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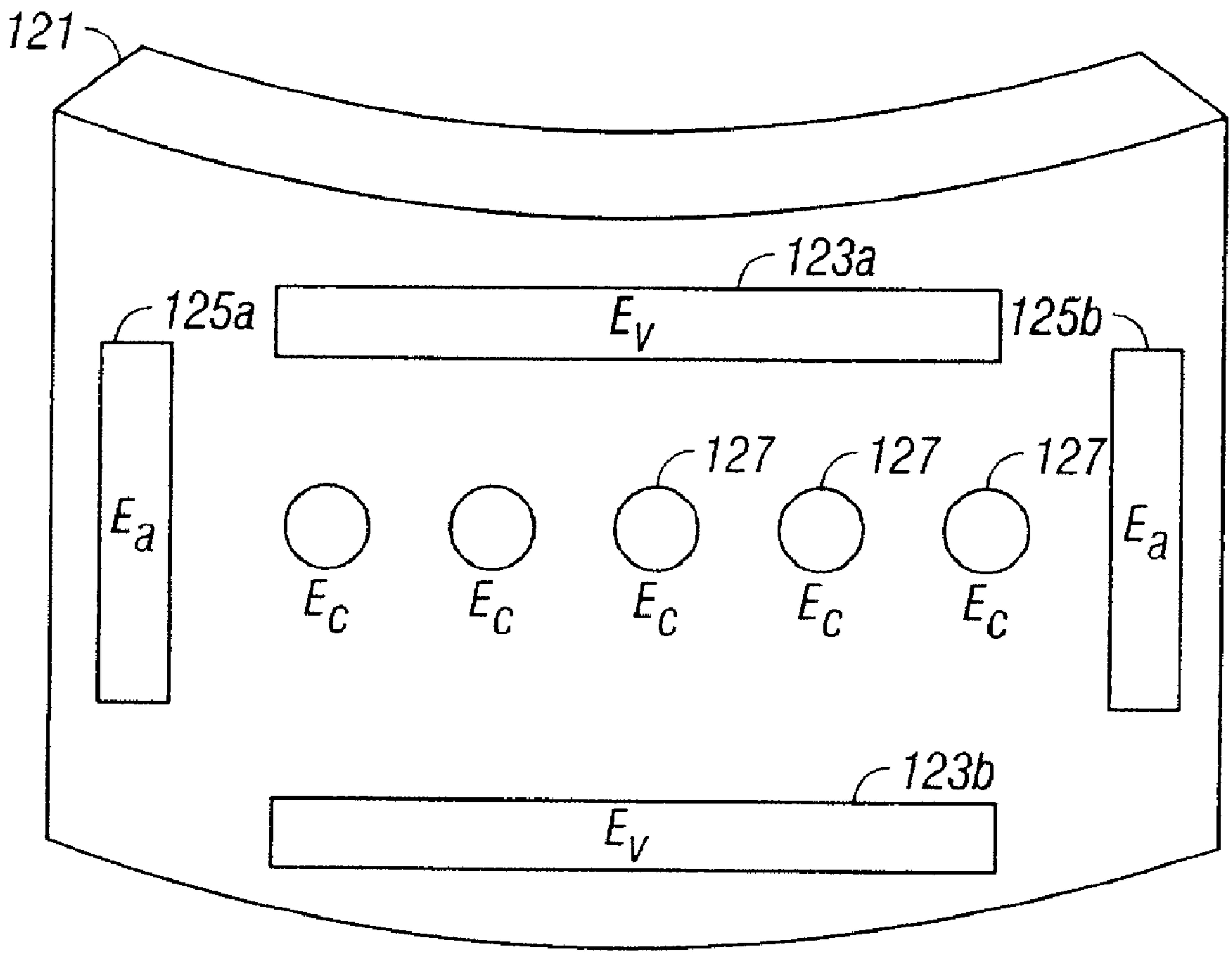

(57) **Abrégé/Abstract:**
A resistivity imaging device injects currents in two orthogonal directions using two pairs of return electrodes and performing impedance measurements of the buttons placed between the returns.

ABSTRACT

A resistivity imaging device injects currents in two orthogonal directions using two pairs of return electrodes and performing impedance measurements of the buttons placed between the returns.

