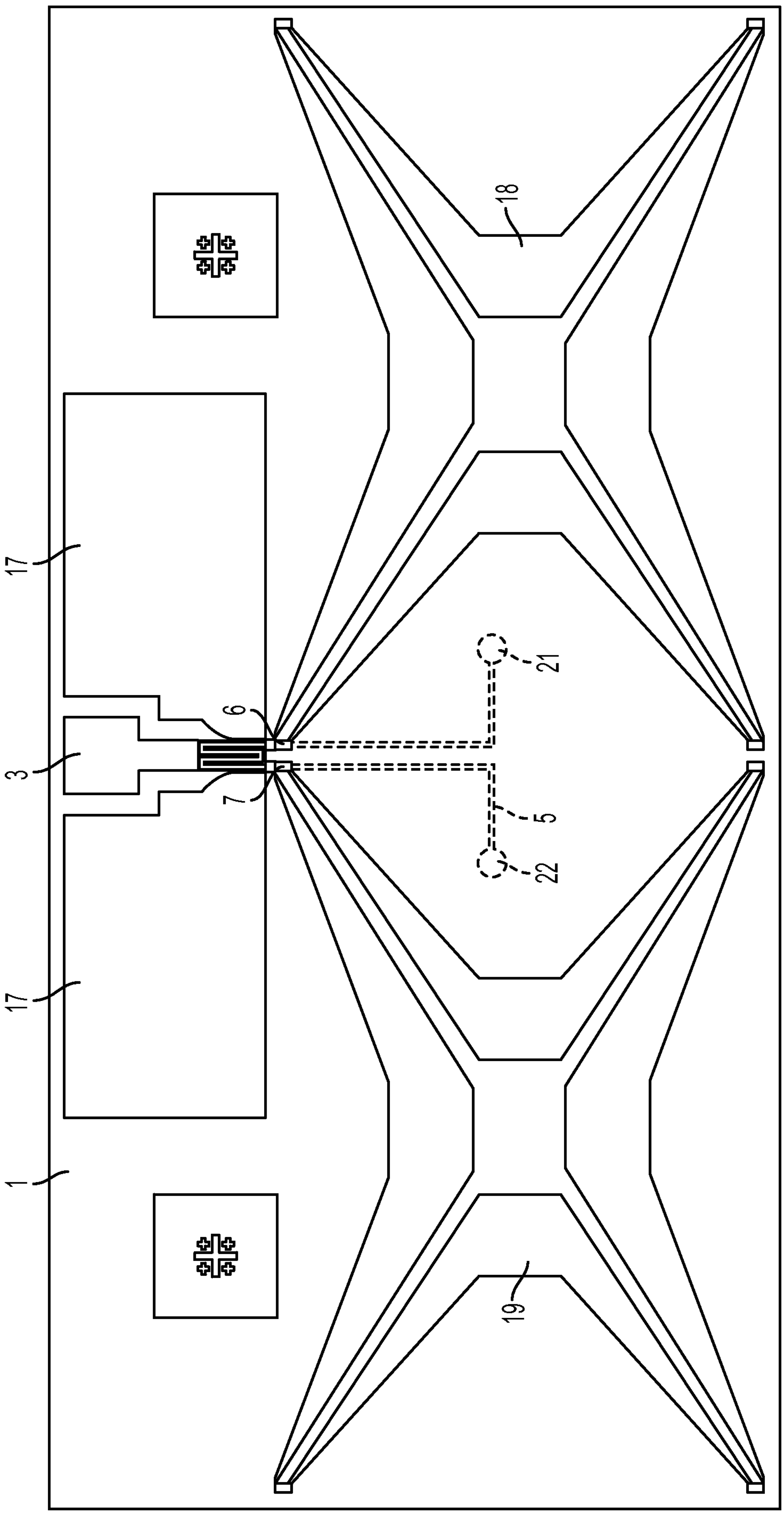


FIG. 3

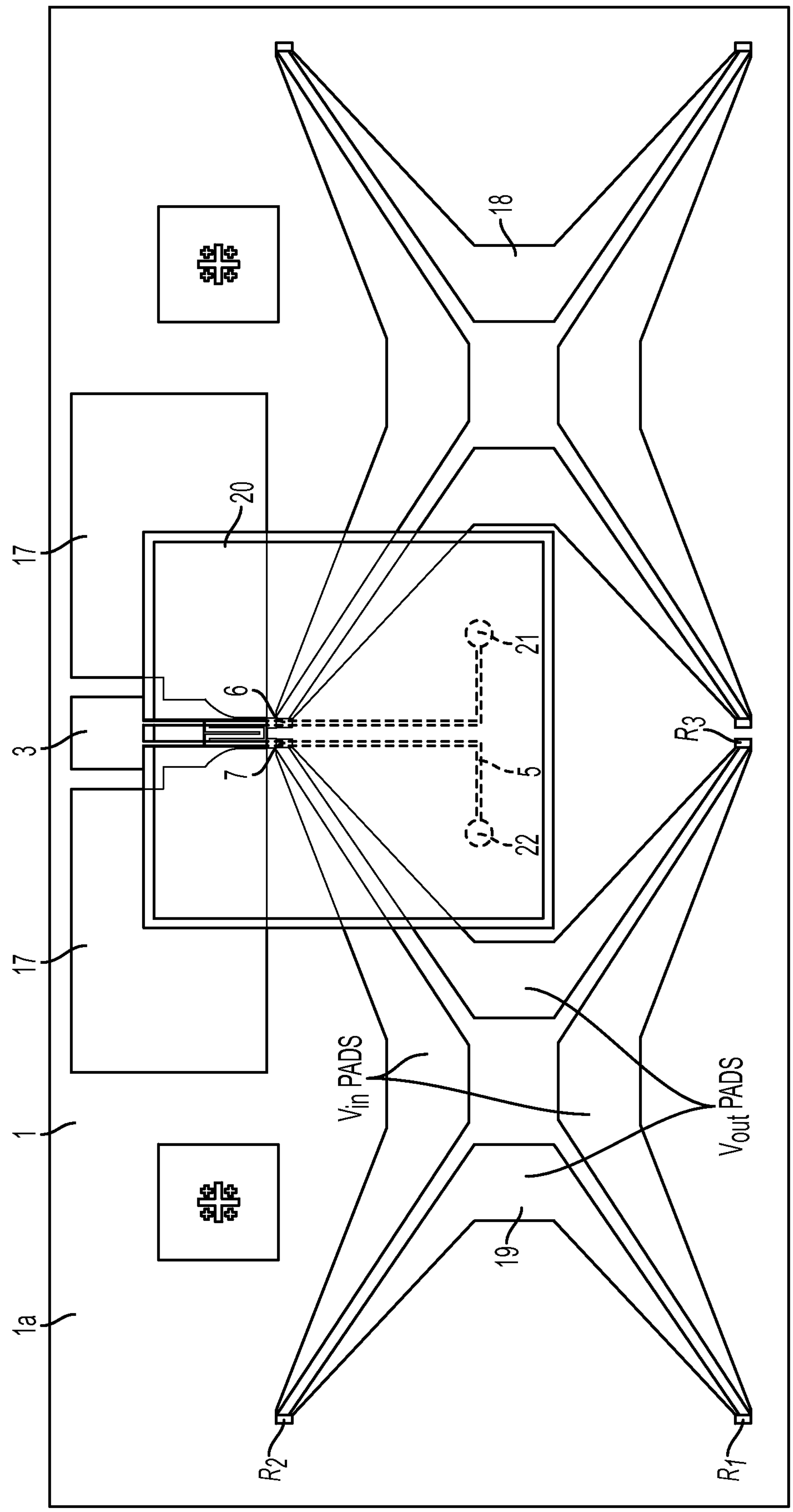


FIG. 4A

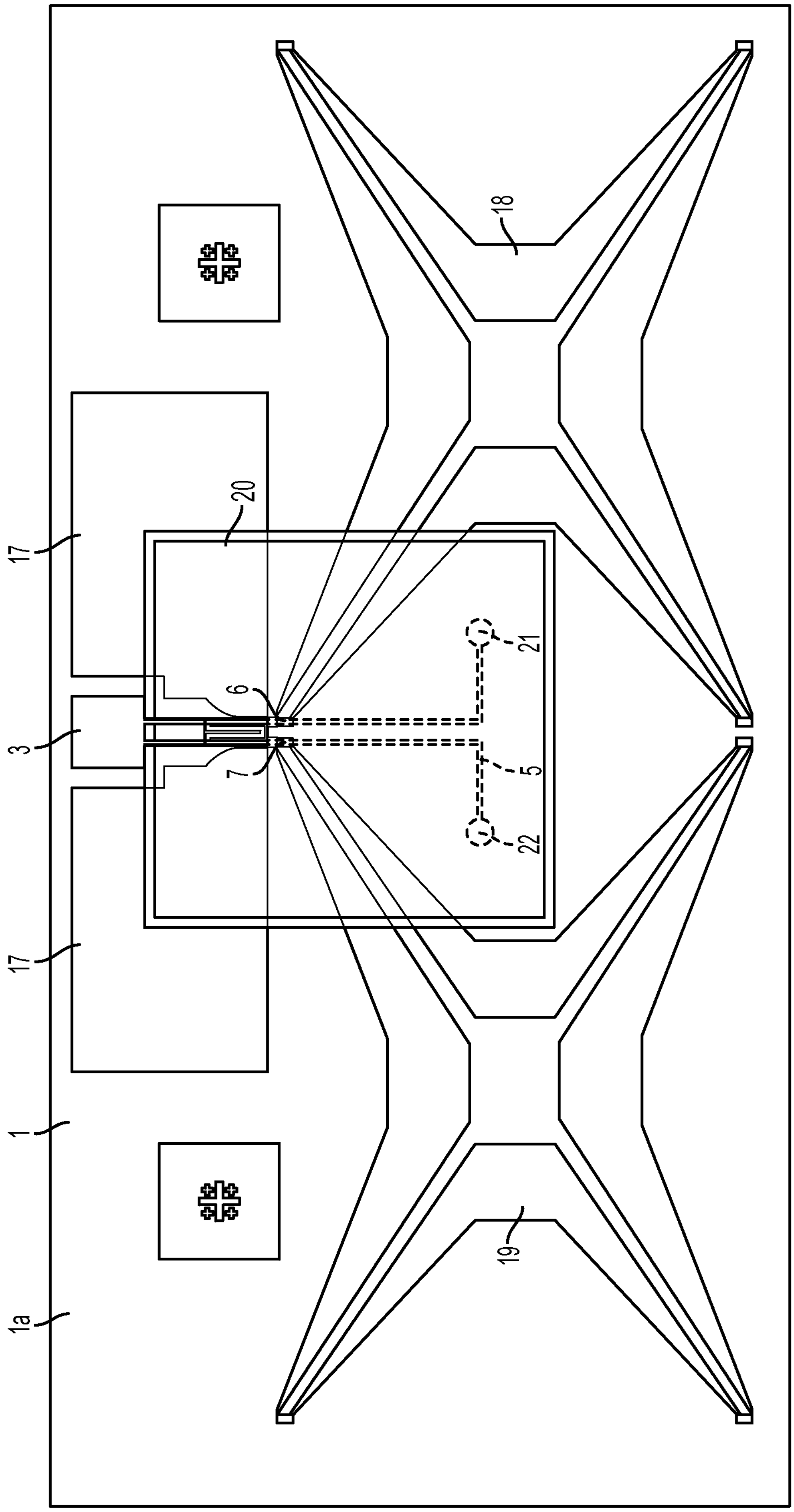


FIG. 4B

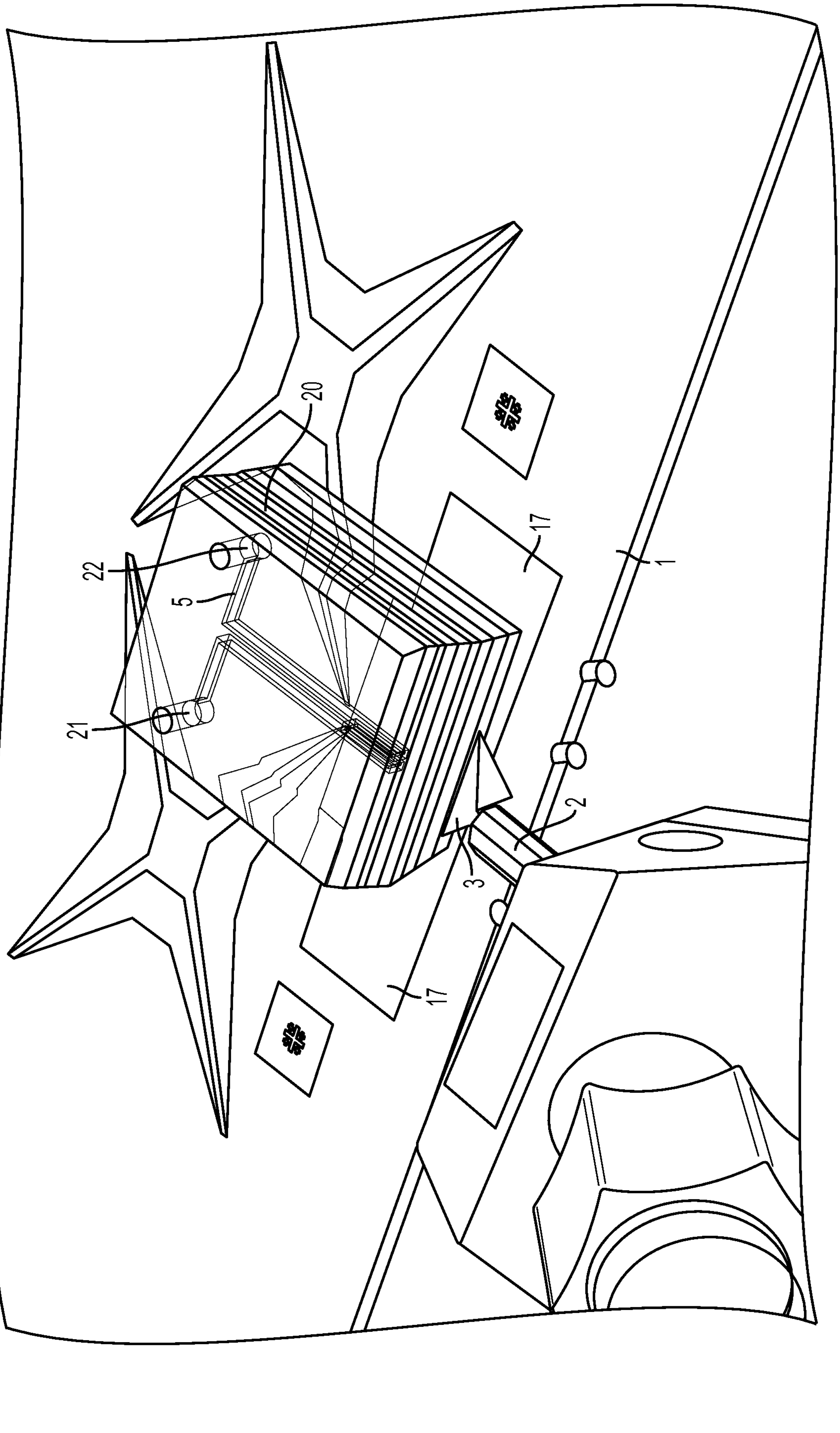


FIG. 5

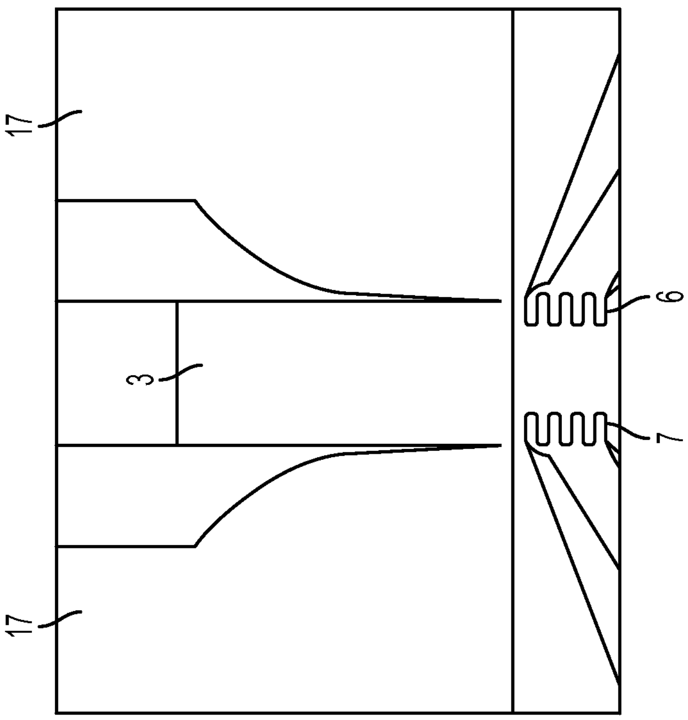


FIG. 6

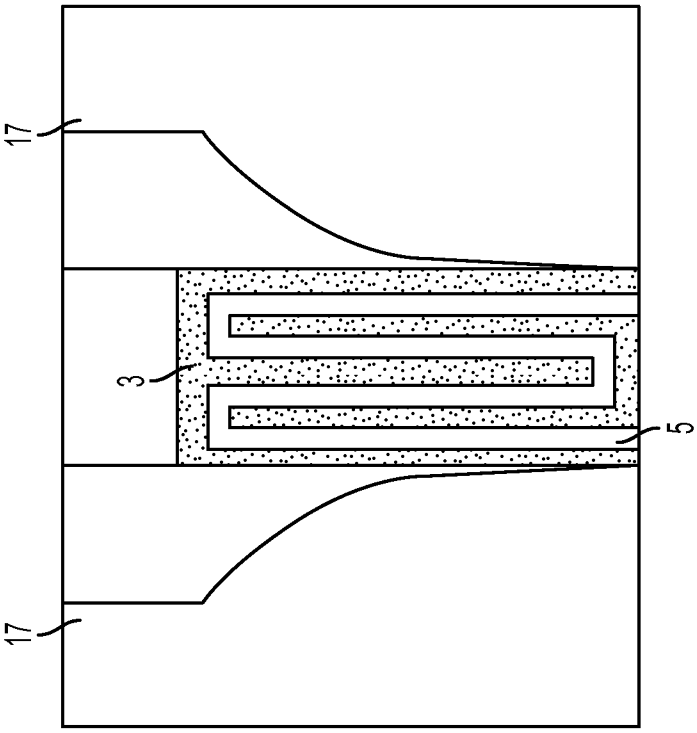


FIG. 7

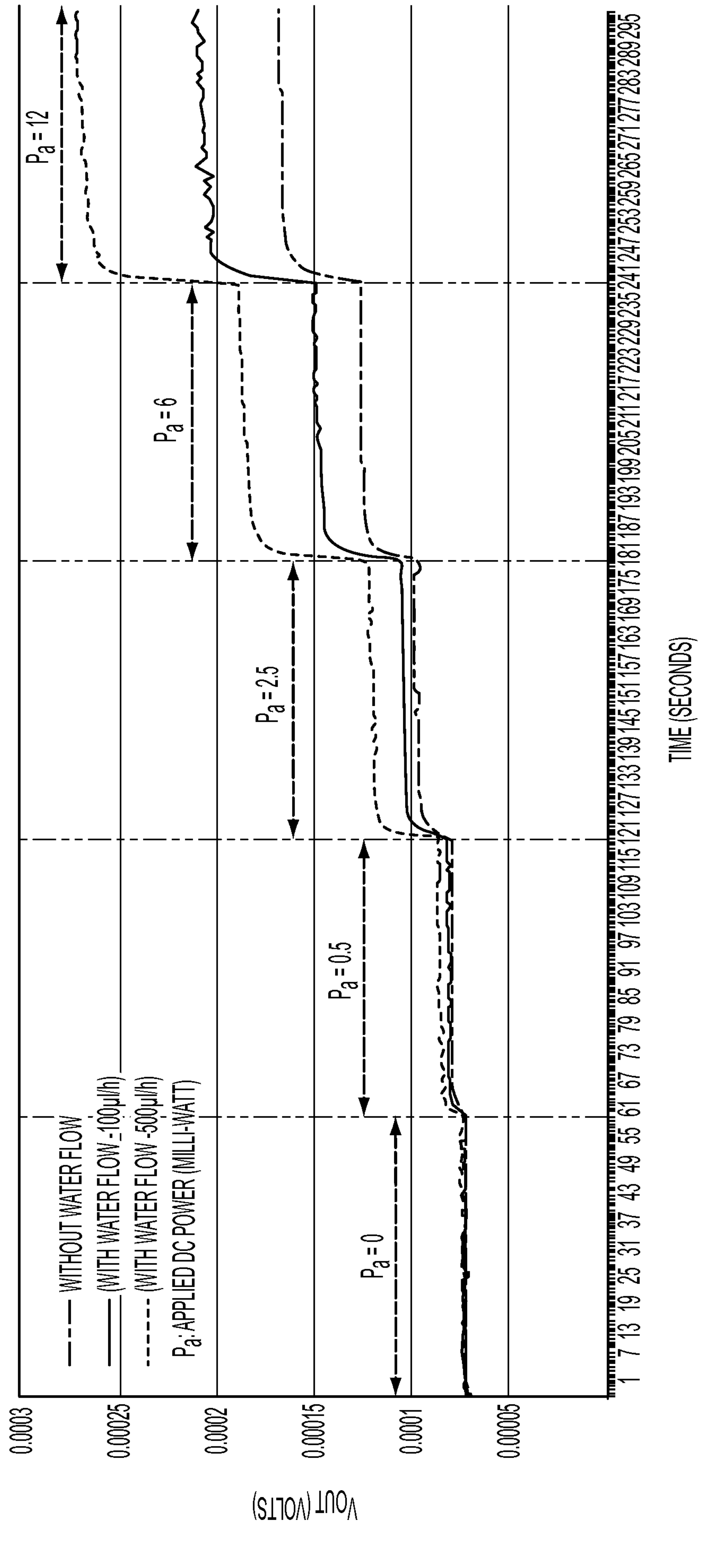

WITHOUT WATER FLOW
(WITH WATER FLOW -100μl/h)
(WITH WATER FLOW -500μl/h)
P_a: APPLIED DC POWER (MILLI-WATT)
P_a = 0
P_a = 0.5
P_a = 2.5
P_a = 6
P_a = 12
0.0003
0.00025
0.0002
0.00015
0.0001
0.00005
V_{OUT} (VOLTS)
TIME (SECONDS)