584-41454-WO

TWO-AXIAL PAD FORMATION RESISTIVITY IMAGER

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BACKGROUND OF THE INVENTION

1. Field of the Invention

[0001] This invention generally relates to exploration for hydrocarbons involving electrical investigations of a borehole penetrating an earth formation. More specifically, this invention relates to highly localized borehole investigations employing the introduction and measuring of individual survey currents injected into the wall of a borehole by capacitive coupling of electrodes on a tool moved along the borehole with the earth formation.

2. Background of the Art

[0002] Electrical earth borehole logging is well known and various devices and various techniques have been described for this purpose. Broadly speaking, there are two categories of devices used in electrical logging devices. In the first category, a measure electrode (current source or sink) are used in conjunction with a diffuse return electrode (such as the tool body). A measure current flows in a circuit that connects a current source to the measure electrode, through the earth formation to the return electrode and back to the voltage source in the tool. In inductive measuring tools, an antenna within the measuring instrument induces a current flow within the earth formation. The magnitude of the induced current is detected using either the same antenna or a separate receiver antenna. The present invention belongs to the first category.

[0003] There are several modes of operation: in one, the current at the measuring electrode is maintained constant and a voltage is measured while in the second mode, the voltage of the electrode is fixed and the current flowing from the electrode is measured. Ideally, it is desirable that if the current is varied to maintain constant the voltage measured at a monitor electrode, the current is inversely proportional to the resistivity of the earth formation being investigated. Conversely, it is desirable that if this current is maintained constant, the voltage measured at a monitor electrode is proportional to the resistivity of the earth formation being investigated.

Ohm's law teaches that if both current and voltage vary, the resistivity of the earth formation is proportional to the ratio of the voltage to the current.

[0004] *Birdwell* (US Patent 3365658) teaches the use of a focused electrode for determination of the resistivity of subsurface formations. A survey current is emitted from a central survey electrode into adjacent earth formations. This survey current is focused into a relatively narrow beam of current outwardly from the borehole by use of a focusing current emitted from nearby focusing electrodes located adjacent the survey electrode and on either side thereof. *Ajam* et al (US Patent 4122387) discloses an apparatus wherein simultaneous logs may be made at different lateral distances through a formation from a borehole by guard electrode systems located on a sonde which is lowered into the borehole by a logging cable. A single oscillator controls the frequency of two formation currents flowing through the formation at the desired different lateral depths from the borehole. The armor of the logging cable acts as the current return for one of the guard electrode systems, and a cable electrode in a cable electrode assembly immediately above the logging sonde acts as the current return for the second guard electrode system. Two embodiments are also disclosed for measuring reference voltages between electrodes in the cable electrode assembly and the guard electrode systems

[0005] Techniques for investigating the earth formation with arrays of measuring electrodes have been proposed. See, for example, the U.S. Pat. No. 2930969 to *Baker*, Canadian Patent No. 685727 to *Mann et al.*, U.S. Patent No. 4468623 to *Gianzero*, U.S. Patent No. 5502686 to *Dory et al.* and U.S. Patent 6,714,014 to *Evans*.

SUMMARY OF THE INVENTION

[0006] One embodiment of the invention is an apparatus for evaluating an earth formation. The apparatus comprises a two-terminal resistivity sensor on a pad. The pad is configured to be proximate to a wall of a borehole. One of the two terminals comprises a first electrode on the pad, the first electrode configured to convey a current into the earth formation.

A return electrode is horizontally displaced from the first electrode. A processor is configured to determine a resistivity property of the earth formation from the current in the first electrode. The pad may comprise more than one pad. The first electrode may comprise a plurality of current electrodes azimuthally disposed on the pad. The determined resistivity property may be a horizontal resistivity of the earth formation. The apparatus may include an additional return electrode vertically separated from the current electrode, and the processor may further be configured to determine from a current in the first electrode an additional property of the earth formation. The additional property may be a vertical resistivity of the earth formation.

[0007] Another embodiment of the invention is a method of evaluating an earth formation. A pad is extended from a body of a logging tool to near the borehole wall. A current is conveyed into the formation using a plurality of current electrodes on the at least one pad. A pair of horizontally separated return electrodes are positioned on the at least one pad. A resistivity property of the earth formation is determined from the currents in the plurality of current electrodes. More than one pad may be used. The current electrodes may be positioned azimuthally on the pad. The resistivity property may be a horizontal resistivity of the earth formation. The pair of horizontally separated return electrodes may be open-circuited, a pair of vertically separated return electrodes may be positioned on the pad and an additional property of the earth formation determined from the currents in the current electrode. The additional property may be a vertical resistivity of the earth formation.

[0008] Another embodiment of the invention is a computer readable medium for use with an apparatus which senses a resistivity parameter of an earth formation penetrated by a borehole. The apparatus includes a pad with a plurality of current electrodes and a pair of horizontally spaced-apart return electrodes. The medium includes instructions which enables a processor to estimate the resistivity parameter based on currents in the current electrodes. The computer readable medium may be a ROM, an EPROM, anEAROM, a flash memory, and/or an optical disk

[0008a] A further embodiment of the invention is an apparatus for evaluating an earth formation penetrated by a borehole. The apparatus comprises a pad, a first electrode, a return electrode, and a processor. The pad is configured to be proximate to a wall of the borehole. The first electrode is disposed on the pad, and is configured to convey a current into the earth formation. The return electrode is horizontally displaced from the first electrode. The processor is configured to: determine a resistivity property of the earth formation from the current in the first electrode and a voltage between the first electrode and the return electrode; and record the resistivity property on a suitable medium.

[0008b] A yet further embodiment of the invention is a method of evaluating an earth formation. The method comprises the follow steps. A current is conveyed into the earth formation using a pad-mounted current electrode proximate to a wall of a borehole in the formation. The current is received in a return electrode horizontally separated from the current electrode. A resistivity property of the earth formation is determined from the current in the current electrode and a voltage between the current electrode and the return electrode. The determined resistivity property is recorded on a suitable medium.

[0008c] An even further embodiment of the invention is a computer readable medium for use with an apparatus for evaluating an earth formation penetrated by a borehole. The apparatus comprises at least one pad, at least one current electrode, and at least one return electrode. The at least one pad is conveyed in a borehole the at least one pad proximate to a wall of the borehole. The at least one current electrode is disposed on the at least one pad, the at least one current electrode configured to convey a current into the earth formation. The at least one return electrode is horizontally displaced from the at least one current electrode. The medium comprises instructions that enable a processor to determine a resistivity property of the earth formation from the current in the at least one current electrode and a voltage between the at least one current electrode and the at least one return electrode.

BRIEF DESCRIPTION OF THE FIGURES

[0009] The present invention is best understood with reference to the accompanying figures in which like numerals refer to like elements and in which:

Fig. 1 (prior art) shows an exemplary logging tool suspended in a borehole;

Fig. 2A (prior art) is a mechanical schematic view of an exemplary imaging tool;

Fig. 2B (prior art) is a detail view of an electrode pad of an exemplary logging tool;

Fig. 3 is an equivalent circuit representation of a resistivity tool in a borehole;

Fig. 4 is an illustration of the electrode configuration of one embodiment of the present invention; and

Fig. 5 is a plot showing the response of the device of **Fig. 4** to a layered earth model with different tool standoffs.

DETAILED DESCRIPTION OF THE INVENTION

[0010] Fig. 1 shows an exemplary imaging tool **10** suspended in a borehole **12**, that penetrates earth formations such as **13**, from a suitable cable **14** that passes over a sheave **16** mounted on drilling rig **18**. By industry standard, the cable **14** includes a stress member and seven conductors for transmitting commands to the tool and for receiving data back from the tool as well as power for the tool. The tool **10** is raised and lowered by draw works **20**. Electronic module **22**, on the surface **23**, transmits the required operating commands downhole and in return, receives data back which may be recorded on an archival storage medium of any desired type for concurrent or later processing. The data may be transmitted in analog or digital form. Data processors such as a suitable computer **24**, may be provided for performing data analysis in the field in real time or the recorded data may be sent to a processing center or both for post processing of the data.