FIG. 8

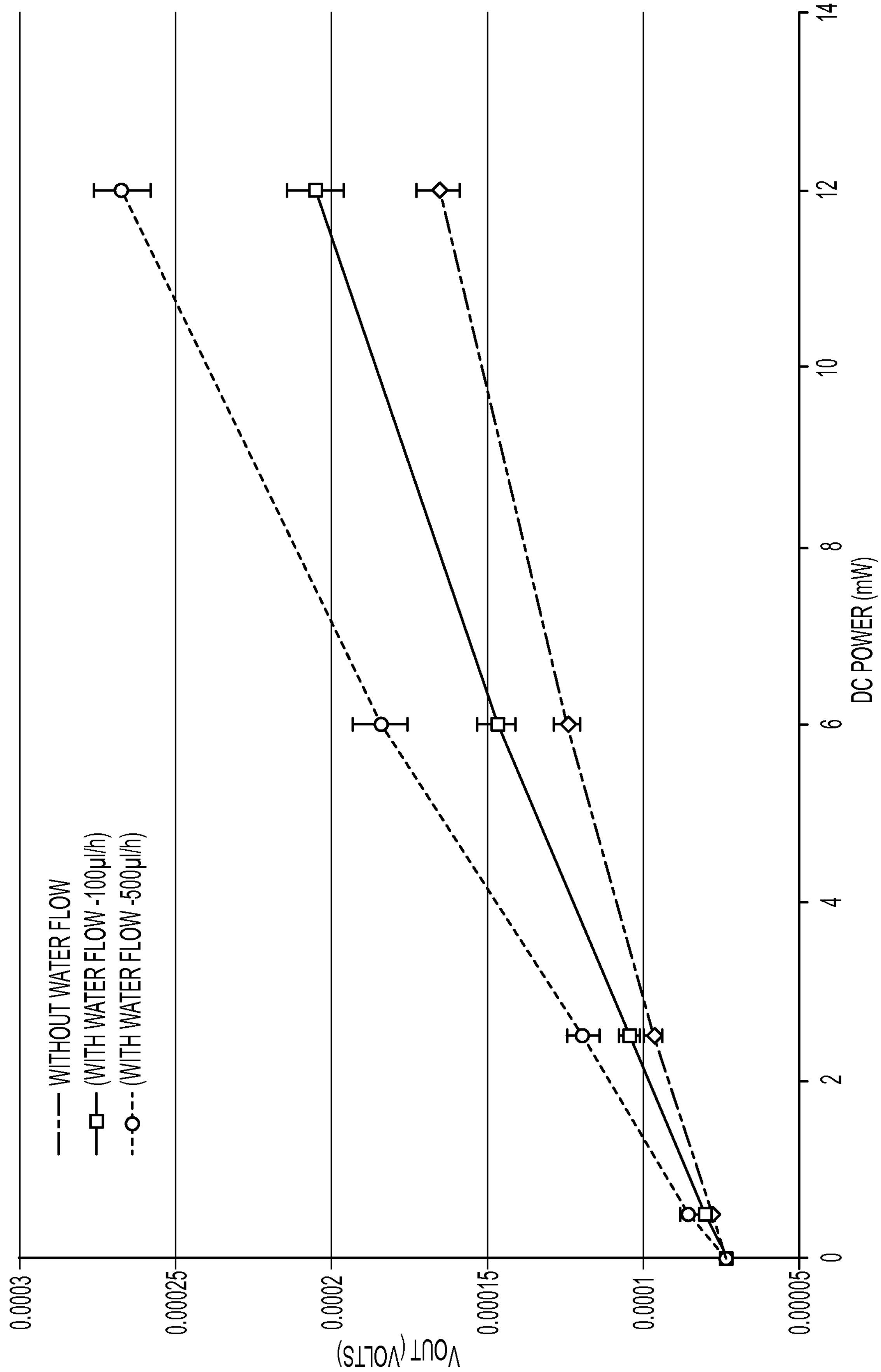

WITHOUT WATER FLOW
(WITH WATER FLOW -100µl/h)
(WITH WATER FLOW -500µl/h)
0.0003
0.00025
0.0002
0.00015
0.0001
0.00005
VOUT (VOLTS)
0
2
4
6
8
10
12
14
DC POWER (mW)

FIG. 9

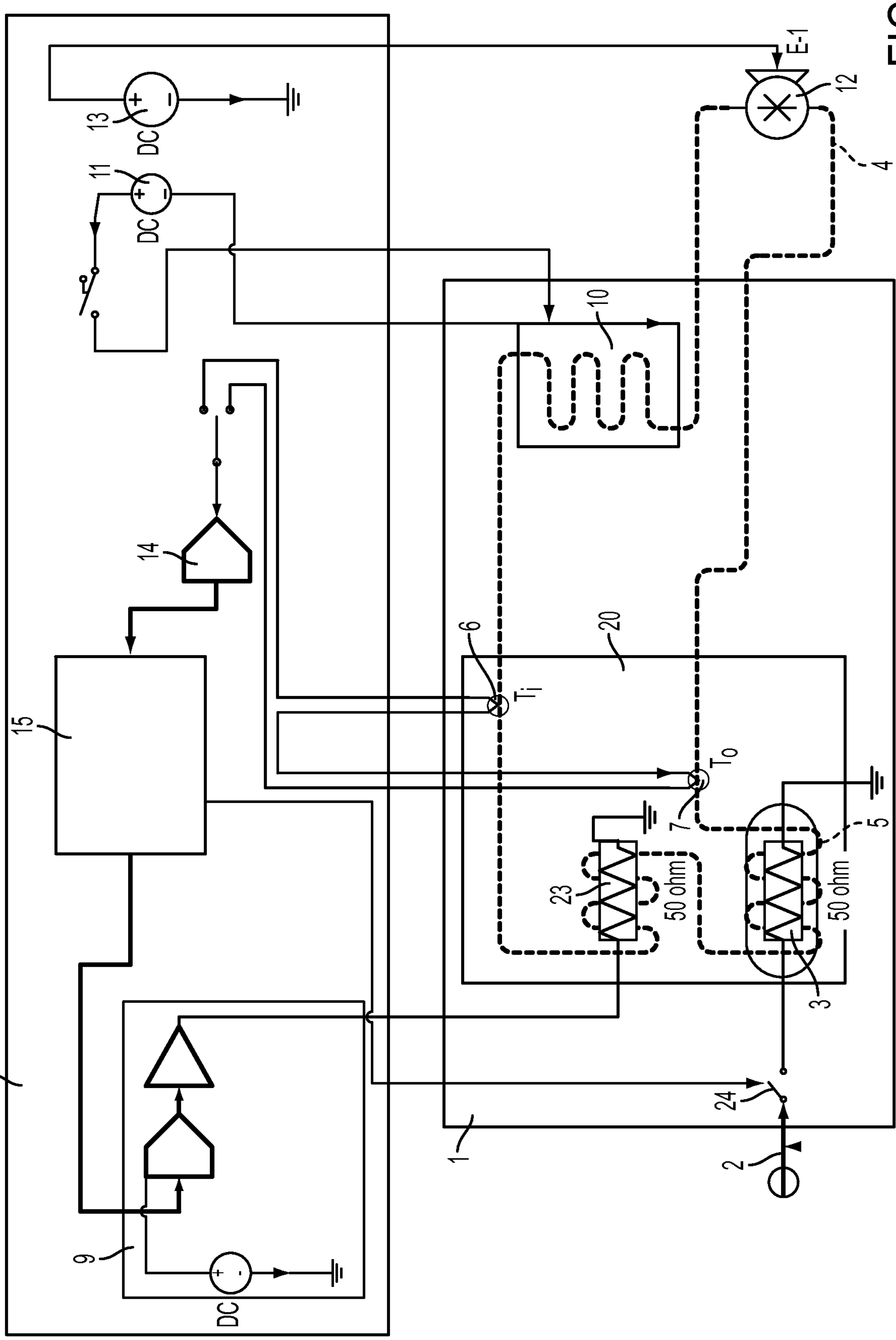

E-1
12
13
DC
11
DC
4
10
14
6
Ti
20
15
To
7
5
23
50 ohm
50 ohm
3
16
24
1
2
9
DC

FIG. 10

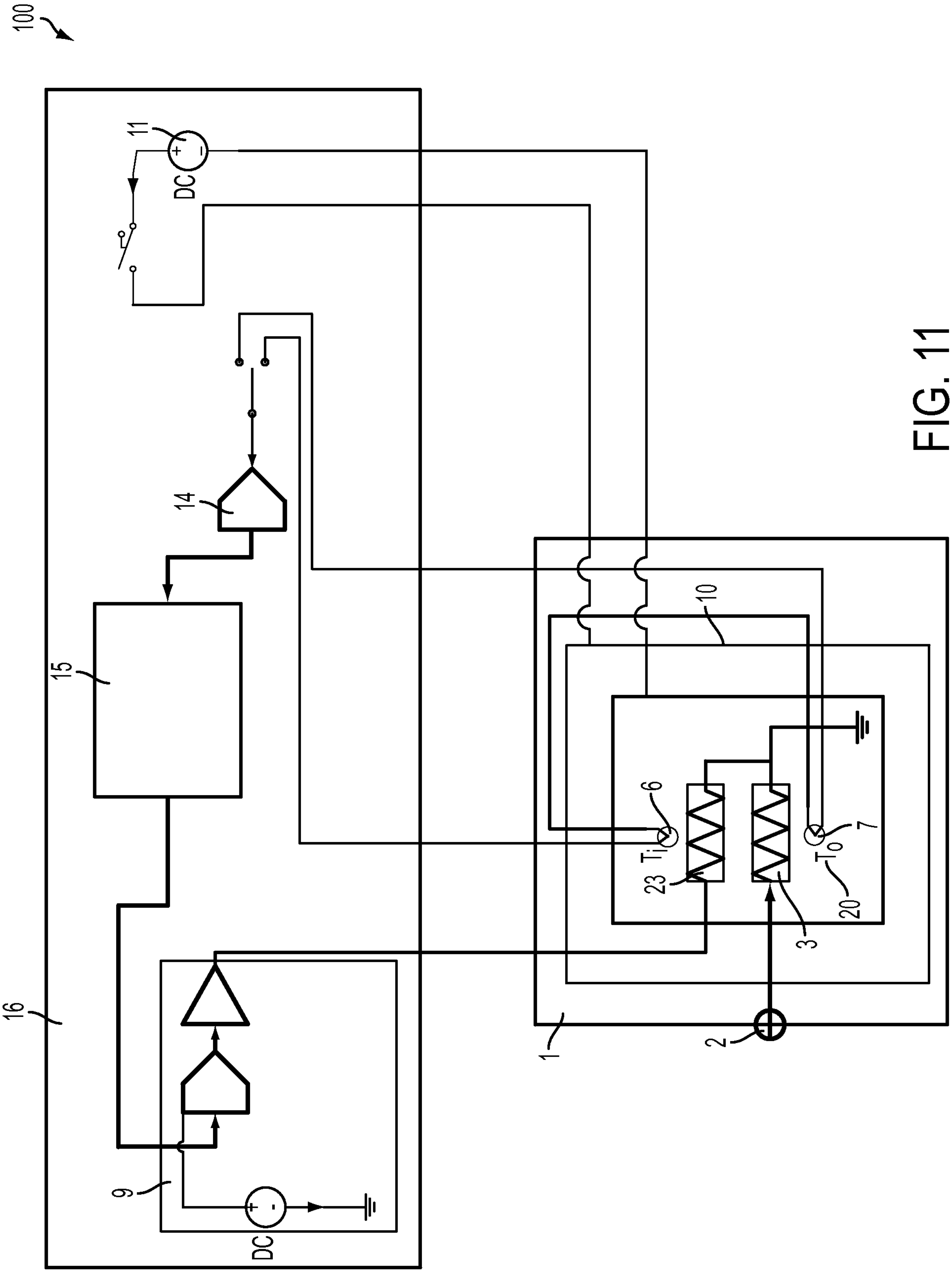


FIG. 11

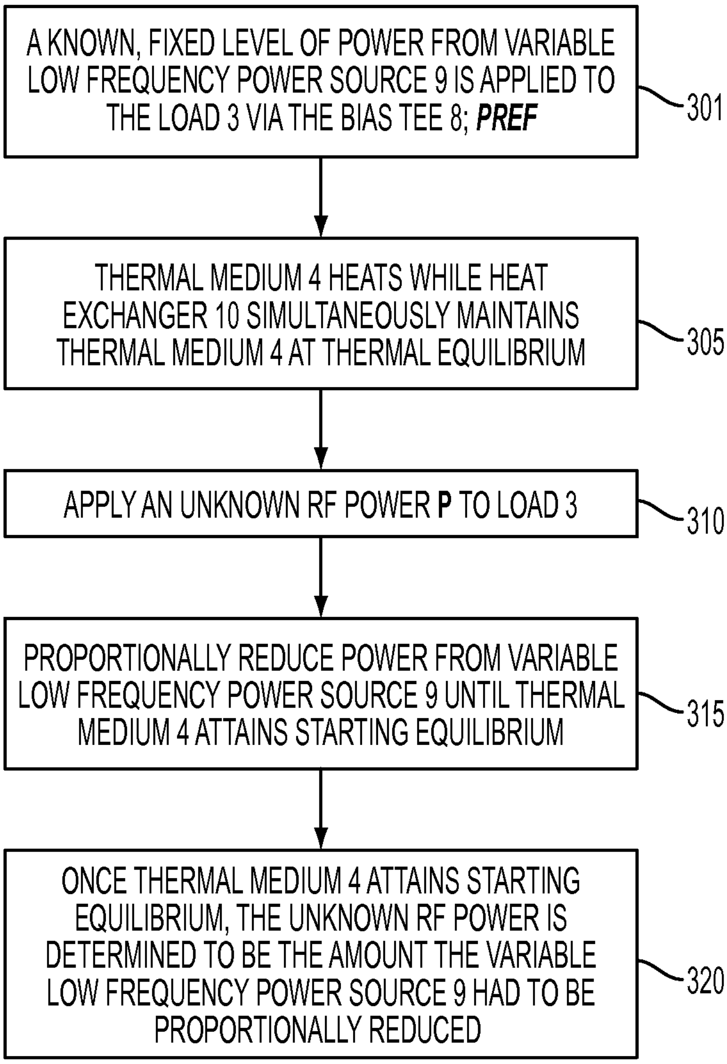

A KNOWN, FIXED LEVEL OF POWER FROM VARIABLE LOW FREQUENCY POWER SOURCE 9 IS APPLIED TO THE LOAD 3 VIA THE BIAS TEE 8; PREF
301
THERMAL MEDIUM 4 HEATS WHILE HEAT EXCHANGER 10 SIMULTANEOUSLY MAINTAINS THERMAL MEDIUM 4 AT THERMAL EQUILIBRIUM
305
APPLY AN UNKNOWN RF POWER P TO LOAD 3
310
PROPORTIONALLY REDUCE POWER FROM VARIABLE LOW FREQUENCY POWER SOURCE 9 UNTIL THERMAL MEDIUM 4 ATTAINS STARTING EQUILIBRIUM
315
ONCE THERMAL MEDIUM 4 ATTAINS STARTING EQUILIBRIUM, THE UNKNOWN RF POWER IS DETERMINED TO BE THE AMOUNT THE VARIABLE LOW FREQUENCY POWER SOURCE 9 HAD TO BE PROPORTIONALLY REDUCED
320

FIG. 12

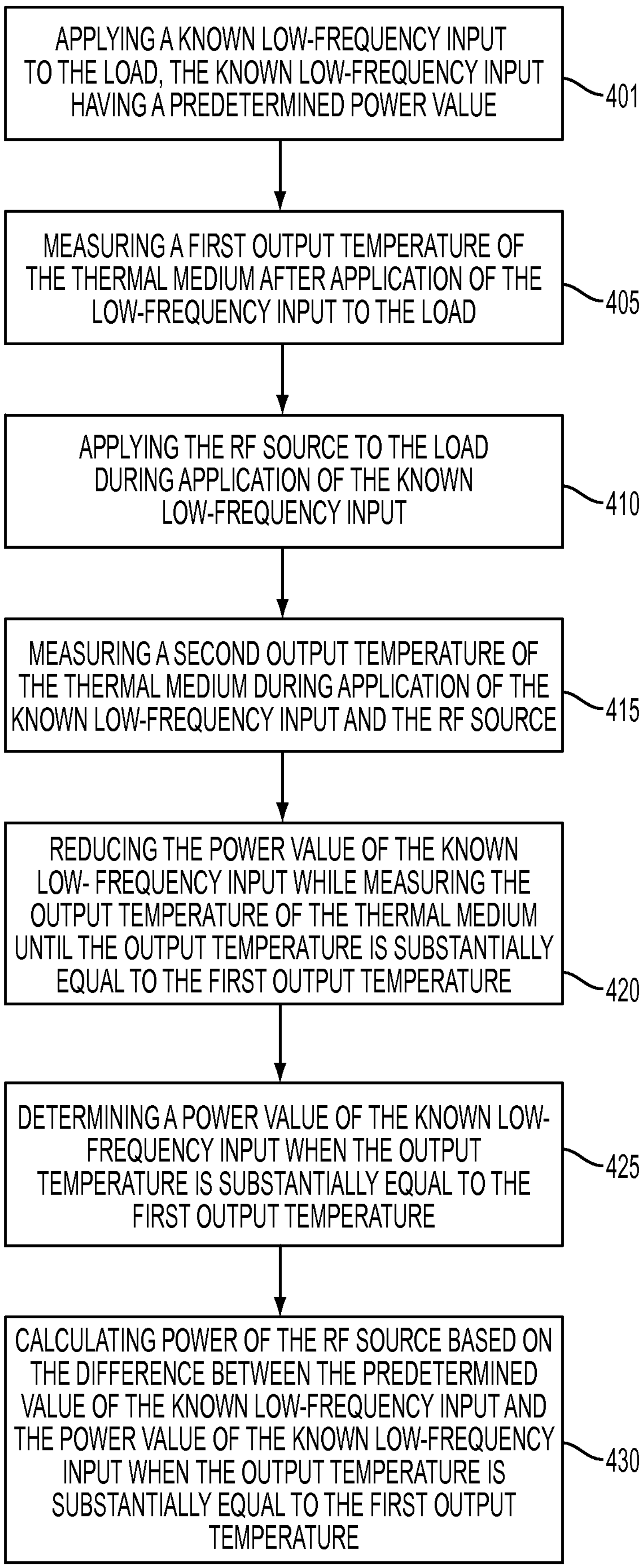

APPLYING A KNOWN LOW-FREQUENCY INPUT TO THE LOAD, THE KNOWN LOW-FREQUENCY INPUT HAVING A PREDETERMINED POWER VALUE
401
MEASURING A FIRST OUTPUT TEMPERATURE OF THE THERMAL MEDIUM AFTER APPLICATION OF THE LOW-FREQUENCY INPUT TO THE LOAD
405
APPLYING THE RF SOURCE TO THE LOAD DURING APPLICATION OF THE KNOWN LOW-FREQUENCY INPUT
410
MEASURING A SECOND OUTPUT TEMPERATURE OF THE THERMAL MEDIUM DURING APPLICATION OF THE KNOWN LOW-FREQUENCY INPUT AND THE RF SOURCE
415
REDUCING THE POWER VALUE OF THE KNOWN LOW- FREQUENCY INPUT WHILE MEASURING THE OUTPUT TEMPERATURE OF THE THERMAL MEDIUM UNTIL THE OUTPUT TEMPERATURE IS SUBSTANTIALLY EQUAL TO THE FIRST OUTPUT TEMPERATURE
420
DETERMINING A POWER VALUE OF THE KNOWN LOW-FREQUENCY INPUT WHEN THE OUTPUT TEMPERATURE IS SUBSTANTIALLY EQUAL TO THE FIRST OUTPUT TEMPERATURE
425
CALCULATING POWER OF THE RF SOURCE BASED ON THE DIFFERENCE BETWEEN THE PREDETERMINED VALUE OF THE KNOWN LOW-FREQUENCY INPUT AND THE POWER VALUE OF THE KNOWN LOW-FREQUENCY INPUT WHEN THE OUTPUT TEMPERATURE IS SUBSTANTIALLY EQUAL TO THE FIRST OUTPUT TEMPERATURE
430