[0011] Fig. 2a is a schematic external view of a borehole sidewall imager system. The tool **10** comprising the imager system includes resistivity arrays **26** and, optionally, a mud cell **30** and a circumferential acoustic televiewer **32**. Electronics modules **28** and **38** may be located at suitable locations in the system and not necessarily in the locations indicated. The components may be mounted on a mandrel **34** in a conventional well-known manner. The outer diameter of the assembly is about 5 inches and about fifteen feet long. An orientation module **36** including a magnetometer and an accelerometer or inertial guidance system may be mounted above the imaging assemblies **26** and **32**. The upper portion **38** of the tool **10** contains a telemetry module for sampling, digitizing and transmission of the data samples from the various components uphole to surface electronics **22** in a conventional manner. If acoustic data are acquired, they are preferably digitized, although in an alternate arrangement, the data may be retained in analog form for transmission to the surface where it is later digitized by surface electronics **22.**

[0012] Also shown in **Fig. 2A** are three resistivity arrays **26** (a fourth array is hidden in this view. Referring to **Figs. 2A** and **2B**, each array includes measure electrodes **41a, 41b,... 41n** for injecting electrical currents into the formation, focusing electrodes **43a, 43b** for horizontal focusing of the electrical currents from the measure electrodes and focusing electrodes **45a, 45b** for vertical focusing of the electrical currents from the measure electrodes. By convention, "vertical" refers to the direction along the axis of the borehole and "horizontal" refers to a plane perpendicular to the vertical.

[0013] The approximate schematic circuit diagram is presented in **Fig. 3.** It shows that the current in the circuit depends on the internal impedance of the tool Z_i, the impedance due to the standoff between return electrode and formation Z_R, the impedance due to the gap between receiver and formation Zg and the formation impedance Z_f. If U is the applied voltage then the current in the circuitry is

$$I = \frac{U}{Z_i + Z_R + Z_g + Z_f} \qquad (1).$$

[0014] In its turn the formation impedence Z_f is comprised of the resistivity Z_L of the layer placed in the vicinity of the measurement button and some background impedance Z_B which depends on resistivities of layers placed between current and return electrodes. The resolution of the impedance measurements is highly driven by the relative contribution of Z_L into the measured impedance Z - the higher the contribution of Z_L into the effective impedance Z compared to Z_i, Z_R, Zg and Z_B the better the resolution of the measurements to the resistivity change in the vicinity of the measurement button.

[0015] The electrode configuration used in an embodiment of the present invention is illustrated in **Fig. 4.** A pad **121** is provided with a set of current electrodes **127.** Also provided on the pad is a pair of vertically separated return electrodes **123a, 123b** and a pair of horizontally separated return electrodes **125a, 125b.** In a vertical well and horizontally laminated structure high vertical resolution is provided by the pair of two horizontally separated return electrodes **125a, 125b.** The same current electrodes (buttons) in combination with the pair of vertically separated electrodes **123a, 123b** provides high resolution in the azimuthal direction.

[0016] **Fig. 5** shows the results of 2D mathematical modeling using the electrode configuration of **Fig. 4.** The well diameter is 8.5 inches (21.6cm). The well is filled with a fluid of resistivity of 10^5 Ω-m resistive mud. The formation comprises an azimuthal sequence of layers with resistivity alternating between 1 Ω-m and 10 Ω-m. The two return electrodes **123a, 123b** are separated by 10 cm. The current buttons are 0.5 x 0.5 in (1.27cm x 1.27cm) and are positioned in the middle between the return electrodes. Transmitter provides an output voltage of 1V at frequency of 10 MHz.. The data in **Fig. 5** correspond to the different cases when the pad standoff is varying from 0 **201,** 1/8" (3.2mm) **203,** ¼" (6.35m) **205,** and 0.5 " (1.27cm) **207**. The curves correspond to the real part of the impedance. It can be seen from **Fig. 5** that the real part of impedance exactly follows formation variation (case of zero standoff). The dynamic range decreases as the standoff is increased; however, the signal has very high azimuthal resolution. It is clear, that with the horizontally separated electrodes **125a, 125b** (which corresponds to rotating the electrodes **123a, 123b** by 90°, the same current will have similar high resolution in the vertical direction.

[0017] In the example given above, the frequency was 10 MHz and the mud resistivity was 10^5 Ω-m. This is for exemplary purposes only. With resistive mud, it is generally desirable that the following relationship hold:

$$\sigma_m < \omega \varepsilon_m \varepsilon_0 \qquad (2),$$

where σ_m if the mud conductivity,ω is the angular frequency, ε_m is the relative permittivity of the mud, and ε_0 is the permittivity of free space.

[0018] Determination of mud resistivity may be made downhole using the method and apparatus described in US6803039 to *Fabris* et al., having the same assignee as the present invention and the contents of which are incorporated herein by reference. The dielectric constant may be determined using the method and apparatus described in US5677631 to *Reittinger* et al., having the same assignee as the present invention and the contents of which are incorporated herein by reference. Alternatively, measurements of the mud resistivity and dielectric constant may be made at the surface and suitable temperature corrections applied. Based on these measurements, the frequency of operation of the tool may be selected.

[0017] It is important to note that the impedance measured in case of the vertically separated electrodes **123a, 123b** depends on both horizontal and vertical resistivity of formation, while the impedance measured in case of azimuthally separated return electrodes **125a, 125** depends on horizontal resistivity only. This permits processing allowing extraction of micro anisotropy of thin laminated formation. Specifically, the data from the azimuthally separated electrodes are used to derive the horizontal resistivity at each point on the borehole wall. The resistivity determined from the vertically separated electrodes will approximately be the geometric mean of the horizontal and vertical resistivities, enabling the determination of the vertical resistivity. This is particularly useful in determining thin laminations of conductive layers that are common in areas such as the Gulf of Mexico. It should be noted that when measurements are being made with the vertically separated return electrodes, the horizontally separated returns would be open-circuited, and when measurements are made with the horizontally separated return electrodes, the vertically separated electrodes would be open-circuited.

[0018] Implicit in the processing of the data is the use of a computer program implemented on a suitable machine readable medium that enables the processor to perform the control and processing. The term processor as used in this application is intended to include such devices as field programmable gate arrays (FPGAs). The machine readable medium may include ROMs, EPROMs, EAROMs, Flash Memories and Optical disks. As noted above, the processing may be done downhole or at the surface.

[0019] While the foregoing disclosure is directed to the preferred embodiments of the invention, various modifications will be apparent to those skilled in the art. It is intended that all variations within the scope and spirit of the appended claims be embraced by the foregoing disclosure.

[0020] The following definitions may be helpful in understanding the present invention:

EAROM: electrically alterable ROM;

Electrode: electric conductor, usually metal, used as either of the two terminals of an electrically conducting medium

EPROM: erasable programmable ROM;

flash memory: a nonvolatile memory that is rewritable;

induction: based on a relationship between a changing magnetic field and the electric field created by the change;

logging tool: The downhole hardware needed to make a log. The term is often shortened to simply "tool.";

machine readable medium: something on which information may be stored in a form that can be understood by a computer or a processor;

Optical disk: a disc shaped medium in which optical methods are used for storing and retrieving information;

pad: That part of a logging tool that is pressed against the borehole wall

ROM: Read-only memory;

Resistivity: electrical resistance of a conductor of unit cross-sectional area and unit length. Determination of resistivity is equivalent to determination of its inverse (conductivity);

What is claimed is:

1. An apparatus for evaluating an earth formation penetrated by a borehole, the apparatus comprising:

(a) a pad configured to be proximate to a wall of the borehole;

(b) a first electrode disposed on the pad, the first electrode being configured to convey a current into the earth formation;

(c) a return electrode horizontally displaced from the first electrode; and

(d) a processor configured to:

(A) determine a resistivity property of the earth formation from the current in the first electrode and a voltage between the first electrode and the return electrode, and

(B) record the resistivity property on a suitable medium.

2. The apparatus of claim 1 wherein the pad comprises a plurality of pads.

3. The apparatus of claim 1 wherein the first electrode further comprises a plurality of current electrodes disposed azimuthally on the pad.

4. The apparatus of claim 1 wherein the determined resistivity property comprises a horizontal resistivity of the earth formation.