FIG. 13

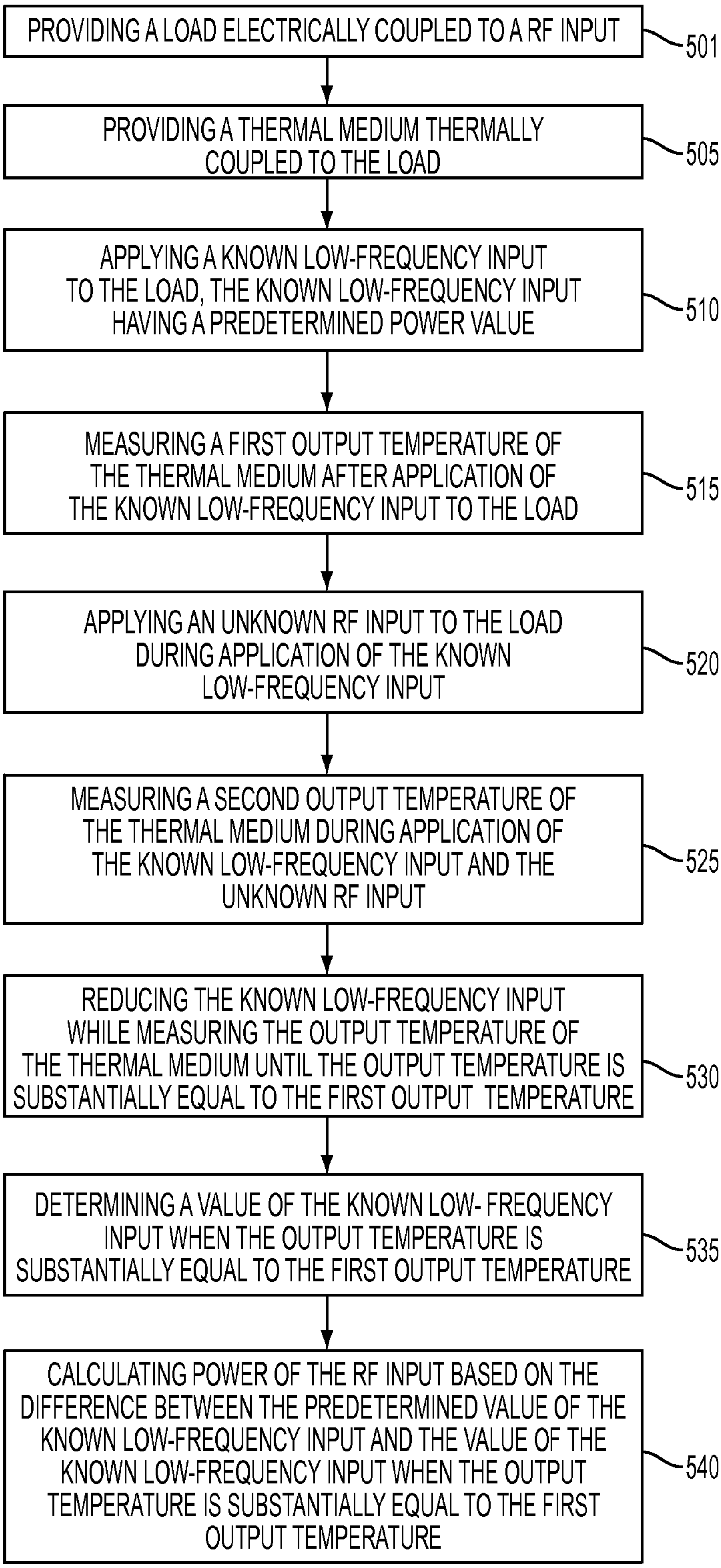

PROVIDING A LOAD ELECTRICALLY COUPLED TO A RF INPUT
501
PROVIDING A THERMAL MEDIUM THERMALLY COUPLED TO THE LOAD
505
APPLYING A KNOWN LOW-FREQUENCY INPUT TO THE LOAD, THE KNOWN LOW-FREQUENCY INPUT HAVING A PREDETERMINED POWER VALUE
510
MEASURING A FIRST OUTPUT TEMPERATURE OF THE THERMAL MEDIUM AFTER APPLICATION OF THE KNOWN LOW-FREQUENCY INPUT TO THE LOAD
515
APPLYING AN UNKNOWN RF INPUT TO THE LOAD DURING APPLICATION OF THE KNOWN LOW-FREQUENCY INPUT
520
MEASURING A SECOND OUTPUT TEMPERATURE OF THE THERMAL MEDIUM DURING APPLICATION OF THE KNOWN LOW-FREQUENCY INPUT AND THE UNKNOWN RF INPUT
525
REDUCING THE KNOWN LOW-FREQUENCY INPUT WHILE MEASURING THE OUTPUT TEMPERATURE OF THE THERMAL MEDIUM UNTIL THE OUTPUT TEMPERATURE IS SUBSTANTIALLY EQUAL TO THE FIRST OUTPUT TEMPERATURE
530
DETERMINING A VALUE OF THE KNOWN LOW- FREQUENCY INPUT WHEN THE OUTPUT TEMPERATURE IS SUBSTANTIALLY EQUAL TO THE FIRST OUTPUT TEMPERATURE
535
CALCULATING POWER OF THE RF INPUT BASED ON THE DIFFERENCE BETWEEN THE PREDETERMINED VALUE OF THE KNOWN LOW-FREQUENCY INPUT AND THE VALUE OF THE KNOWN LOW-FREQUENCY INPUT WHEN THE OUTPUT TEMPERATURE IS SUBSTANTIALLY EQUAL TO THE FIRST OUTPUT TEMPERATURE
540

FIG. 14

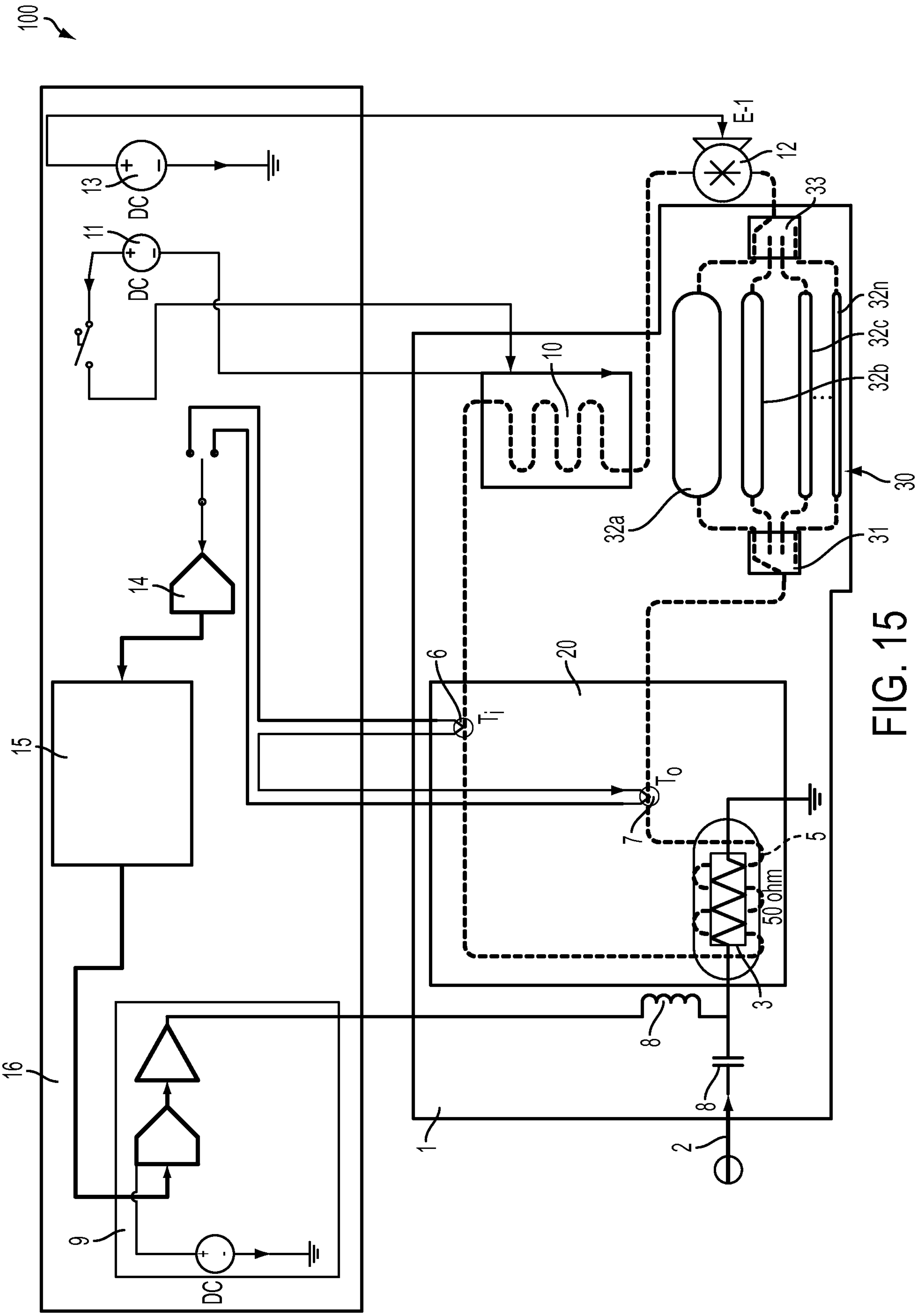

100
DC
13
DC
11
E-1
12
33
10
32a
32b
32c
32n
30
31
14
15
20
6
T_i
T_o
7
5
50 ohm
3
8
8
2
1
16
9
DC

FIG. 15

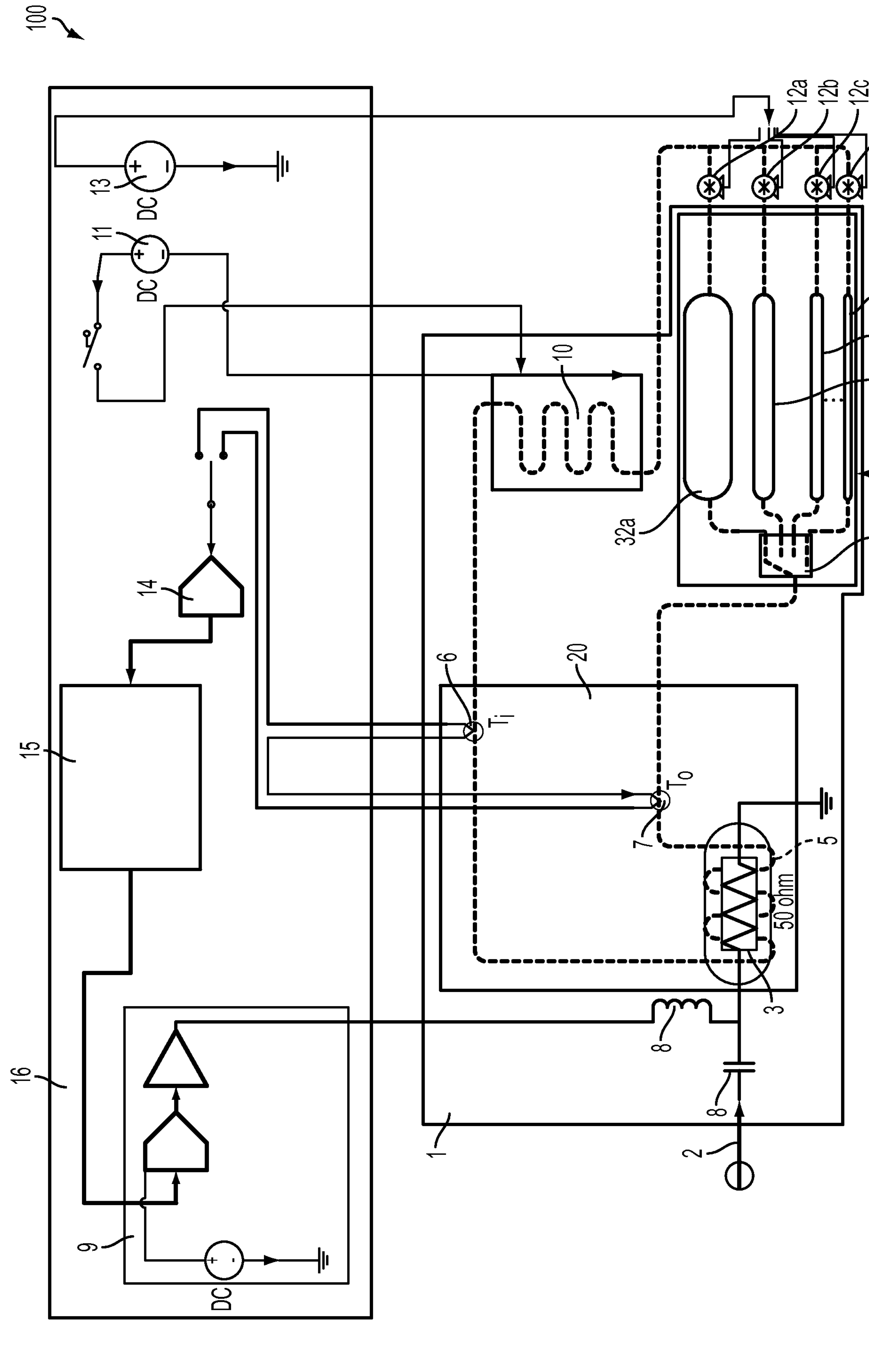

100
12a
12b
12c
12n
13
DC
11
DC
10
32n
32c
32b
30
32a
31
14
20
15
6
T_i
T_o
7
5
50 ohm
3
8
8
16
1
2
9
DC

FIG. 16

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2014/017426

A. CLASSIFICATION OF SUBJECT MATTER

G01K 17/00(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)
G01K 17/00; G01K 17/06; G01H 25/48; G01N 25/20; G01K 17/16

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: calorimeter, radio frequency, power, temperature sensor, load and circuit

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5186540 A (WALSH et al.) 16 February 1993 See abstract; column 4, lines 5-22; column 5, lines 35-39, 61-65; column 6, lines 20-33, 42-62; column 7, lines 12-22 and figure 1.	1-4,15-19,30-32
A	US 4048852 A (SAKAKIBARA et al.) 20 September 1977 See abstract; column 4, lines 4-25; claim 1 and figure 1.	1-4,15-19,30-32
A	US 2010-0046573 A1 (SCHICK et al.) 25 February 2010 See abstract; paragraph 30 and figure 2.	1-4,15-19,30-32
A	US 4531843 A (KUHNLEIN et al.) 30 July 1985 See abstract and claim 1.	1-4,15-19,30-32
A	US 3869914 A (KOEHLER et al.) 11 March 1975 See abstract; column 3, lines 51-67; claim 1 and figure 1.	1-4,15-19,30-32

☐ 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
24 June 2014 (24.06.2014)	**24 June 2014 (24.06.2014)**

Name and mailing address of the ISA/KR
International Application Division
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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2014/017426

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☒ Claims Nos.: 6-9 and 21-24
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
Claims 6-9 and 21-24 are unclear because they refer to multiple dependent claims which do not comply with PCT Rule 6.4(a).

3. ☒ Claims Nos.: 5,10-14,20 and 25-29
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required addtional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of any additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2014/017426

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5186540 A	16/02/1993	None	
US 4048852 A	20/09/1977	JP 1106739 C	30/07/1982
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		JP 51-147371 A	17/12/1976
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US 2010-0046573 A1	25/02/2010	AU 2009-256035 A1	10/12/2009
		CA 2725861 A1	10/12/2009
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		EP 2283346 A1	16/02/2011
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		EP 0092042 A3	15/05/1985
		EP 0092042 B1	16/09/1987
US 3869914 A	11/03/1975	US 03869914 A	11/03/1975

(19)中华人民共和国国家知识产权局

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(51)Int.Cl.
G01K 17/00(2006.01)

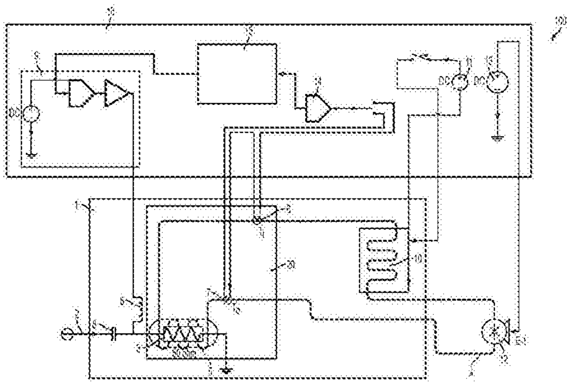
权利要求书3页 说明书11页 附图16页

(54)发明名称

用于RF功率测量的微制造热量计

(57)摘要

公开了射频(RF)功率热量计，其具有电耦合到RF输入的负载、电耦合到负载的可变低频电源并被配置成施加低频偏置到负载。RF功率热量计包括热耦合到负载的热介质。此外，RF功率热量计包括热耦合到热介质的出口温度传感器，该出口温度传感器被设置用于测量由于所述负载加热导致的热介质的温度。RF功率热量计还具有电路，被配置成使用与RF负载热接触的热介质的温度测量结合低频偏置来测量电耦合到RF输入的RF源的平均功率。还公开了使用RF功率热量计测量RF功率的方法。



CN 105143841 A

1.一种射频(RF)功率热量计,包括:

负载,电耦合到RF输入,该RF输入被配置成电耦合到RF电源;

可变低频电源,电耦合到所述负载,该可变低频电源被配置成施加低频功率到所述负载;

热介质,热耦合到所述负载;

出口温度传感器,热耦合到所述热介质,该出口温度传感器被设置用于测量由于所述负载加热导致的所述热介质的温度;

电路,被配置成通过以下计算电耦合到所述RF输入的所述RF源的功率:

使用来自所述低频电源的可变偏置基于所述热介质的温度测量来确定所述RF源的平均功率。

2.根据权利要求1所述的RF功率热量计,其中确定所述RF源的平均功率包括:

施加已知低频输入到所述负载,该已知低频输入具有预定功率值;

在施加所述低频输入到所述负载之后测量所述热介质的第一输出温度;

在施加所述已知低频输入期间施加所述RF源到所述负载;

在施加所述已知低频输入和所述RF源期间测量所述热介质的第二输出温度;

在测量所述热介质的所述输出温度时降低所述已知低频输入的所述功率值,直到所述输出温度基本等于所述第一输出温度;

在所述输出温度基本等于所述第一输出温度时,确定所述已知低频输入的功率值;以及

基于所述已知低频输入的所述预定值与当所述输出温度基本等于所述第一输出温度时所述已知低频输入的所述功率值之间的差来计算所述RF源的功率。

3.根据权利要求1或2所述的RF功率热量计,其中所述可变低频电源是交流电电压源。

4.根据权利要求1或2所述的RF功率热量计,其中所述可变低频电源是直流电电压源。

5.根据上述任意一项权利要求所述的RF功率热量计,其中所述热介质是通过热介质通道流通的流体。

6.根据权利要求5所述的RF功率热量计,其中通过所述热介质通道的所述热介质流体的流量是可变的。

7.根据权利要求6所述的RF功率热量计,所述RF功率热量计还包括包括多个流体通道的流体通道路径阵列,被配置成改变通过所述热介质通道的所述热介质流体的所述流量。

8.根据权利要求7所述的RF功率热量计,其中所述流体通道路径阵列包括与多个流体通道在流体上连接的流体开关,所述流体通道路径阵列的每个流体通道具有不同的长度和/或水力直径。

9.根据权利要求8所述的RF功率热量计,其中所述流体通道路径阵列的每个流体通道具有热介质泵。

10.根据权利要求1-4中任意一项权利要求所述的RF功率热量计,其中所述热介质是与热交换器热耦合的衬底。

11. 根据上述任意一项权利要求所述的 RF 功率热量计，其中所述出口温度传感器是惠斯通桥。

12. 根据上述任意一项权利要求所述的 RF 功率热量计，其中所述功率热量计被配置成测量大约 100μW 与 100mW 之间的功率。

13. 根据上述任意一项权利要求所述的 RF 功率热量计，其中所述功率热量计被配置成测量下至 0Hz 以及远高于 12GHz 频率的功率。

14. 根据上述任意一项权利要求所述的 RF 功率热量计，其中所述 RF 功率热量计还包括不导电衬底，其中所述负载和输出传感器在所述不导电衬底上被微制造。

15. 一种 RF 功率热量计，包括具有热介质和低频电源的微制造的热量计；所述功率热量计被配置成使用来自所述低频电源的可变偏置基于所述热介质的温度测量来确定 RF 源的平均功率。

16. 一种测量射频 (RF) 功率的方法，该方法包括：

提供电耦合到 RF 输入的负载；

提供热耦合到所述负载的热介质；

施加已知低频输入到所述负载，该已知低频输入具有预定功率值；

在施加所述已知低频输入到所述负载之后测量所述热介质的第一输出温度；

在施加所述已知低频输入期间施加未知 RF 输入到所述负载；

在施加所述已知低频输入和所述未知 RF 输入期间测量所述热介质的第二输出温度；

在测量所述热介质的所述输出温度同时降低所述已知低频输入，直到所述输出温度基本等于所述第一输出温度；

当所述输出温度基本等于所述第一输出温度时确定所述已知低频输入的值；以及

基于所述已知低频输入的所述预定值与当所述输出温度基本等于所述第一输出温度时的所述已知低频输入的值之间的差来计算所述 RF 输入的功率。

17. 根据权利要求 16 所述的方法，其中所述方法通过使用微制造 RF 功率热量计而被执行。

18. 根据权利要求 17 所述的方法，其中所述可变低频输入是交流电电压源。

19. 根据权利要求 17 或 18 所述的方法，其中所述可变低频输入是直流电电压源。

20. 根据权利要求 17-19 中任意一项权利要求所述的方法，其中所述热介质是通过热介质通道流通的流体。

21. 根据权利要求 20 所述的 RF 功率热量计，其中通过所述热介质通道的所述热介质流体的流量是可变的。

22. 根据权利要求 21 所述的 RF 功率热量计，还包括包括多个流体通道的流体通道路径阵列，被配置成改变通过所述热介质通道的所述热介质流体的所述流量。

23. 根据权利要求 22 所述的 RF 功率热量计，其中所述流体通道路径阵列包括与多个流体通道流体上连接的流体开关，所述流体通道路径阵列的每一个流体通道具有不同的长度和 / 或水力直径。

24. 根据权利要求 23 所述的 RF 功率热量计，其中所述流体通道路径阵列的每一个流体通道具有热介质泵。

25. 根据权利要求 17-20 中任意一项权利要求所述的方法，其中所述热介质是热耦合

到热交换器的衬底。

26. 根据权利要求 17-25 中任意一项权利要求所述的方法，其中所述输出温度通过使用惠斯通桥温度传感器而被得到。

27. 根据权利要求 17-26 中任意一项权利要求所述的方法，其中所述功率热量计被配置成测量大约 100μW 与 100mW 之间的功率。

28. 根据权利要求 17-27 中任意一项权利要求所述的方法，其中所述功率热量计被配置成测量下至 0Hz 和远高于 12GHz 的频率的功率。

29. 根据权利要求 17-28 中任意一项权利要求所述的方法，其中所述 RF 功率热量计还包括不导电衬底；其中所述负载和输出传感器在所述不导电衬底上被微制造。

30. 一种测量射频功率的方法，该方法包括：

使用与 RF 负载热接触的热介质的温度测量结合 DC 偏置来测量平均功率。

31. 根据权利要求 30 所述的测量射频功率的方法，其中所述方法包括：

使用流过 RF 负载的流体的温度测量结合 DC 偏置来测量平均功率。

32. 一种射频 (RF) 功率热量计，包括：

负载，电耦合到 RF 输入；

可变低频电源，电耦合到所述负载，该可变低频电源被配置成施加低频偏置到所述负载；

热介质，热耦合到所述负载；

热耦合到所述热介质的出口温度传感器，该出口温度传感器被设置用于测量由于所述负载加热导致的所述热介质的温度；

电路，被配置成使用与 RF 负载热接触的所述热介质的温度测量结合所述低频偏置来测量电耦合到所述 RF 输入的 RF 源的平均功率。

用于 RF 功率测量的微制造热量计

[0001] 相关申请的交叉引用

[0002] 本申请要求 2013 年 2 月 22 日申请的题为“MICROFABRICATED CALORIMETER FOR RF POWER MEASUREMENT”的美国临时专利申请序列号 No.61/767,872 的优先权，其全部通过引用的方式结合于此。

技术领域

[0003] 本发明主要涉及射频 (RF) 功率测量。特别地，本发明涉及用于 RF 功率测量的微制造 (microfabricated)DC 替代热量计和使用该热量计的方法。

背景技术

[0004] RF 功率是频繁测量的量，因为其他 RF 电学量，像电流、电压和阻抗难以测量及在 RF 设备中量化。在低频，通过解释已知阻抗上的电压和电流来进行功率测量。但是，在高频，例如 RF 频率，阻抗变化明显且因此直接的功率测量不可行。

[0005] 传统地，手持 RF 功率计通过将高频 RF 功率直接转换成 DC 信号，例如通过使用肖特基 (Schottky) 或砷化镓 (Gallium-Arsenide) 二极管，并测量该 DC 信号来得到直接测量的 RF 功率。但是，使用这些传统直接测量技术的测量计的精度对测量的 RF 信号的频率和波形很敏感。

[0006] 因此，需要对 RF 信号频率或波形不敏感的手持 RF 功率计。

发明内容

[0007] 根据本发明的一个方面，提供了射频 (RF) 功率热量计。RF 功率热量计具有电耦合到 RF 输入的负载，该 RF 输入被配置成被电耦合到 RF 电源 ；电耦合到该负载的可变低频电源，且被配置成提供低频功率给负载 ；热耦合到负载的热介质 ；热耦合到热介质的出口温度传感器，该出口温度传感器被设置以测量由于负载加热导致的热介质的温度 ；电路，被配置成通过以下方式来计算电耦合到 RF 输入的 RF 源的功率 ：使用低频电源的可变偏置基于热介质的温度测量来确定 RF 源的平均功率。

[0008] 在本发明的另一方面中，确定 RF 源的平均功率包括 ：将已知的低频输入施加到负载，该已知的低频输入具有预定功率值 ；在将低频输入施加到负载之后测量热介质的第一输出温度 ；在施加已知低频输入期间施加 RF 源到负载 ；在施加已知低频输入和 RF 源期间测量热介质的第二输出温度 ；在测量热介质的输出温度的时候降低已知低频输入的功率值，直到输出温度基本上等于第一输出温度 ；当输出温度基本上等于第一输出温度时确定已知低频输入的功率值 ；以及基于已知低频输入的预定值与当输出温度基本等于第一输出温度时已知低频输入的功率值之间的差来计算 RF 源的功率。

[0009] 在本发明的另一方面中，可变低频电源是交流电电压源。

[0010] 在本发明的另一方面中，可变低频电源是直流电电压源。

[0011] 在本发明的另一方面中，热介质是通过热介质通道流通的流体。

[0012] 在本发明的另一方面中，通过热介质通道的热介质流体的流量是可变的。

[0013] 在本发明的另一方面中，包括多个流体通道的流体通道路径阵列被配置成改变通过热介质通道的热介质流体的流量。

[0014] 在本发明的另一方面中，流体通道路径阵列包括与多个流体通道进行流体上连通的流体开关，每个流体通道路径阵列的每个流体通道具有不同长度和 / 或水力直径。

[0015] 在本发明的另一方面中，流体通道路径阵列的每个流体通道具有热介质泵。

[0016] 在本发明的另一方面中，热介质是与热交换器热耦合的衬底。

[0017] 在本发明的另一方面中，出口温度传感器是惠斯通桥 (Wheatstone bridge)。

[0018] 在本发明的另一方面中，功率热量计被配置成测量大约 100μW 与 100mW 之间的功率。

[0019] 在本发明的另一方面中，功率热量计被配置成在下至 0Hz 以及远高于 12GHz 的频率测量功率。

[0020] 在本发明的另一方面中，功率热量计被配置成在大约 0Hz 与大约 12GHz 之间的频率测量功率。

[0021] 在本发明的另一方面中，RF 功率热量计还包括不导电衬底；其中负载和输出传感器在该不导电衬底上被微制造。

[0022] 在本发明的进一步的方面中，RF 功率热量计是具有热介质和低频电源的微制造热量计；功率热量计被配置成使用低频电源的可变偏置基于热介质的温度测量来确定 RF 源的平均功率。

[0023] 根据本发明的另一个方面，提供了测量 RF 功率的方法。该测量 RF 功率的方法包括：提供电耦合到 RF 输入的负载；提供热耦合到负载的热介质；施加已知低频输入到负载，该已知低频输入具有预定功率值；在施加已知低频输入到负载之后测量热介质的第一输出温度；在施加已知低频输入期间施加未知 RF 输入到负载；在施加已知低频输入和未知 RF 输入期间测量热介质的第二输出温度；在测量热介质的输出温度时降低已知低频输入，直到输出温度基本等于第一输出温度；当输出温度基本定于第一输出温度时确定已知低频输入的值；以及基于已知低频输入的预定值与当输出温度基本等于第一输出温度时已知低频输入的值之间的差来计算 RF 输入的功率。

[0024] 在本发明的另一方面中，使用微制造 RF 功率热量计来执行该方法。

[0025] 在本发明的另一方面中，可变低频输入是交流电电压源。

[0026] 在本发明的另一方面中，可变低频输入是直流电电压源。

[0027] 在本发明的另一方面中，热介质是通过热介质通道流通的流体。

[0028] 在本发明的另一方面中，通过热介质通道的热介质流体的流量是可变的。

[0029] 在本发明的另一方面中，包括多个流体通道的流体通道路径阵列被配置成改变通过热介质通道的热介质流体的流量。

[0030] 在本发明的另一方面中，流体通道路径阵列包括与多个流体通道进行流体连通的流体开关，流体通道路径阵列的每个流体通道具有不同长度和 / 或水力直径。

[0031] 在本发明的另一方面中，流体通道路径阵列的每个流体通道具有热介质泵。

[0032] 在本发明的另一方面中，热介质是热耦合到热交换器的衬底。

[0033] 在本发明的另一方面中，使用惠斯通桥温度传感器来得到输出温度。

[0034] 在本发明的另一方面中，功率热量计被配置成测量在大约100μW与100mW之间的功率。

[0035] 在本发明的另一方面中，功率热量计被配置成在下至0Hz和远高于12GHz的频率测量功率。

[0036] 在本发明的另一方面中，功率热量计被配置成在大约0Hz与大约12GHz之间的频率测量功率。

[0037] 在本发明的另一方面中，RF功率热量计还包括不导电衬底；其中负载和输出传感器在该不导电衬底上被微制造。

[0038] 根据本发明的另一方面，测量射频功率的方法包括：使用在RF负载上移动的流体的温度测量结合DC偏置来测量平均功率。

[0039] 根据本发明的另一方面，测量射频功率的方法包括使用与RF负载热接触的热介质的温度测量结合DC偏置来测量平均功率。

[0040] 根据本发明的另一方面，射频(RF)功率热量计包括：电耦合到RF输入的负载；电耦合到负载的可变低频电源，并被配置成施加低频偏置到负载；热耦合到负载的热介质；热耦合到热介质的出口温度传感器，该出口温度传感器被设置用于测量由于负载加热导致的热介质的温度；以及电路，被配置成使用与RF负载热接触的热介质的温度测量结合低频偏置来测量电耦合到RF输入的RF源的平均功率。

[0041] 本领域技术人员通过以下在附图中示出并通过说明的方式描述的具体实施方式中可以更清楚本发明的优点。可以知道，本发明能够有其他不同的实施方式，且其细节能够在许多方面进行修改。

附图说明

[0042] 现在通过示例方式并结合附图描述本发明的实施方式，其中尤其示出了本发明的这些和其他特征以及其他优点，在附图中：

[0043] 图1是常规RF绝对流热量计的框图；

[0044] 图2是根据本发明的实施方式的微制造RF功率测量热量计的框图；

[0045] 图3是根据本发明的实施方式的微制造RF功率测量热量计的第一衬底的布局；

[0046] 图4a-b描绘了根据本发明的实施方式的微制造RF功率测量热量计的第一衬底和第二衬底；

[0047] 图5描绘了根据本发明的实施方式的微制造RF功率测量热量计的第一衬底和第二衬底；

[0048] 图6是根据本发明的实施方式的微制造RF功率测量热量计的第一衬底的部分特写；

[0049] 图7是根据本发明的实施方式的微制造RF功率测量热量计的第一衬底的部分特写；

[0050] 图8是根据本发明的实施方式的针对微制造RF功率测量热量计在不同DC功率的测量电压vs时间的图；

[0051] 图9是根据本发明的实施方式针对微制造RF功率测量热量计在多个流量的测量电压vs施加的DC功率的图；

[0052] 图 10 是根据本发明的实施方式的微制造 RF 功率测量热量计的框图；

[0053] 图 11 是根据本发明的另一实施方式的微制造 RF 功率测量热量计的框图；

[0054] 图 12 是根据本发明的实施方式的使用微制造 RF 功率测量热量计测量功率的方法的流程图；

[0055] 图 13 是根据本发明的实施方式的使用微制造 RF 功率测量热量计测量功率的另一方法的流程图；

[0056] 图 14 是根据本发明的实施方式的使用微制造 RF 功率测量热量计测量功率的另外方法的流程图；

[0057] 图 15 是根据本发明的实施方式的微制造 RF 功率测量热量计的框图；以及

[0058] 图 16 是根据本发明的实施方式的微制造 RF 功率测量热量计的框图。

[0059] 应当注意所有这些附图是示意图且没有按比例绘制。这些图的部分的相对尺寸和比例被放大或缩小示出以为了附图的清晰和方便。相同的附图标记一般用于指不同实施方式中相应或相似的特征。因此，附图和说明书为认为性质上是示意性而非限制性。

具体实施方式

[0060] 说明书和权利要求书中使用的近似语言可以用于修改可允许变化的任意量化表述而不导致其相关的基础功能的改变。因此，例如“大约”这样的术语修改的值不应限于指定的精确值。在至少一些情况中，近似语言可以对应于用于测量值的仪器的精度。范围限制可以被结合和 / 或互换，且这种范围被确定并包括其中描述的所有小范围，除非上下文或语言另有指明。除了在该操作示例或另有指明，说明书和权利要求书中使用的涉及成分的量、反应条件等的所有数字或表达被理解为在所有情况中由术语“大约”来修改。

[0061] “可选的”或“可选地”是指随后描述的事件或环境可以发生或可以不发生，或者随后确定的材料可以存在或可以不存在，以及描述包括事件或环境发生或材料存在的实例，以及事件或环境不发生或材料不存在的实例。

[0062] 这里使用的术语“包括”、“包含”、“具有”或任意其他变化旨在涵盖非封闭式包括。例如，包括一些元素的过程、方法、物品或设备不必仅限于这些元素，而是可以包括没有明确列出或内在地在该过程、方法、物品或设备中的其他元素。

[0063] 单数形式“一”、“一个”和“该”包括多数形式，除非上下文明确另有指明。

[0064] 微波 RF 功率测量的基础概念是高频功率转换成 DC 信号并测量该得到的 DC 信号。RF 功率测量热量计，例如图 1 中示出的绝对流 RF 功率测量热量计，已经被研究并显示是在某些情况中用于 RF 功率测量的可接受方法。

[0065] 图 1 中示出了常规 RF 绝对流热量计的系统级框图。RF 功率被传递到内部负载电阻。该负载电阻是中空的且具有通过该电阻的工作流体流。泵用于将该流体从储库流通到负载并然后在通过将其传递通过热交换器而散热之后将该流体流回储库。该储库足够大以稳定工作流体并保持平均温度恒定。温度传感器用于测量通过负载之前和之后的流体之间的温度差。传感器通常是热敏电阻，是由于其快速响应和敏感性。流传感器用于确定通过负载的流体的质量流量。通过热力学第一定律，能够根据温度差、质量流量和流体的比热来确定 RF 功率。

[0066] 例如图 1 示出的绝对流热量计太大而不能设置在手持包中，需要使用增加不确定

性并降低精度的流量计，并具有大热质，这在使用DC替代方法时导致长平衡周期和测量获取时间。

[0067]　但是，图2中示出的微制造RF功率测量热量计100能够测量具有100μW至100mW的平均功率的信号。测量的信号的范围能够从低频信号到超过12GHz的信号。此外，图2的热量计100没有使用流量计，这允许在手持设备形式因素的读取的功率测量精度小于0.2％。

[0068]　转到图2，示出的微制造RF功率热量计100的实施方式具有第一衬底1、印刷电路板组件16以及RF输入2。印刷电路板组件16包含可变低频电源9、控制和处理电子设备15、温度测量电子设备14、热交换器电源11以及泵电源13。在一些实施方式中，印刷电路板组件16还包含泵12。但是在其他实施方式中，泵12没有被安装在印刷电路板组件16上。第一衬底1由玻璃构成并提供用于以下制造的组件的基：负载3、热介质4、热介质通道5、入口温度传感器6、出口温度传感器7、偏置三通器8以及热交换器10。可以理解第一衬底10还可以由其他材料构成，包括但不限于石英、陶瓷、硅或砷化镓(GaAs)。

[0069]　在一个示意性实施方式中，RF输入2能够被配置为铜质传输线，其提供到负载3的电路径和从负载3的电流返回路径17。可以理解RF输入2的传输线还可以由其他材料构成，包括但不限于铝、金或铂。负载3是由氮化钽(TaN)制成的电阻器，其吸收电能量并将电能量转换成热。可以想到负载3也可以由其他材料构成，包括但不限于钽、镍络铁合金(NiCr)或三氧化铼(ReO_3)。

[0070]　在图2的实施方式中，热介质4是在热介质通道5中接触负载3、入口温度传感器6、出口温度传感器7和热交换器10的矿物油冷却液。热介质冷却液4通过泵12被通过热介质通道5。该热介质冷却液4从负载3接收热量并将该热量携带到出口温度传感器7。可以想到热介质冷却液4还可以是另一材料，包括但不限于水、矿物油、苯、甲醇或制冷剂。

[0071]　入口温度传感器6测量在冷却液通过负载3并从其接收热量之前热介质通道5中的热介质冷却液4的温度。入口温度传感器6用于在仅来自可变低频电源9的功率被施加到负载3时，且在来自可变低频电源9的功率和来自RF输入2的功率被施加到负载3时，将热介质4维持在入口温度传感器6处的恒定温度。在该实施方式中，入口温度传感器6由铂构成。但是，可以想到入口温度传感器6可以由具有高电阻温度系数(TCR)的其他材料构成，包括但不限于多晶硅或铝。

[0072]　出口温度传感器7测量在冷却液流过负载3并从其接收热量之后热介质通道5中的热介质冷却液4的温度。出口温度传感器7用于当仅来自可变低频电源9的功率被施加到负载时确定在出口温度传感器7处的热介质冷却液温度4，以及还当随着来自可变低频电源9的功率按比例地从负载3移除来自RF输入2的功率被施加到负载3时确定出口温度传感器7处的热介质冷却液温度4，以试图确定何时可变低频电源9从负载3移除的功率等于RF输入2施加到负载3的功率。在该实施方式中，出口温度传感器7由铂构成。但是，可以想到出口温度传感器7可以由具有高电阻温度系数(TCR)的其他材料构成，包括但不限于多晶硅或铝。