5. The apparatus of claim 1 further comprising an additional return electrode vertically separated from the first electrode; and wherein the processor determines from a current in the first electrode an additional property of the earth formation.

6. The apparatus of claim 5 wherein the return electrode further comprises an open-circuited pair of electrodes.

7. The apparatus of claim 6 wherein the additional property comprises a vertical resistivity of the earth formation.

8. The apparatus of claim 1 further comprising a logging tool configured to carry the pad, and a conveyance device which configured to convey the logging tool into the borehole.

9. The apparatus of claim 1 wherein the pad is extendable from a body of a logging tool.

10. The apparatus of claim 1 wherein the return electrode further comprises a pair of return electrodes.

11. The apparatus of claim 1 wherein the processor is configured to determine a real part of an impedance.

12. A method of evaluating an earth formation, the method comprising:

(a) conveying a current into the earth formation using a pad-mounted current electrode proximate to a wall of a borehole in the formation;

(b) receiving the current in a return electrode horizontally separated from the current electrode;

(c) determining a resistivity property of the earth formation from the current in the current electrode and a voltage between the current electrode and the return electrode; and

(d) recording the determined resistivity property on a suitable medium.

13. The method of claim 12 wherein the determined resistivity property comprises a horizontal resistivity of the earth formation.

14. The method of claim 12 wherein the return electrode further comprises a first pair of return electrodes, the method further comprising:

(i) open-circuiting the first pair of return electrodes;

(ii) positioning a second pair of vertically separated return electrodes on the at least one pad; and

(iii) determining from currents from the current electrodes an additional property of the earth formation.

15. The method of claim 14 wherein the additional property comprises a vertical resistivity of the earth formation.

16. The method of claim 12 wherein conveying the current further comprises using a plurality of current electrodes.

17. The method of claim 16 further comprising positioning the plurality of current electrodes azimuthally on a pad.

18. The method of claim 12 further comprising positioning the current electrode on a pad extendable from a body of a logging us tool.

19. The method of claim 18 further comprising using current electrodes on a plurality of pads.

20. The method of claim 12 wherein determining the resistivity property of the earth formation further comprises determining a real part of an impedance at the current electrode.

21. A computer readable medium for use with an apparatus for evaluating an earth formation penetrated by a borehole, the apparatus comprising:

(a) at least one pad conveyed in a borehole the at least one pad proximate to a wall of the borehole;

(b) at least one current electrode disposed on the at least one pad, the at least one current electrode configured to convey a current into the earth formation; and

(c) at least one return electrode horizontally displaced from the at least one current electrode;

the medium comprising instructions that enable a processor to determine a resistivity property of the earth formation from the current in the at least one current electrode and a voltage between the at least one current electrode and the at least one return electrode.

22. The medium of claim 21 further comprising at least one of (i) a ROM, (ii) an EPROM, (iii) an EAROM, (iv) a flash memory, and (v) an optical disk.