[0073]　偏置三通器8由分开的电容器和电感器构成。来自可变低频电源9的功率通过偏置三通器8被施加到负载3。可变低频电源9是精度可变DC电压源或精度低频AC电压源。

[0074]　热交换器10是有源或无源热交换器，其将热介质冷却液4维持在通过冷却热介质

4 的热平衡。当热交换器 10 是有源热交换器时，热交换器电源 11 存在并提供功率给热交换器 10。此外由热介质泵电源 13 供电的热介质泵 12 将热介质冷却液 4 流过热介质通道 5。在一个实施方式中，热介质泵 12 是压电泵，但可以想到本领域技术人员可以选择使用另一合适类型的泵。

[0075] 温度测量电子设备 14 通过使用模数转换器将来自入口温度传感器 6 和出口温度传感器 7 的电信号转换成电压值或数值以供控制和处理电子设备 15 进行进一步处理。控制和处理电子设备 15 读取入口温度传感器 6 和出口温度传感器 7 的温度。此外，控制和处理电子设备 15 还控制可变低频电压电源 9 施加到负载 3 的功率量。控制和处理电子设备 15 还具有处理器和存储器，用于存储和获取处理器执行的程序并用于处理入口温度传感器 6 和出口温度传感器 7 的温度测量。

[0076] 可以看出，图 2 的微制造 RF 功率热量计 100 包括薄的非导电第一衬底 1，在该衬底 1 上安装有吸收负载 3。负载 3 是电阻性的并包括沉积在第一衬底 1 上的薄膜。负载 3 的形状和大小被确定由此反射的 RF 能量的最小量基于连接到微制造 RF 功率热量计 100 的 RF 输入（传输线）2 的电阻抗来实现。在第一衬底 1 的同一侧上绕着负载 3 在第一衬底 1 上沉积导电材料，并用作电流到 RF 输入（传输线）2 的返回路径。两个温度传感器，入口温度传感器 6 和出口温度传感器 7 被沉积在第一衬底上的负载 3 附近，但是不接触负载 3。在一些实施方式中，偏置三通器也在第一衬底 1 上被微制造。

[0077] 二氧化硅绝缘层被施加在第一衬底 1 的整个顶面 1a，覆盖之前所述的这些层。第一衬底 1 的底面（未示出）没有任何沉积材料。由聚二甲基硅氧烷 (PDMS) 构成的第二衬底 20 被构成具有热介质通道 5 以容纳热介质冷却液 4。第二衬底 20 被联结到第一衬底 1 由此流过热介质通道 5 的热介质冷却液 4 与负载 3、入口温度传感器 6 和出口温度传感器 7 接触并热耦合。

[0078] 更具体地，第一衬底 1 上的组件的微制造通过首先在第一衬底 1 上旋转涂覆正性光阻 (Shipley 1818) 来执行。然后使用常规的 UV 光刻方法来对第一衬底 1 形成图案。然后，使用电子束蒸镀来沉积铝。Shipley 1818 正性光阻的另一层被施加以覆盖所有的图案并被暴露以产生负载 3、入口温度传感器 6 和出口温度 7 图案。氮化钽通过 DC 喷涂被填充到光阻模，且丙酮用于剥离。

[0079] 接下来，聚二甲基硅氧烷 (PDMS) 用于产生第二衬底 20，包含微流体热介质通道 5 和用于泵 12 和热交换器 10 的入口连接 21 以及出口连接 22。通过旋转涂覆负性光阻 (MicroChem，SU-82050) 并在硅晶片上形成图案来产生第二衬底 20。微流体热介质通道 5 的宽度是 100μm。在制成 UV 暴露的光阻之后，软模被形成。然后，PDMS 混合物被倾倒在该软模上，之后是在 80℃固化半个小时。最终，PDMS 复制物被打孔以形成入口连接 21 和出口连接 22。然后第二衬底 20 被设置在第一衬底 1 上并通过氧气等离子处理 20 秒被联结在第一衬底 1 上。图 4a-b 示出了制造的第二衬底 20。热交换器 10 被帖附到热介质通道 5 上的第二衬底 20 上。微型热介质泵 12 驱动热介质流体 4 通过热介质通道 5 和热交换器 10。在一些实施方式中，微型热介质泵 12 被安装在 PCBA 16 上。

[0080] 图 3 和图 4a-b 描绘了在第一衬底 1 上微制造的负载 3、返回电路路径 17、入口温度传感器 6 和出口温度传感器 7 的布局。还描绘了根据 RF 功率测量热量计 100 的实施方式的在第二衬底 20 上微制造的热介质通道 5、微流体入口 21 和微流体出口 22。图 5 示出了

安装在第一衬底 1 上的第二衬底 20。此外，图 5 还示出了连接到衬底 1 的负载 3 和返回电流路径 17 的 RF 输入 2。图 6 是根据 RF 功率测量热量计 100 的实施方式的第一衬底 1 的入口温度传感器 6、出口温度传感器 7、负载 3 和电流返回路径 17 的特写视图。图 7 是根据 RF 功率测量热量计 100 的实施方式的第一衬底 1 的负载 3 和电流返回路径 17、以及第二衬底 20 的微流体热介质通道 5 的特写视图。可以理解在第一衬底 1 的一些实施方式中，负载 3 和 RF 输入 2 能够具有沉积在负载 3 的同侧、负载 3 和 RF 输入 2 的相反侧或负载 3 和 RF 输入 2 的同侧和相反侧的组合的用于电流返回路径 17 的导电材料（例如，悬浮的共面波导、接地的微条或接地的共面波导）。

[0081] 如图 3 和图 4a-b 中可以看出，在一些实施方式中，入口温度传感器 6 位于入口温度传感器惠斯通桥 18 中，以及出口温度传感器 7 位于在第一衬底 1 上对称制造的出口温度传感器惠斯通桥 19 中。惠斯通桥 18 和 19 使得入口温度传感器 6 和出口温度传感器 7 更精确检测热介质 4 的温度变化。此外，即使第二衬底 20 在图 3 中未示出，为了便于理解，也关于负载 3、入口温度传感器 6 和出口温度传感器 7 描绘了热介质通道 5、微流体入口 21 和微流体出口 22。

[0082] 在操作中，每个惠斯通桥 18 和 19 上的一对衬垫用于施加 DC 电压 (V_{in}= 0.5V) 以及另一对衬垫用于测量输出电压。以下等式描述了 V_{out}、V_{in}和 R_{sensor}之间的关系

[0083] $$V_{out}=\left(\frac{R_{sensor}}{R_3+R_{sensor}}-\frac{R_2}{R_1+R_2}\right)*V_{in}$$

[0084] 回到惠斯通桥 19，在负载 3 上施加的功率生成热量，该热量从负载 3 传输到热介质 4。一旦加热的热介质 4 到达出口温度传感器 7，出口温度传感器 7 的电阻将增加，因此导致惠斯通桥 19 的 V_{out}相应增加。此外，当流过出口温度传感器 7 的热介质 4 的温度降低时，出口温度传感器 7 的电阻降低，使得惠斯通桥 19 的输出 V_{out}相应降低。同理，当流过入口温度传感器 6 的热介质 4 的温度降低时，入口温度传感器 6 的电阻降低，使得惠斯通桥 18 的 V_{out}相应降低。此外，当流过入口温度传感器 6 的热介质 4 的温度上升时，入口温度传感器 6 的电阻增加，导致惠斯通桥 18 的 V_{out}相应增大。

[0085] 图 8 示出了根据输出温度传感器惠斯通桥 19 的时间和在不同流量施加的功率的 V_{out}。可以看出，在图 8 中给负载 3 施加了 5 个不同的 DC 功率值。

[0086] 此外，图 8 还示出了热介质 4 的较高流量能够从负载 3 传输更多的热给出口温度传感器 7。这可以在图 9 中得到确定，其显示了当给定 DC 功率值被施加到负载 3 时较高流量产生更尖 V_{out} vs 施加的功率斜坡。

[0087] 图 10 示出了 RF 功率测量热量计 100 的可替换实施方式，其中偏置三通器 8 被删除并由位于负载 3 的附近的 DC 负载 23 来代替。在具有用通过 RF 输出 2 接收的 RF 功率的负载和用于从可变低频电源 9 接收的功率的分开的负载的实施方式中，接收 RF 功率的负载 3 称为 RF 负载 3，以及接收可变低频功率的负载 23 称为 DC 负载 23。在 DC 替代期间，DC 负载 23 用作辅助电源，用于比较可变低频电源 9 与通过 RF 输入 2 接收的未知 RF 电源之间的热差。当 RF 开关 25 闭合时，功率从通过 RF 输入 2 接收的未知 RF 电源被传递到 RF 负载 3。RF 开关 25 是单极单掷开关，其由控制和处理电子设备 15 控制。

[0088] 图 11 示出了 RF 功率测量热量计 100 的进一步实施方式，其中流体不用作热介质 4。而是，第一衬底 1 用作热介质 4 并用于提供温度参考。此外，用于保持第一衬底 1 在恒

定温度的装置(例如调整冷却装置)被包括在该实施方式中。此外,可以想到在 RF 功率测量热量计 100 的一些实施方式中,用于保持第一衬底 1 在恒定温度的装置是集成安装在第一衬底 1 上的有源或无源热交换器 10。

[0089] 在图 11 中,第一衬底 1 由玻璃构成并提供用于以下制造的组件的基:RF 负载 3、DC 负载 23、入口温度传感器 6、出口温度传感器 7 以及热交换器 10。可以想到第一衬底 1 还可以由其他材料构成,包括但不限于石英、陶瓷、硅或砷化镓 (GaAs)。

[0090] 在一个示意性实施方式中,RF 输入 2 可以被配置为铜质传输线,其提供到 RF 负载 3 的电路径和来自 RF 负载 3 的电流返回路径 17。可以想到 RF 输入 2 的传输线还可以由其他材料构成,包括但不限于铝、金或铂。RF 负载 3 是由氮化钽 (TaN) 制成的电阻器,其吸收电能并将电能转换成热。可以想到 RF 负载 3 还可以由其他材料构成,包括但不限于钽、镍络铁合金 (NiCr) 或氧化铼 (ReO_3)。

[0091] DC 负载 23 是由氮化钽 (TaN) 制成的电阻器,其吸收电能并将电能转化成热。可以想到 DC 负载 23 还可以由其他材料构成,包括但不限于钽、镍络铁合金 (NiCr) 或氧化铼 (Re03)。在 DC 替代期间,DC 负载 23 用作辅助电源,用于比较可变低频电源 9 与通过 RF 输入 2 接收的未知 RF 电源之间的热差。温度传感器 6 和 7 测量第一衬底 1 的温度以确定热平衡。此外,热交换器 10 冷却第一衬底 1 并将第一衬底 1 保持在固定的温度值。温度测量电子设备 14 将来自温度传感器 6 和 7 的电信号转化成电压值或数值。控制和处理电子设备 15 读取温度传感器 6 和 7 的温度,控制可变低频电源 9 以及处理传感器 6 和 7 的温度测量。

[0092] 此外,可变低频电源 9 施加精确可变 DC 或低频电压到 DC 负载 23。在达到第一衬底 1 的热平衡之后,降低给 DC 辅助 23 的功率以用于确定存在于 RF 负载 3 上的 RF 功率。

[0093] 如上所述,RF 功率测量热量计 100 使用 DC 替代来测量通过 RF 输入 2 传递给负载 3 的 RF 功率。DC 替代使用辅助精确电源,例如可变低频电源 9,并比较由可变低频电源 9 施加给负载 3 的功率与通过 RF 输入 2 传递到负载 3 的未知 RF 功率之间的热差。

[0094] DC 替代使用精确的低频电源来比较具有已知输出功率值的低频电源与具有未知输出功率值的 RF 电源之间的热差。低频电源为了保持热平衡而必须降低的功率量用于确定未知 RF 源的功率。来自低频电压源的功率可以被确定的精度水平远高于直接测量高频功率,例如 RF 或微波功率。

[0095] 构想了在 RF 功率测量热量计 100 的一些实施方式中,提供到负载 3、入口温度传感器 6 和出口温度传感器 7 的热介质冷却液 4 的流量可以是可选择的或可变的以改进 RF 功率测量热量计 100 的功率测量范围。沿着热介质通道 5 到负载 3、入口温度传感器 6 和出口温度传感器 7 的热介质冷却液 4 的流量可变帮助保持对变化功率负载的最大温度敏感度。例如,对于较低功率测量,可以使用降低流量来增加敏感度,而较高流量利于较高功率测量降低负载故障。沿着热介质通道 5 的热介质冷却液 4 的流量的任何变化需要在任何功率测量之前稳定流量以及唯一的 DC 校准,例如上述以及图 12-14 中示出的。

[0096] 回到图 15,RF 功率测量热量计 100 的一些实施方式具有流体通道路径阵列 30,其能用于改变沿着热介质通道 5 行进的热介质冷却液 4 的流量。在图 15 中示出的实施方式中,流体通道路径阵列 30 位于出口温度传感器 7 与热介质泵 12 之间,但是,可以想到本领域技术人员能够选择将流体通道路径阵列 30 沿热介质通道 5 放置在另一位置。

[0097] 流体通道路径阵列 30 具有上游流体开关 31、下游流体开关 33 以及多个流体通道 32a-n,“n”是对应于流体通道 32 的数量的字母表中的字母。上游流体开关 31 和下游流体开关 33 从流体上连接到流体通道 32a-n 并被配置成开关流体通道 32a-n 之间的热介质冷却液 4 的流,由此在给定时间仅沿着多个流体通道 32a-n 的一个流体通道引导热介质冷却液 4 ;例如当上游流体开关 31 被配置成引导热介质冷却液 4 沿着流体通道 32a 时,下游流体开关 33 将被配置成从流体通道 32a 接收热介质冷却液 4 并引导来自流体通道 32a 的热介质冷却液 4 向下游通过热介质通道 5。多个流体通道 32a-n 的每一个流体通道在其长度和 / 或水力直径上是唯一修改的,由此给热介质泵 12 呈现不同的压降。

[0098] 可以想到,上游流体开关 31 和下游流体开关 33 的一者或两者可以是阀和 / 或歧管。可以想到,流体通道路径阵列 30 能够直接集成到第一衬底 1,或外部安装。此外,可以想到,上游流体开关 31、流体通道 32a-n 和 / 或下游流体开关 33 的任意一者能够直接集成到第一衬底 1,或外部安装。可以想到,在一些实施方式中,上游流体开关 31 和下游流体开关 33 是手动开关的。在其他实施方式中,上游流体开关 31 和下游流体开关 33 的开关由控制和处理电子设备 15 来控制。

[0099] 转到图 16,RF 功率测量热量计 100 的其他一些实施方式具有流体通道路径阵列 30,其具有上游流体开关 31 和多个流体通道 32a-n。多个流体通道 32a-n 的每一个流体通道具有热介质泵 12a-n。在一些实施方式中,热介质泵 12a-n 共用单个热介质泵电源 13,其能够在给定时间给一个热介质泵 12a-n 供电。在其他实施方式中,每个热介质泵 12a-n 由相应的热介质泵电源 13a-n 单独供电。上游流体开关 31、多个流体通道 32a-n 以及热介质泵 12a-n 从流体上连接并被配置成开关流体通道 32a-n 之间的热介质冷却液 4 的流,由此在给定时间引导热介质冷却液仅沿着多个流体通道 32a-n 的一个流体通道 ;例如当上游流体开关 31 被配置成引导热介质冷却液 4 沿着流体通道 32a 时,相应热介质电源 13 将给相应热介质泵 12a 供电。

[0100] 构思了流体通道路径阵列 30、热介质泵 12a-n 和 / 或热介质泵电源 13a-n 的任意一者能够直接集成到第一衬底 1 上,或外部安装。此外,构思了上游流体开关 31、流体通道 32a-n 和 / 或下游流体开关 33 的任意一者能够直接集成到第一衬底 1 上,或外部安装。构想了在一些实施方式中,上游流体开关 31 和热介质电源 13 是手动开关的。在其他实施方式中,上游流体开关 31 和热介质电源 13 的开关由控制和处理电子设备 15 控制。

[0101] 此外,还构想了在 RF 功率测量热量计 100 的一些实施方式中,热介质泵 12 的热介质泵电源 13 被配置成被降低或调制以改变沿着热介质通道 5 的热介质冷却液 4 的流量。构想了在一些实施方式中,热介质泵 12 的热介质泵电源 13 的降低或调制是手动执行的。在其他实施方式中,构想了热介质泵 12 的热介质泵电源 13 的降低或调制由控制和处理电子设备 15 来控制。构想了本申请中描述和 / 或示出的用于改变沿热介质通道 5 的热介质冷却液 4 的流量的方法和结构的任意一个或多个可以在 RF 功率测量热量计 100 的实施方式中单独使用或组合使用。

[0102] 图 12 示出了 DC 替代的一种方法,其能够结合 RF 功率测量热量计 100 的实施方式使用。在步骤 301 中,来自可变低频电源 9 的已知确定水平的功率经由偏置三通器 8 被施加到负载 3 :Pref。该初始确定的功率值是 $P_{eq} = (V_{eq})^2/R_{load}$。

[0103] 在步骤 305 中,热介质 4 被允许在有源或无源热交换器 10 同时将热介质 4 保持在

热平衡时加热。该平衡由入口温度传感器 6 确定为 Tin。热介质 4 的该温度（出口流体或第一衬底 1 的出口流体）由出口温度传感器 7 监视也在平衡 :Tout。这些初始温度 T_{ineq}和 T_{outeq}由测量电子设备 14 监视。

[0104] 在步骤 310 中，未知 RF 功率 P 现在经由 RF 输入 2 被施加到负载 3。该未知 RF 功率必须等于或小于 P_{eq}。施加到负载 3 的总功率可以是已知和未知功率的和 :Pref+P。

[0105] 在步骤 315 中，初始地该和大于 P_{eq}且热介质 4 的流体或衬底温度将上升。来自可变低频电源 9 的已知功率由控制电子设备 15 按比例降低直到热介质 4 达到被确定为起始平衡（当 Tout ＝ T_{outeq}时）。令该降低的功率是 P_{meas}。入口温度 Tin 必须也被热交换器 10 保持在 Tin ＝ T_{ineq}。

[0106] 在步骤 320 中，当这些条件满足时，未知 RF 功率能被确定为已知电源必须成比例降低的量 :P ＝ P_{eq}-P_{meas}。

[0107] 可以理解，如果未知功率是 0，则 P_{meas}＝ P_{eq}。

[0108] 该测量技术的一个优点是来自低频电压源的功率 Pref 能被确定为比直接测量高频（如，RF）功率的精度水平高得多。

[0109] 转到图 13，示出了确定 RF 源的平均功率的另一实施方式。在步骤 401 中，来自可变低频电源 9 的已知低频输入被施加到负载 3。该已知低频输入具有预定功率值。在步骤 405 中，在施加低频输入到负载 3 之后，热介质 4 的第一输出温度由出口温度传感器 7 来测量。

[0110] 在步骤 410 中，具有未知功率的 RF 源在施加已知低频输入期间被施加到负载 3。在步骤 415 中，在施加已知低频输入和具有未知功率值的 RF 源期间，出口温度传感器 7 测量热介质 4 的第二输出温度。

[0111] 在步骤 420 中，当使用出口温度传感器 7 测量热介质 4 的输出温度时降低已知低频输入的功率值，直到输出温度基本等于第一输出温度。在步骤 425 中，当在步骤 420 中出口温度传感器 7 测量的输出温度基本等于在步骤 401 中出口温度传感器 7 测量的第一输出温度时确定已知低频输入的功率值。

[0112] 在步骤 430 中，基于在步骤 401 中的已知低频输入的预定功率值与当输出温度基本等于在步骤 420 结束时第一输出温度时已知低频输入的功率值之间的差来计算 RF 源的未知功率。

[0113] 转到图 14，还公开了测量 RF 功率的方法。在步骤 501 中，提供了电耦合到 RF 输入 2 的负载 3。在步骤 505 中，提供了电耦合到负载 3 的热介质 4。在步骤 510 中，来自可变低频电源 9 的已知低频输入被施加到负载 3。已知低频输入具有预定功率值。

[0114] 在步骤 515 中，在施加已知低频输入到负载 3 之后测量热介质 4 的第一输出温度。在步骤 520 中，在施加已知低频输入期间具有未知功率的 RF 输入被施加到负载 3。

[0115] 在步骤 525 中，在施加已知低频输入和未知 RF 输入期间测量热介质 4 的第二输出温度。在步骤 530 中，在测量热介质 4 的输出温度时降低已知低频输入，直到输出温度基本等于第一输出温度。

[0116] 在步骤 535 中，当输出温度基本等于第一输出温度时确定已知低频输入的值。在步骤 540 中，基于已知低频输入的预定功率值与当输出温度基本等于第一输出温度时的已知低频输入的功率值之间的差来计算 RF 输入的已知功率值。

[0117] 虽然本发明结合上述特定实施方式来描述，但很明显，许多替代、组合、修改和变形对于本领域技术人员来说是显而易见的。因此，上述的本发明的优选实施方式仅是示意性而非限制性的。在不偏离本发明的实质和范围的情况下可以进行许多改变。本领域技术人员在阅读上述描述后可以了解上述实施方式和其他实施方式的组合，且该组合也包含在本发明中。因此，本发明的范围由所附权利要求书定义，且在文字上或等同上在权利要求书的含义内的所有设备、过程和方法也包含在本发明中。

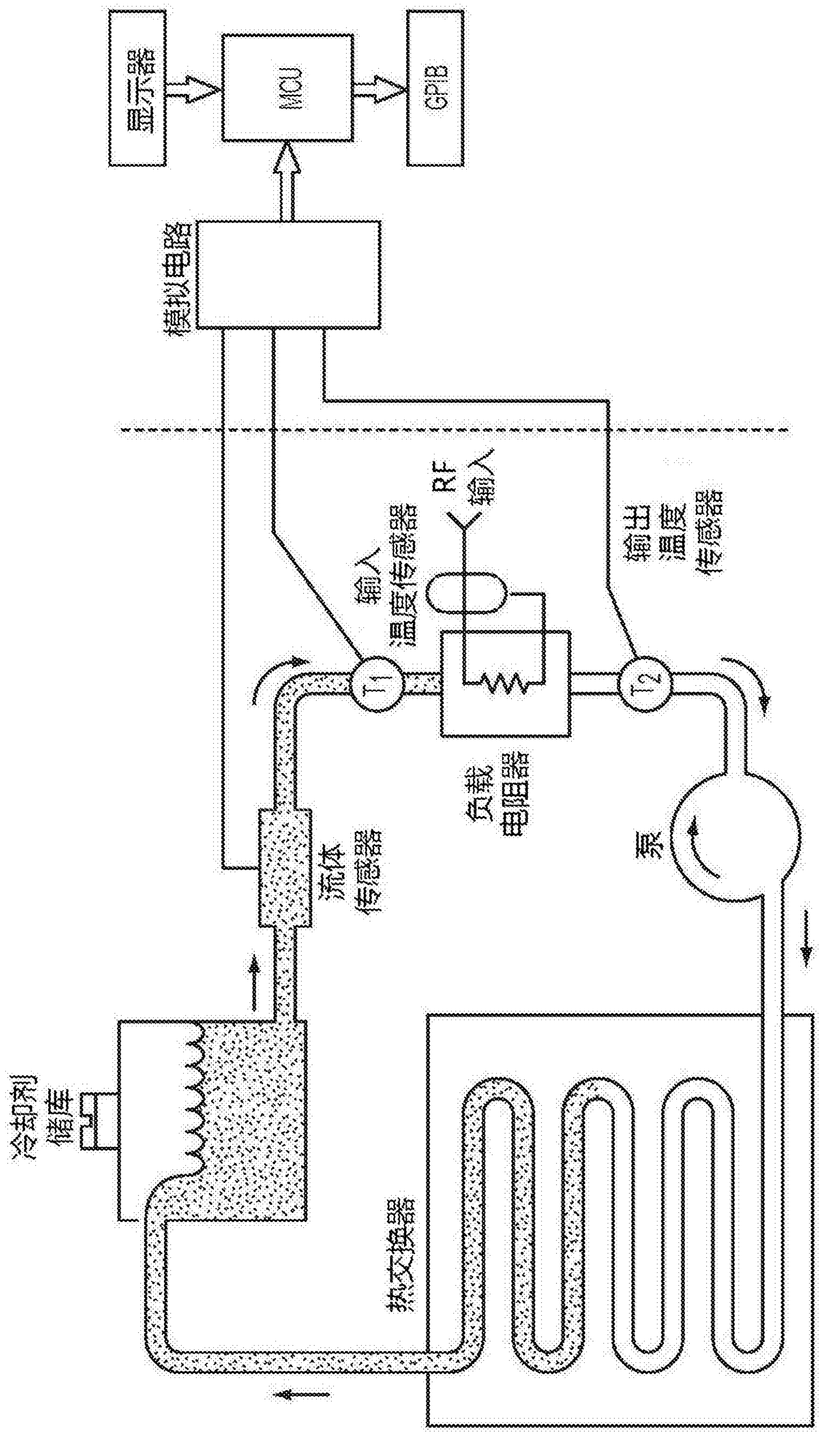

显示器
MCU
GPIB
模拟电路
RF
输入
输入
温度传感器
输出
温度
传感器
T1
T2
负载
电阻器
泵
流体
传感器
冷却剂
储库
热交换器

图 1

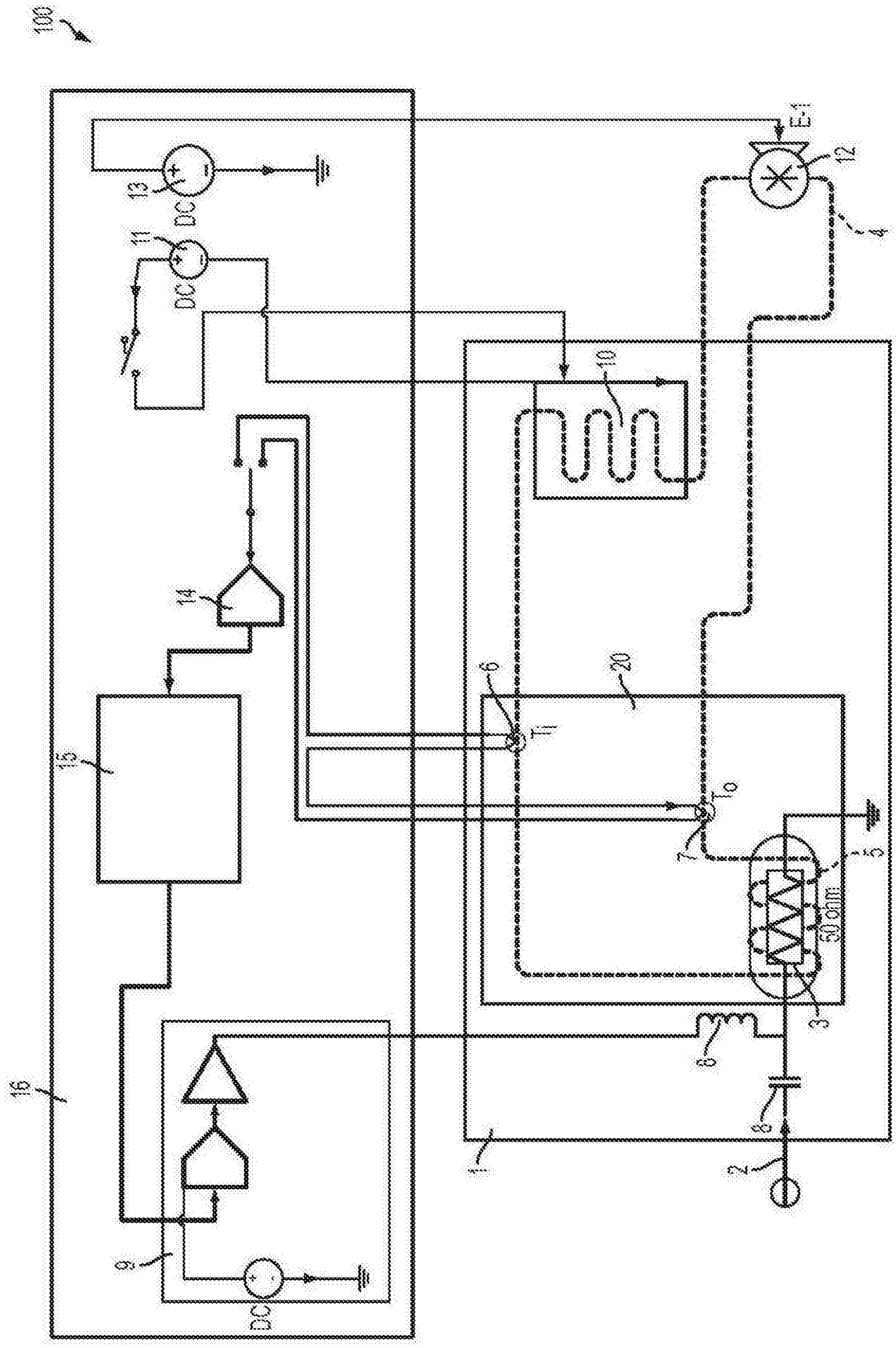


图 2

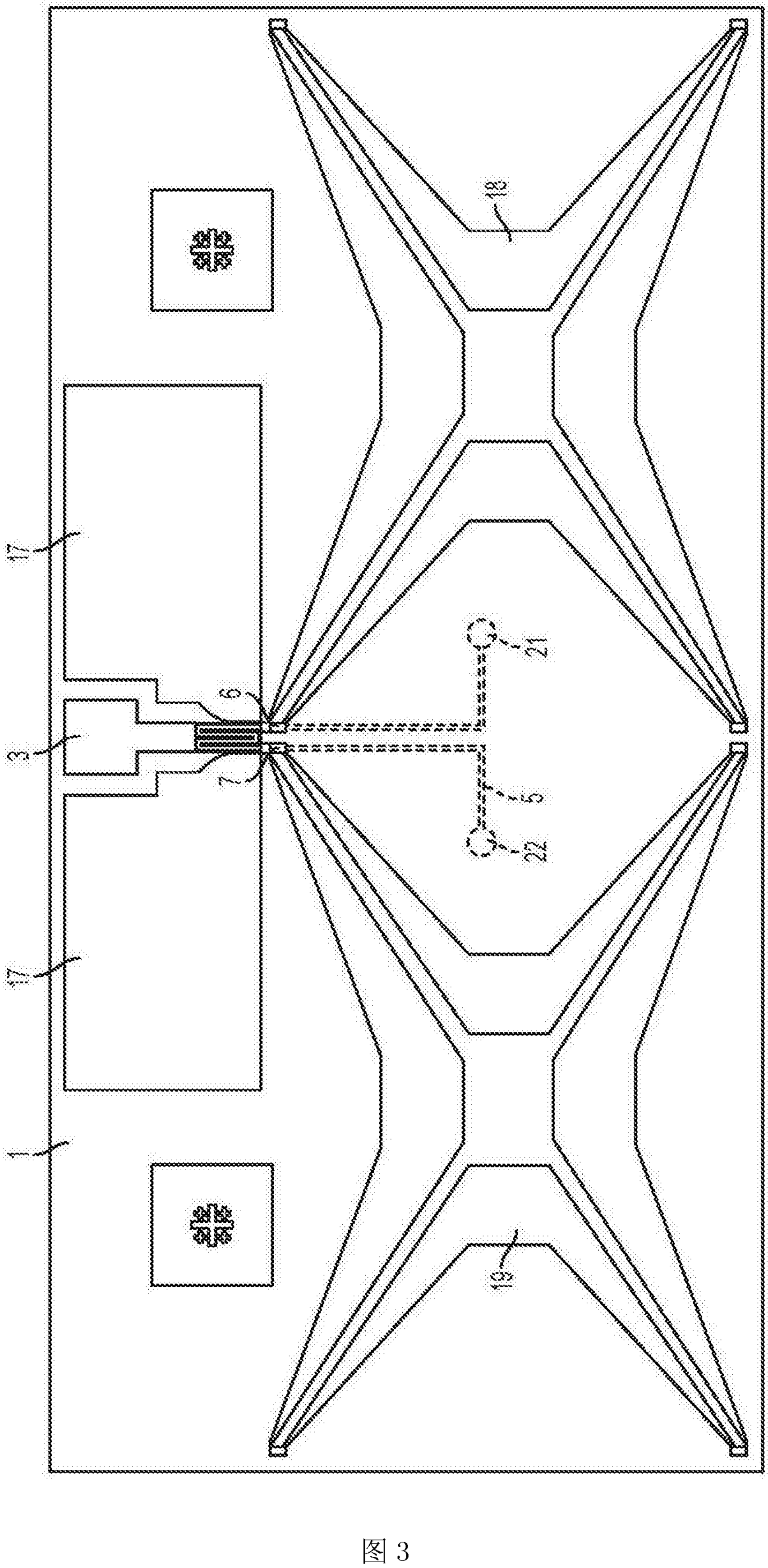


图 3

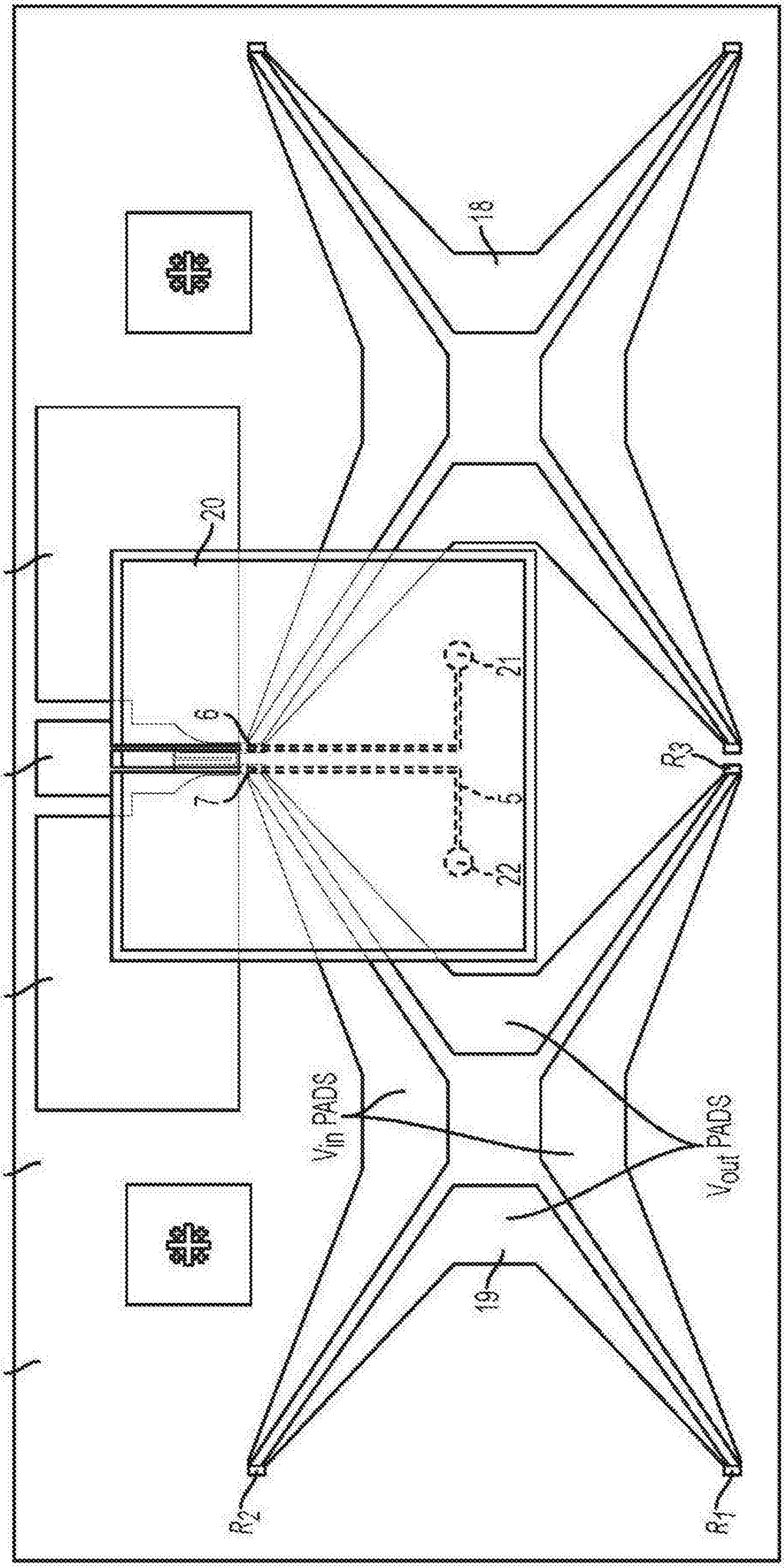