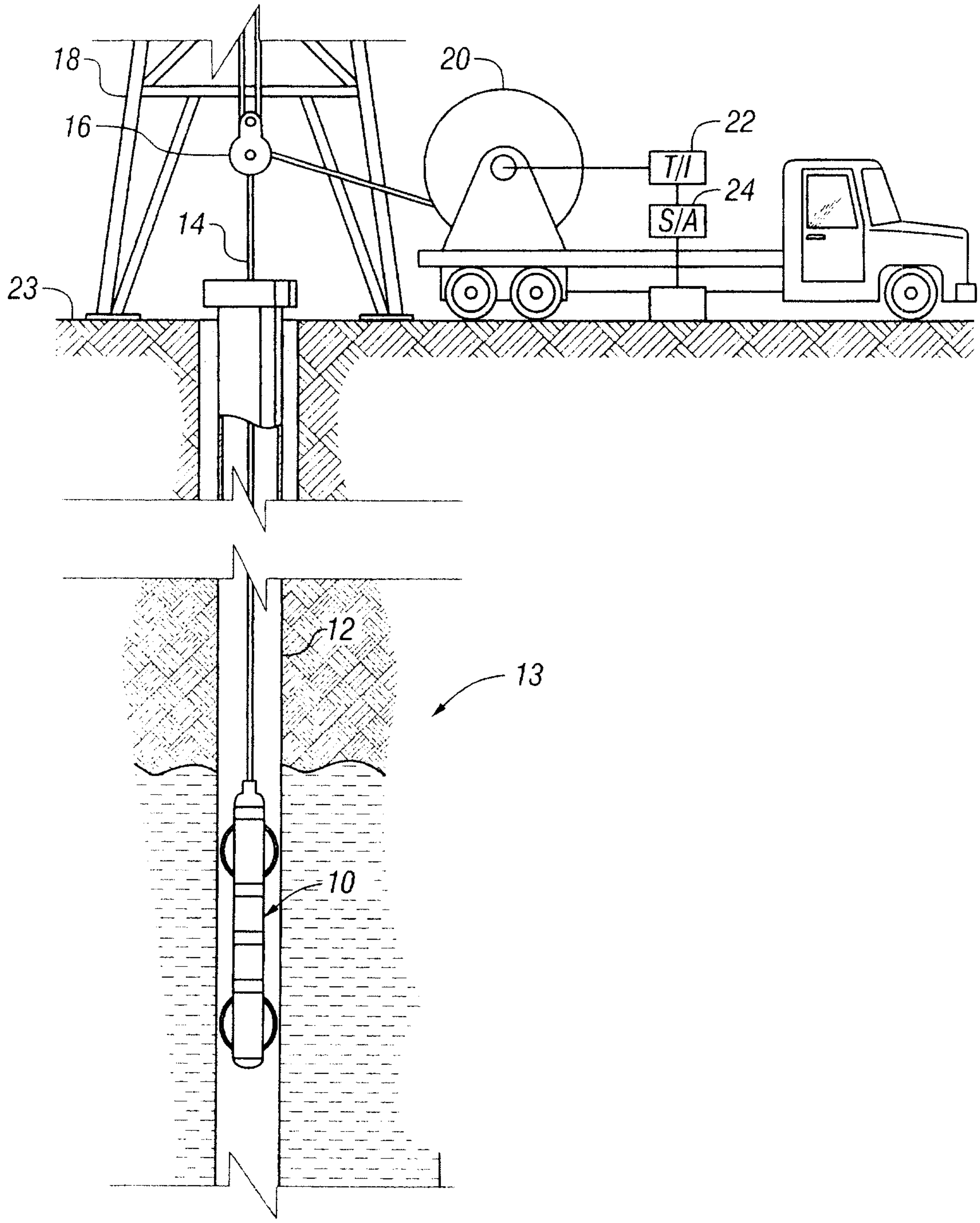


FIG. 1
(Prior Art)

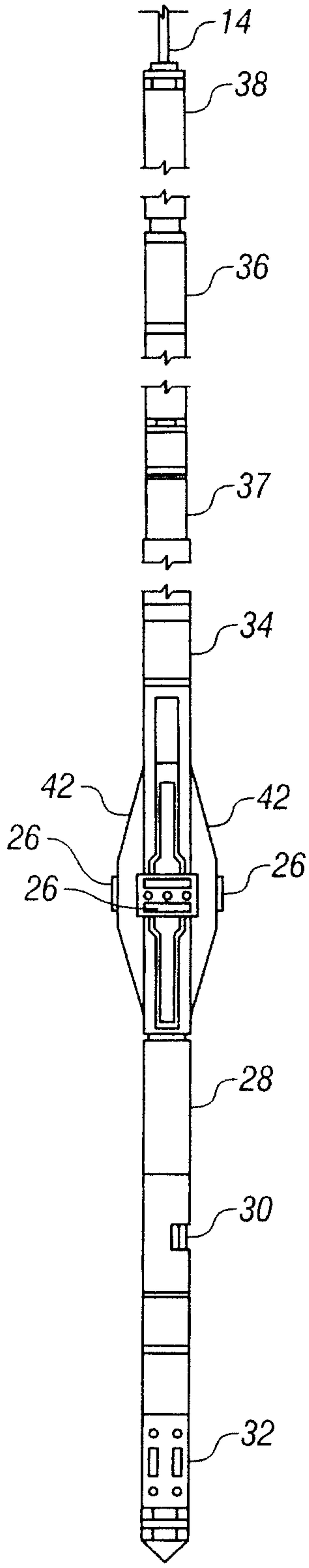


FIG. 2A
(Prior Art)