图 4A

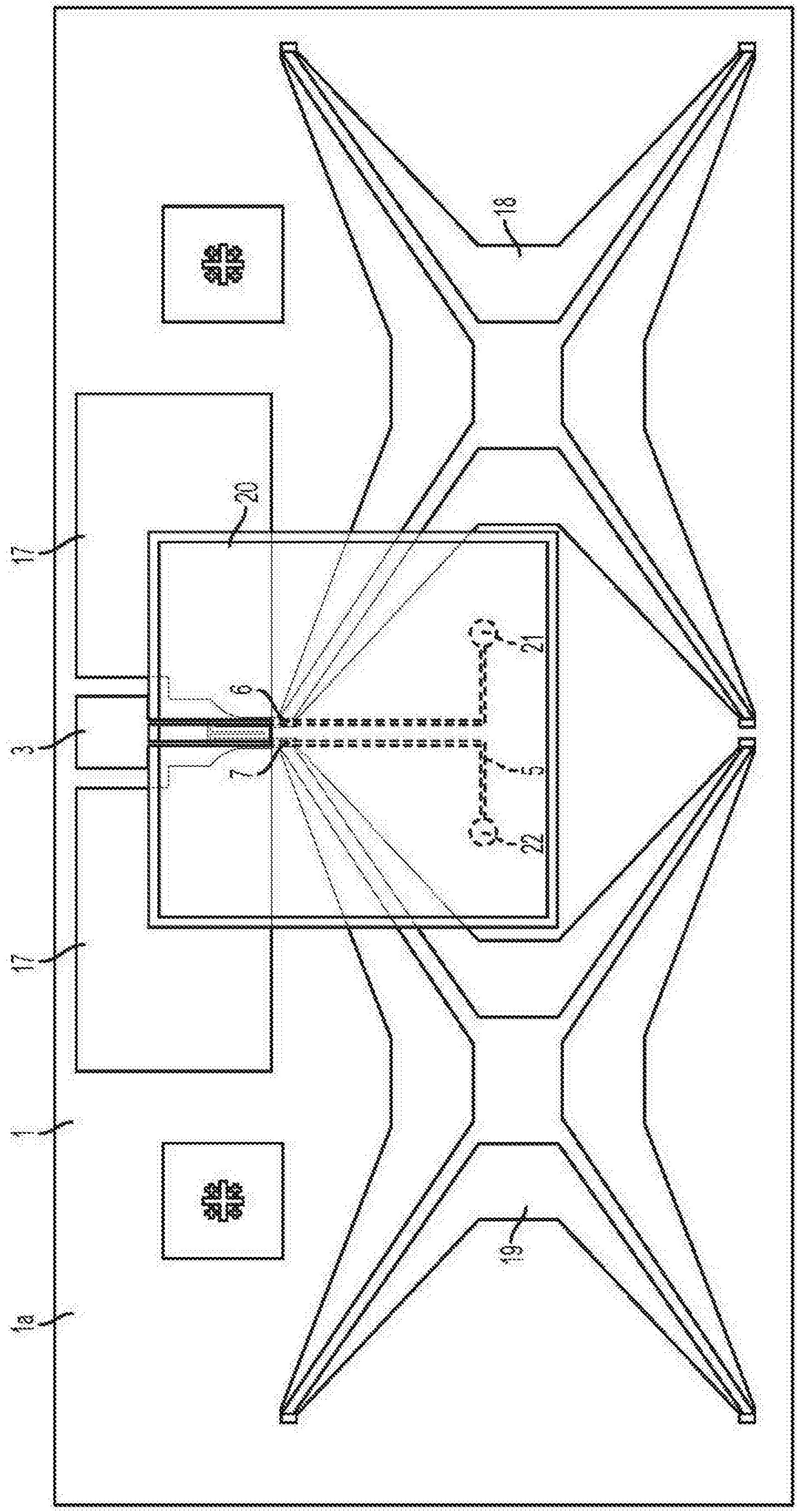


图 4B

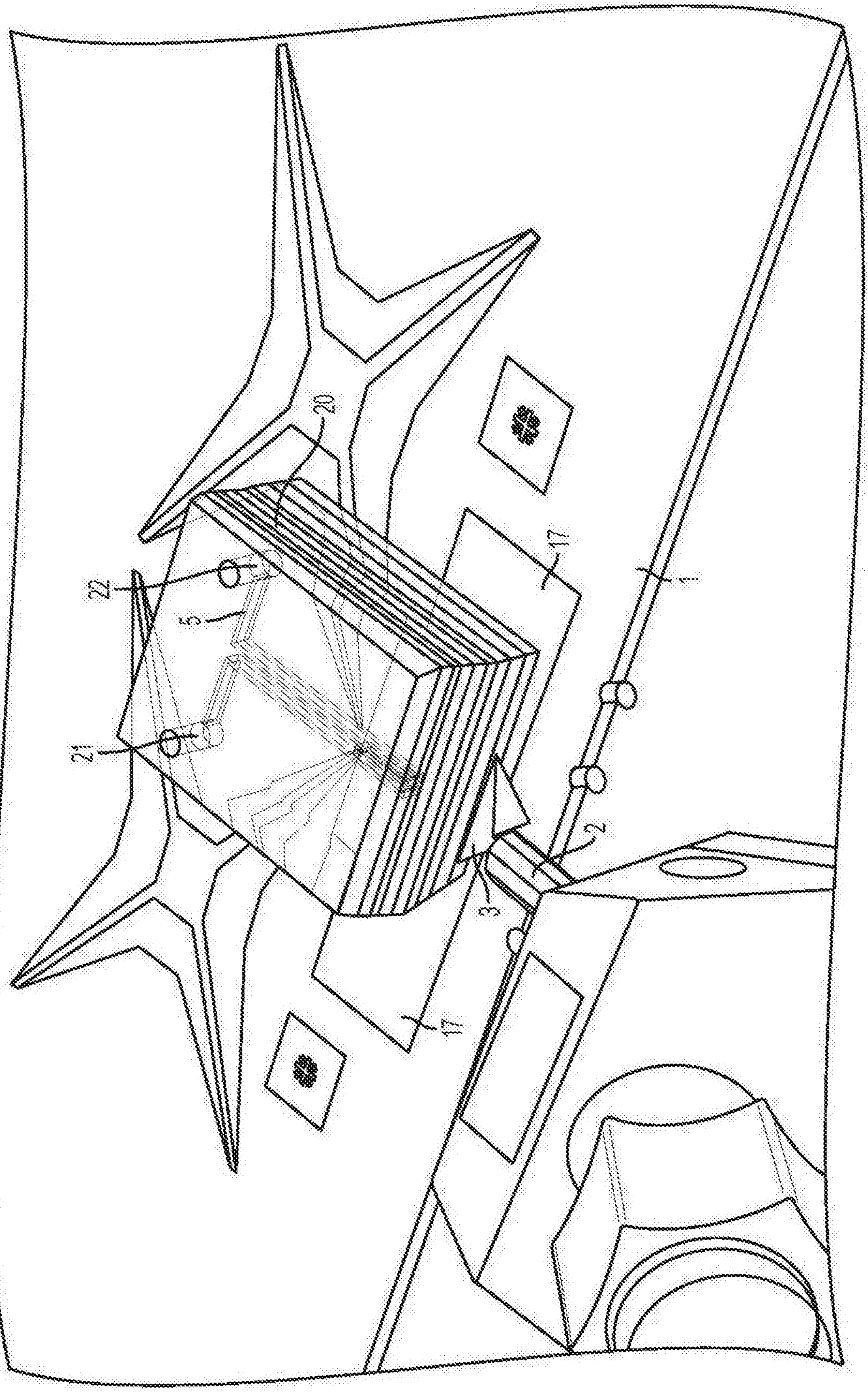


图 5

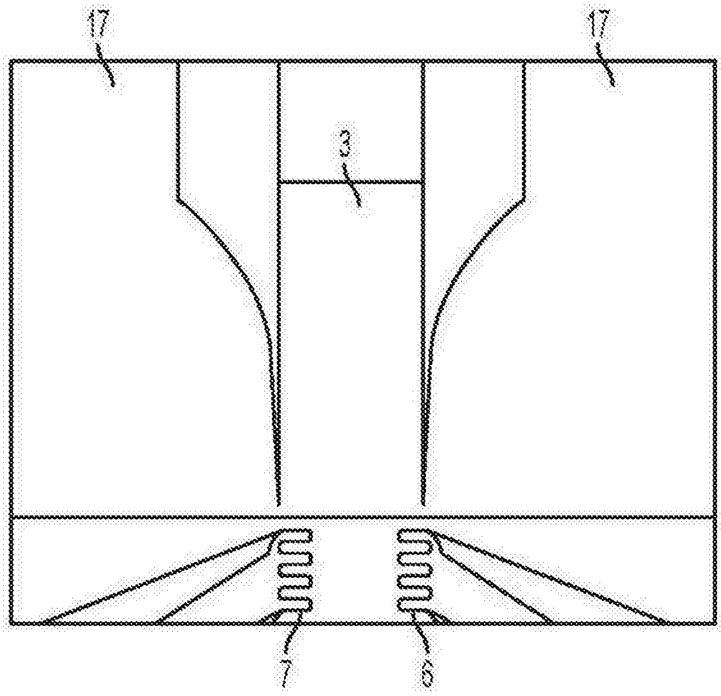


图 6

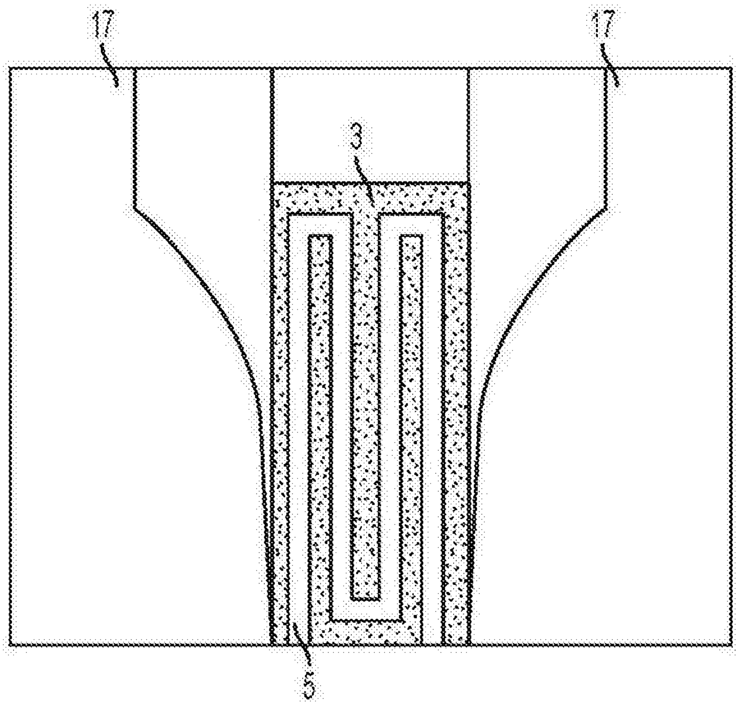


图 7

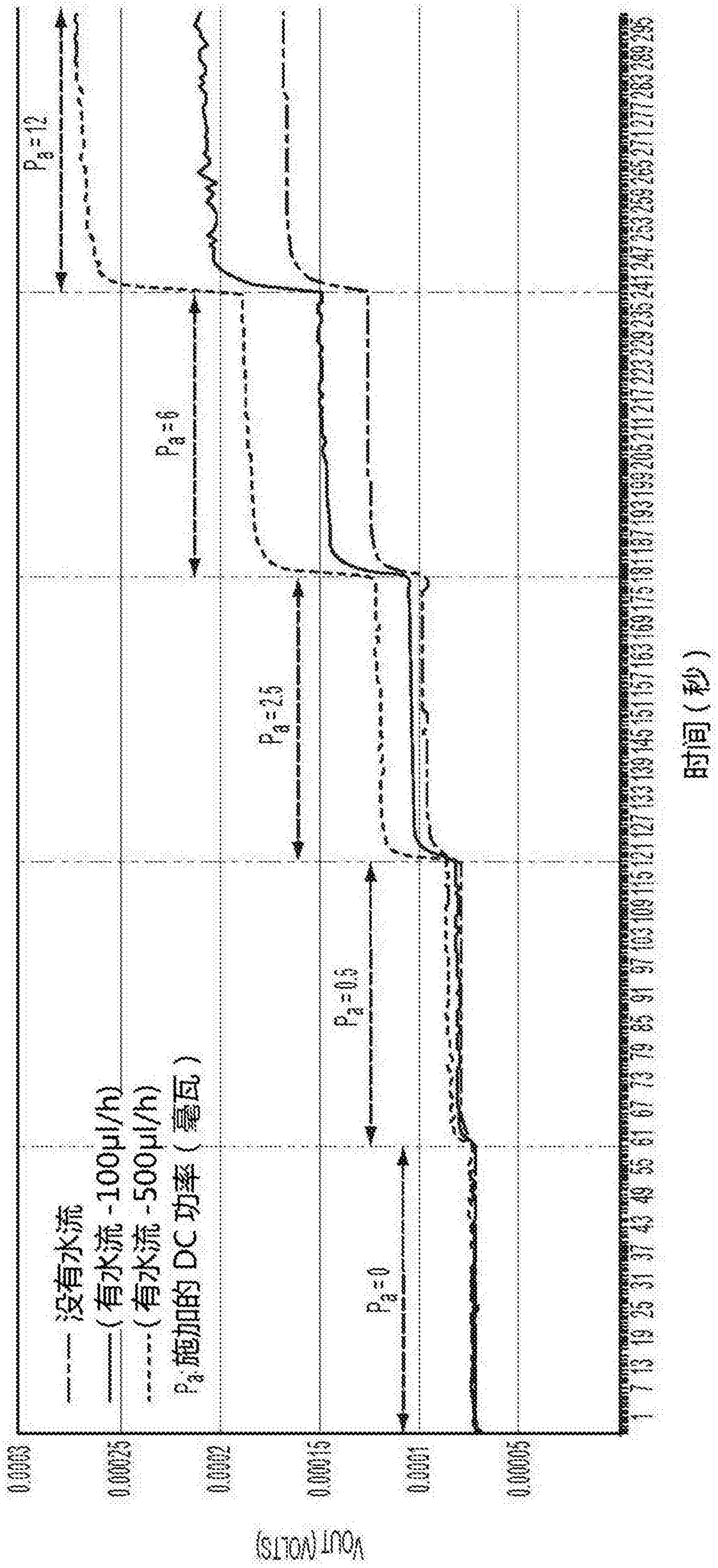
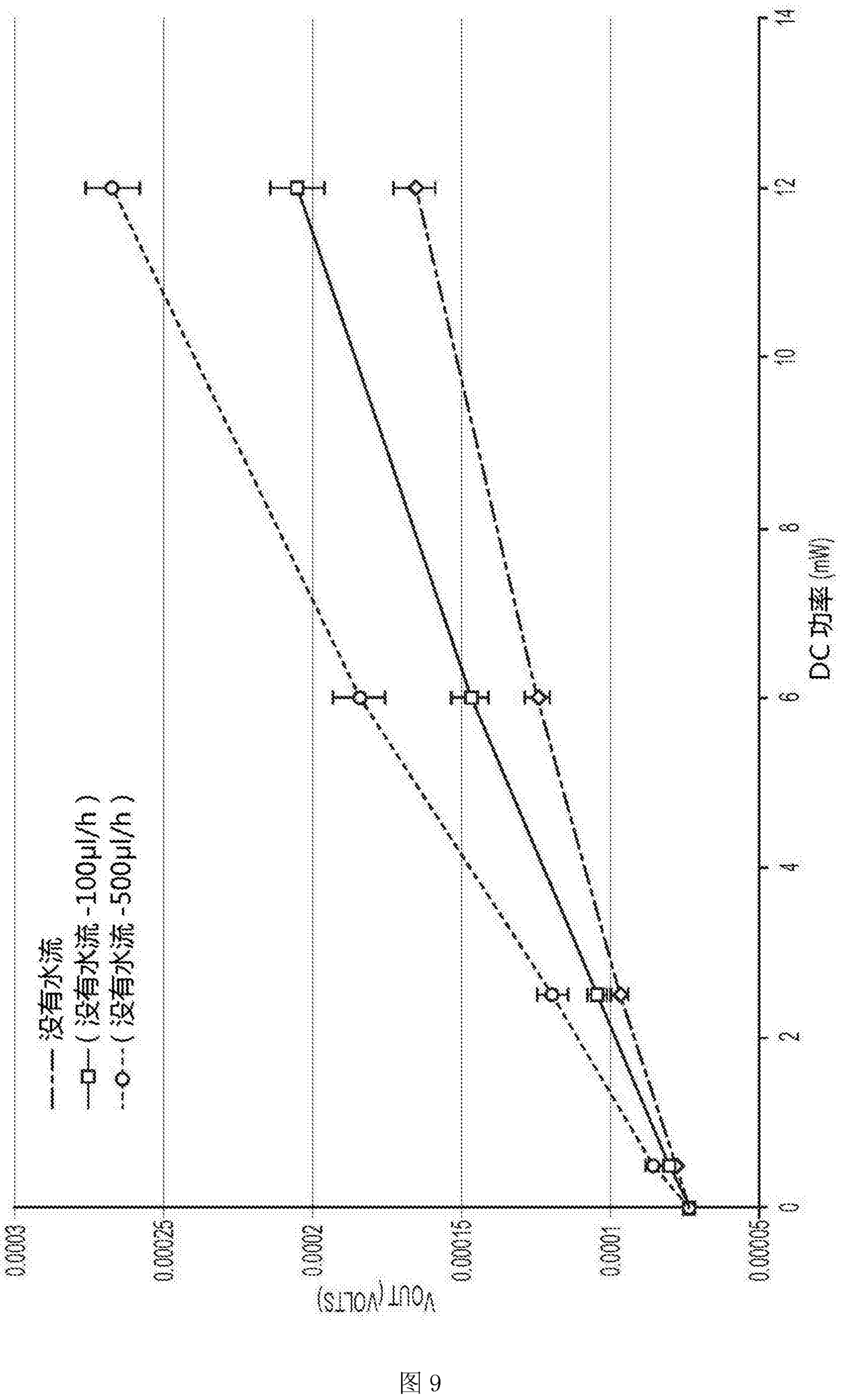

没有水流
（有水流 -100μl/h）
（有水流 -500μl/h）
P_a 施加的 DC 功率（毫瓦）
P_a=0
P_a=0.5
P_a=2.5
P_a=6
P_a=12
0.0003
0.00025
0.0002
0.00015
0.0001
0.00005
Vout (VOLTS)
时间（秒）

图 8



没有水流
（没有水流 -100μl/h）
（没有水流 -500μl/h）
DC 功率 (mW)
VOUT (VOLTS)
0
2
4
6
8
10
12
14
0.00005
0.0001
0.00015
0.0002
0.00025
0.0003

图 9

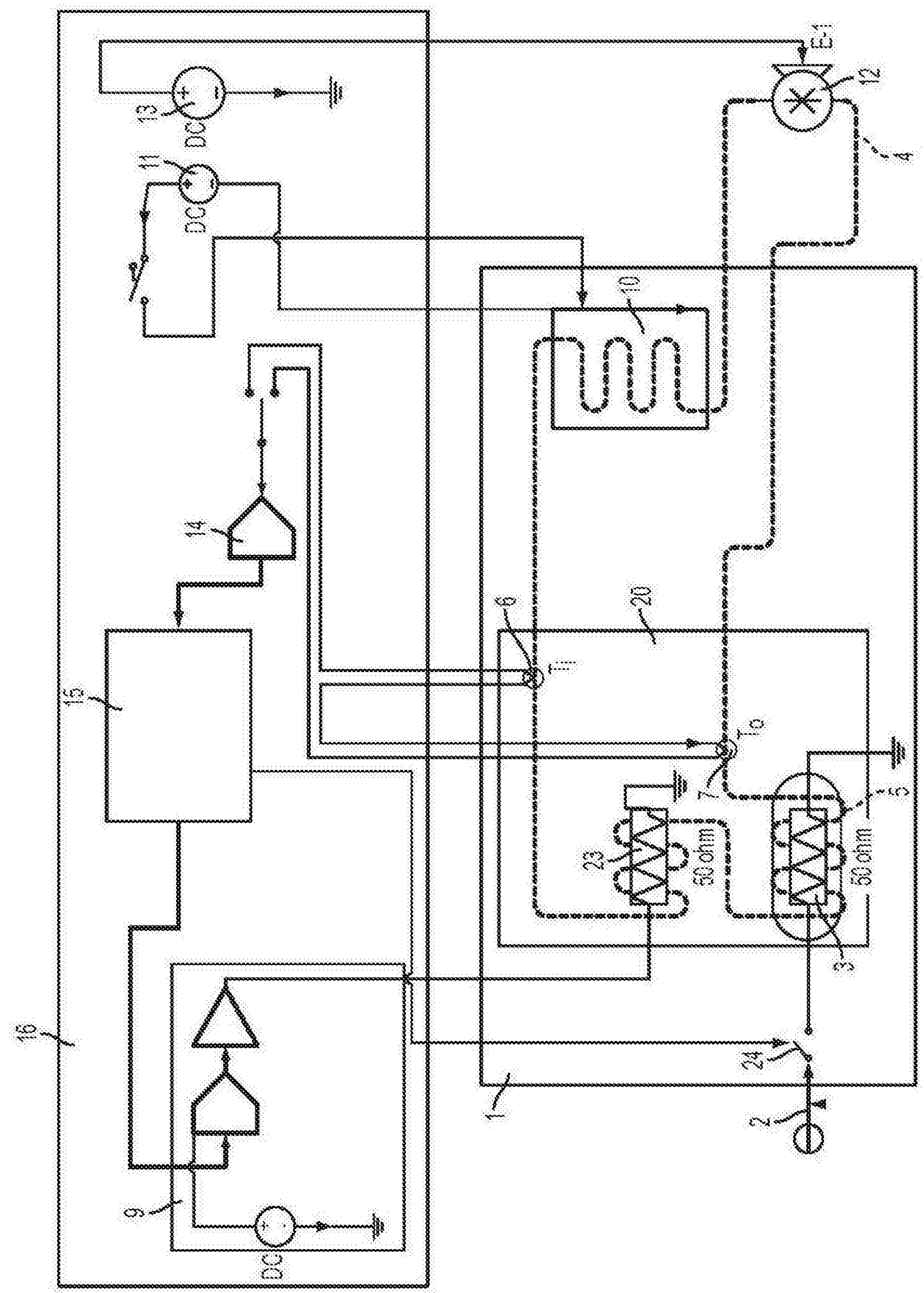

E1
12
4
13
DC
11
DC
10
14
6
20
Ti
15
To
7
5
23
50 ohm
50 ohm
3
16
24
1
2
9
DC

图 10

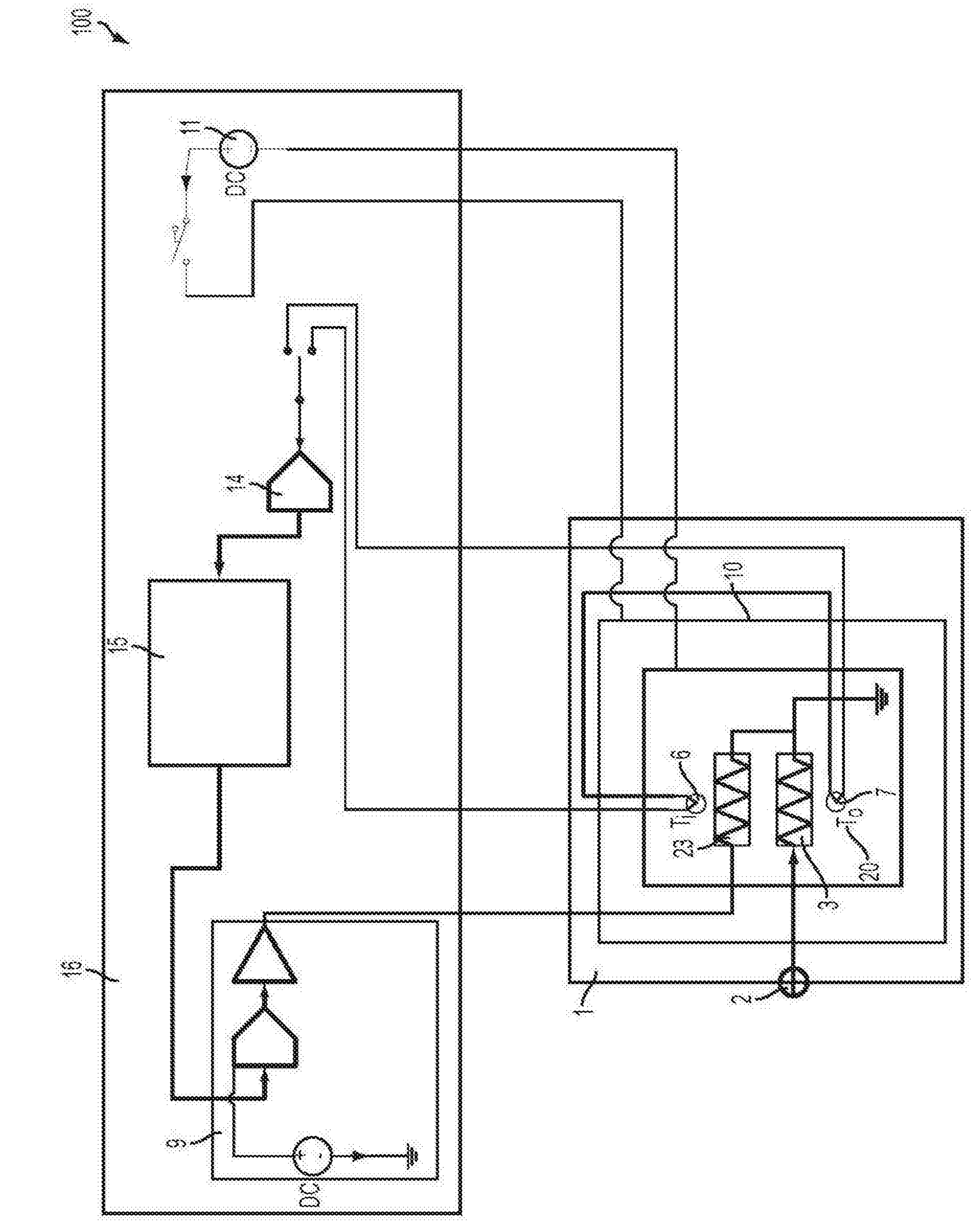


图 11

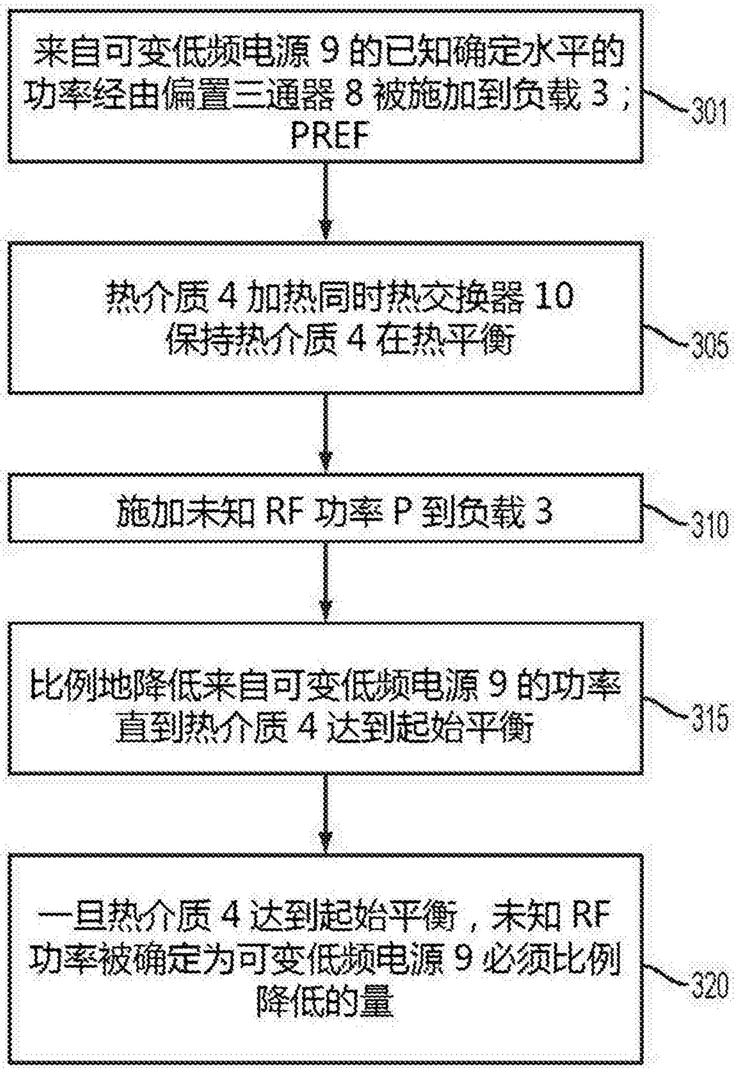

来自可变低频电源 9 的已知确定水平的功率经由偏置三通器 8 被施加到负载 3；PREF
301
热介质 4 加热同时热交换器 10 保持热介质 4 在热平衡
305
施加未知 RF 功率 P 到负载 3
310
比例地降低来自可变低频电源 9 的功率直到热介质 4 达到起始平衡
315
一旦热介质 4 达到起始平衡，未知 RF 功率被确定为可变低频电源 9 必须比例降低的量
320

图 12

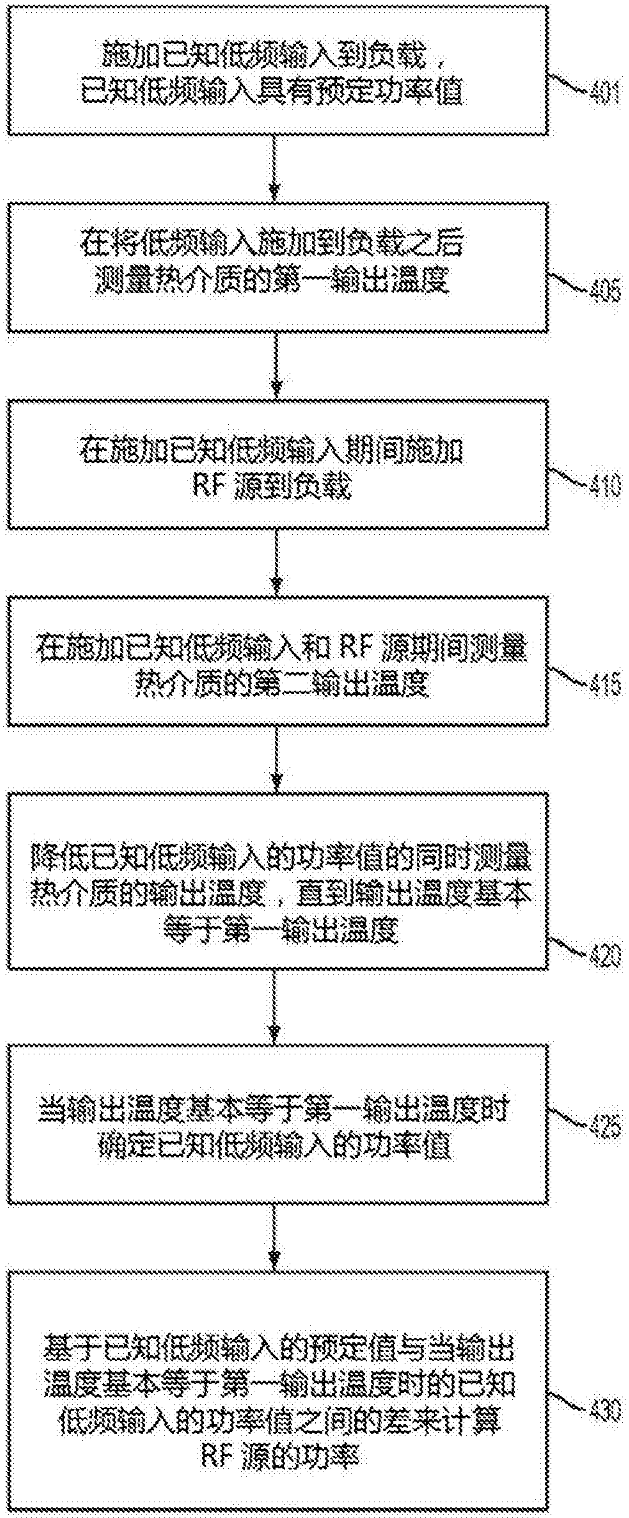

施加已知低频输入到负载，
已知低频输入具有预定功率值
401
在将低频输入施加到负载之后
测量热介质的第一输出温度
405
在施加已知低频输入期间施加
RF 源到负载
410
在施加已知低频输入和 RF 源期间测量
热介质的第二输出温度
415
降低已知低频输入的功率值的同时测量
热介质的输出温度，直到输出温度基本
等于第一输出温度
420
当输出温度基本等于第一输出温度时
确定已知低频输入的功率值
425
基于已知低频输入的预定值与当输出
温度基本等于第一输出温度时的已知
低频输入的功率值之间的差来计算
RF 源的功率
430

图 13

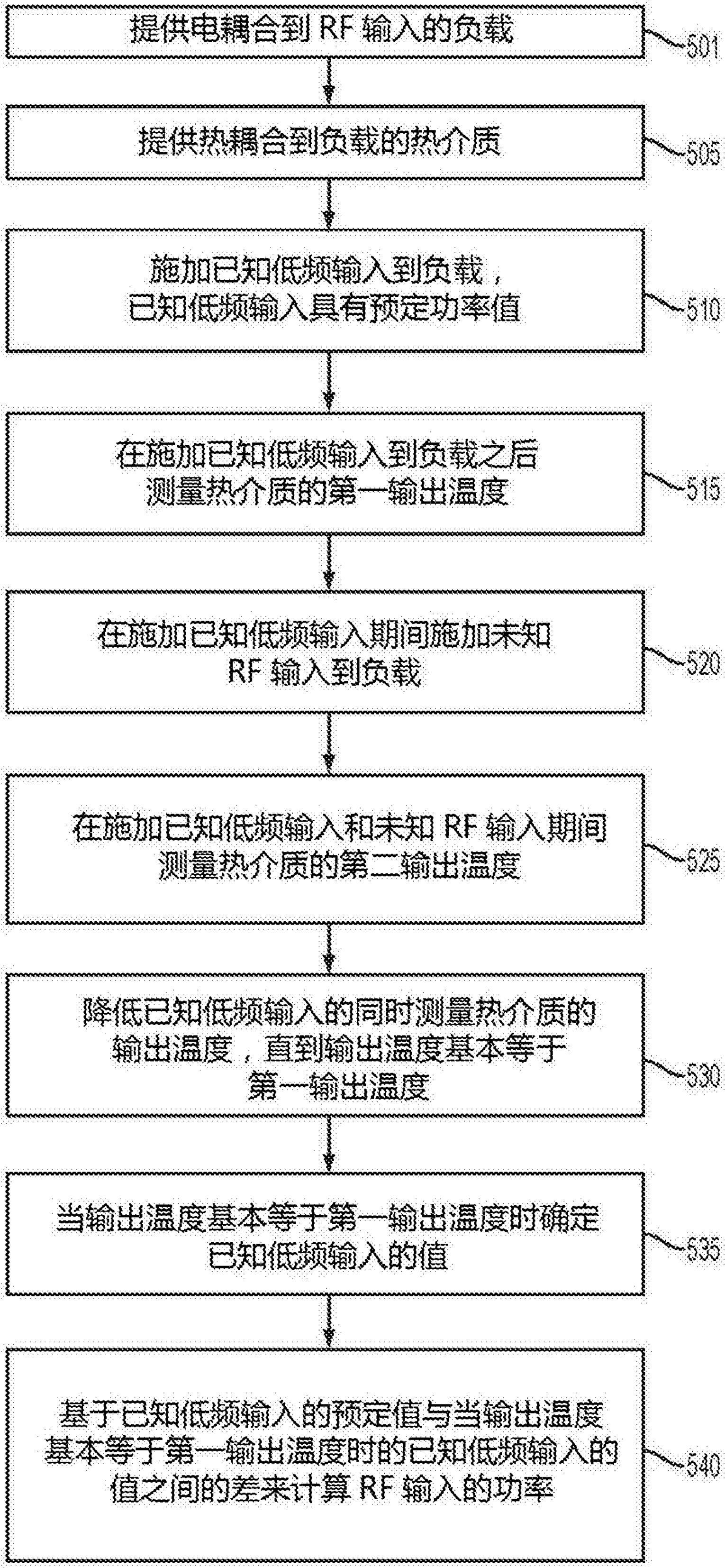

提供电耦合到 RF 输入的负载
501
提供热耦合到负载的热介质
505
施加已知低频输入到负载，
已知低频输入具有预定功率值
510
在施加已知低频输入到负载之后
测量热介质的第一输出温度
515
在施加已知低频输入期间施加未知
RF 输入到负载
520
在施加已知低频输入和未知 RF 输入期间
测量热介质的第二输出温度
525
降低已知低频输入的同时测量热介质的
输出温度，直到输出温度基本等于
第一输出温度
530
当输出温度基本等于第一输出温度时确定
已知低频输入的值
535
基于已知低频输入的预定值与当输出温度
基本等于第一输出温度时的已知低频输入的
值之间的差来计算 RF 输入的功率
540

图 14

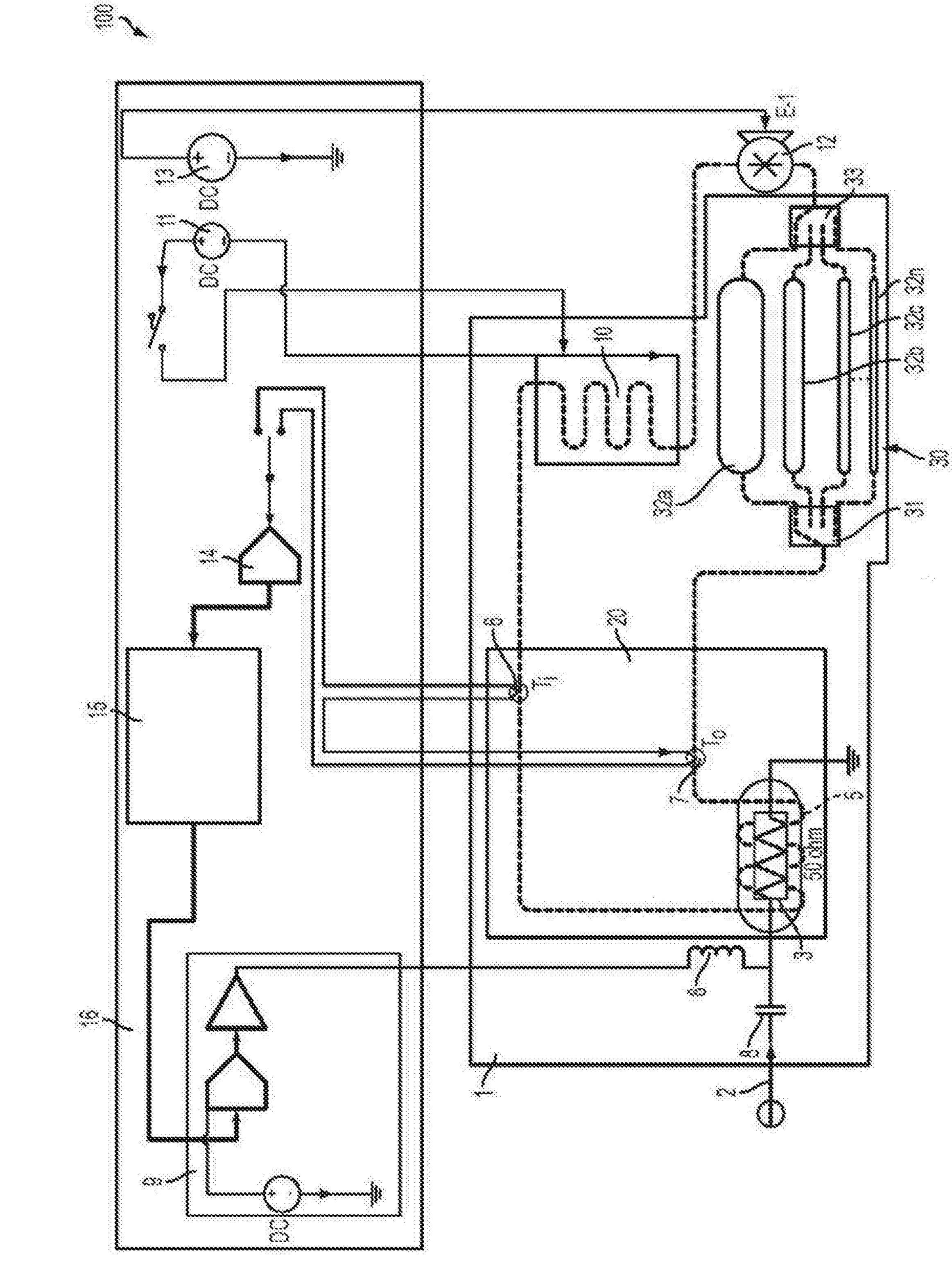


图 15

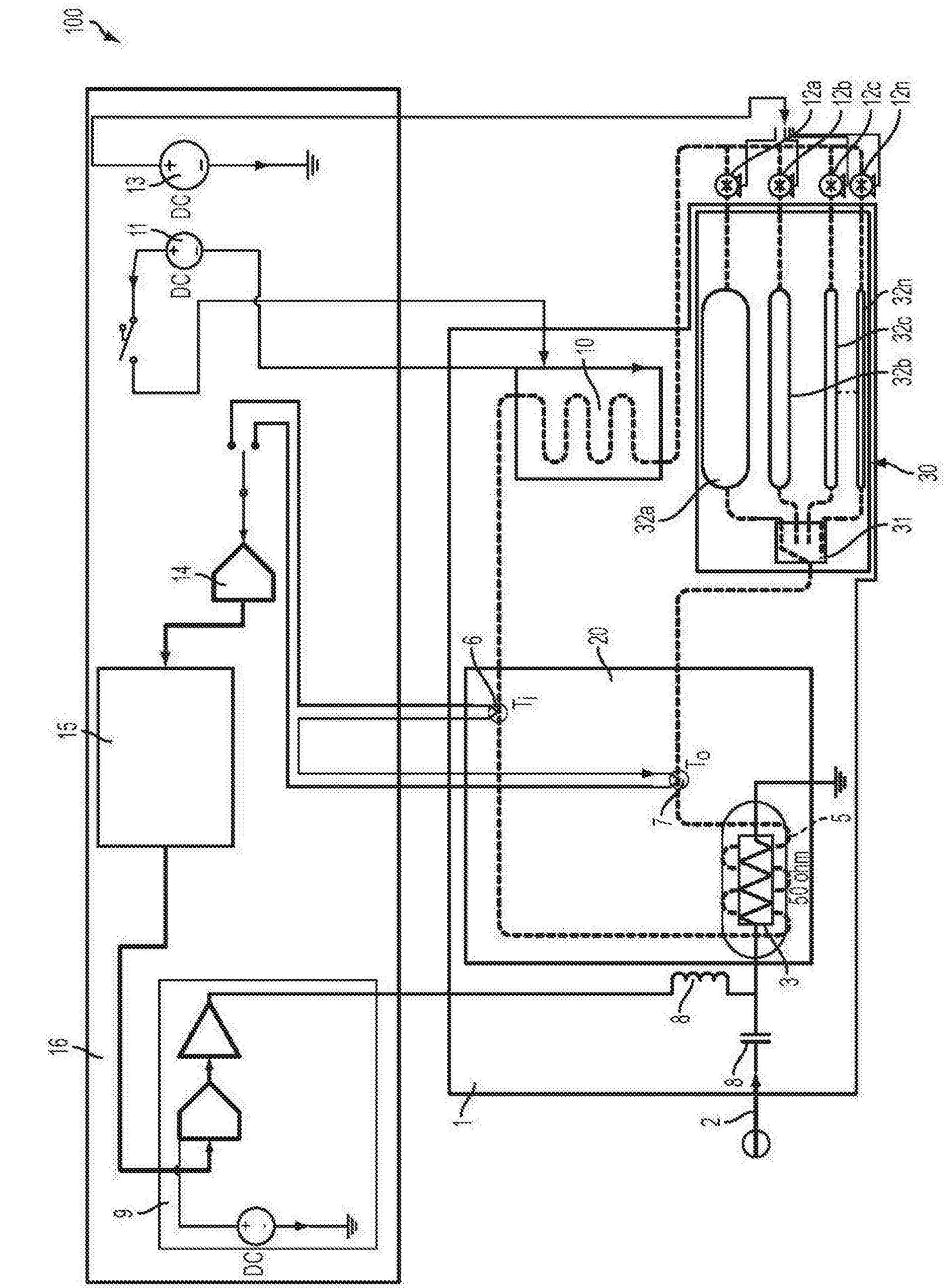

100
13
DC
11
DC
10
12a
12b
12c
12n
32a
32b
32c
32n
30
31
14
15
16
20
6
Ti
To
7
5
50 Ohm
3
8
8
2
1
9
DC

图 16