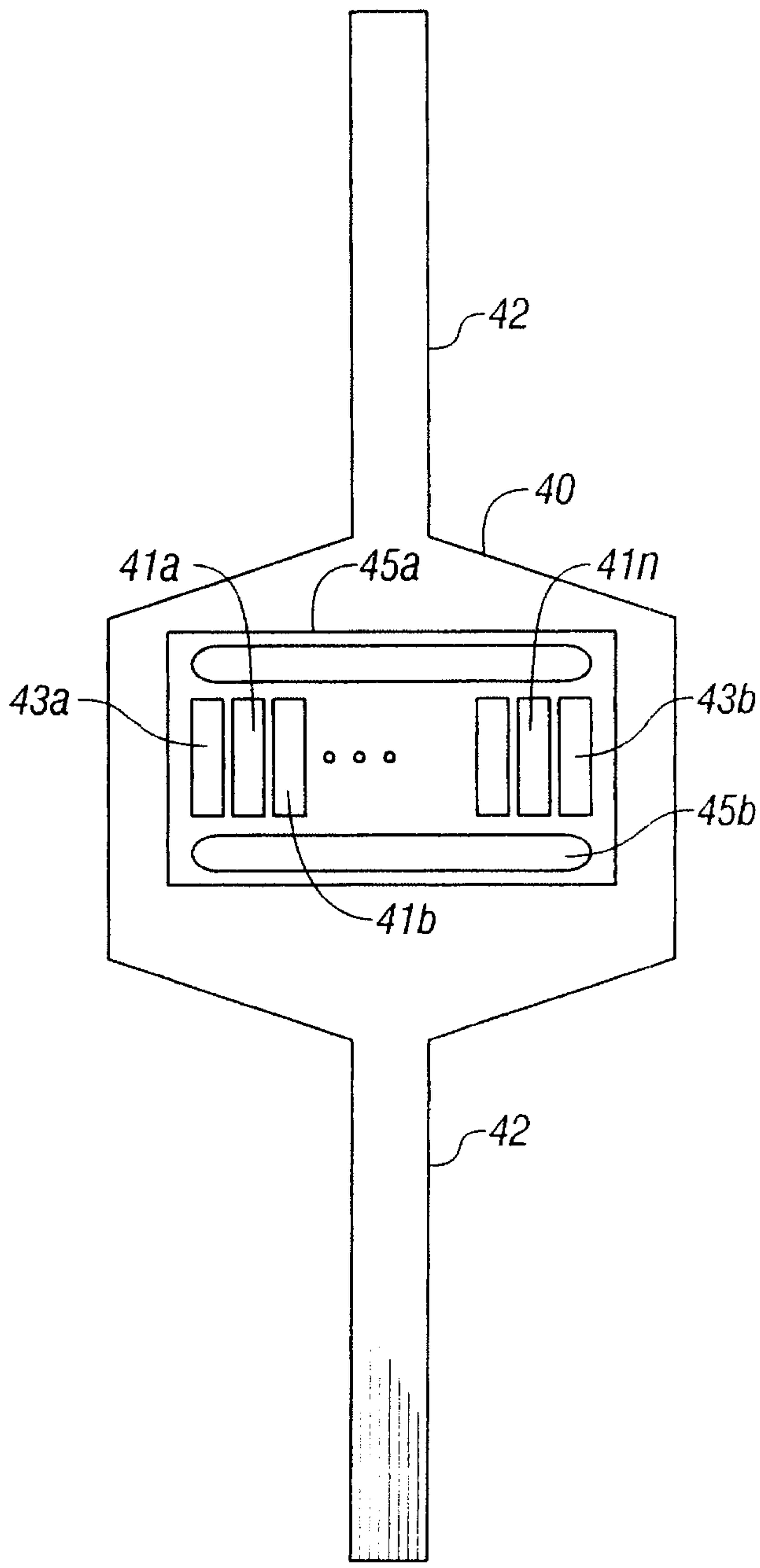
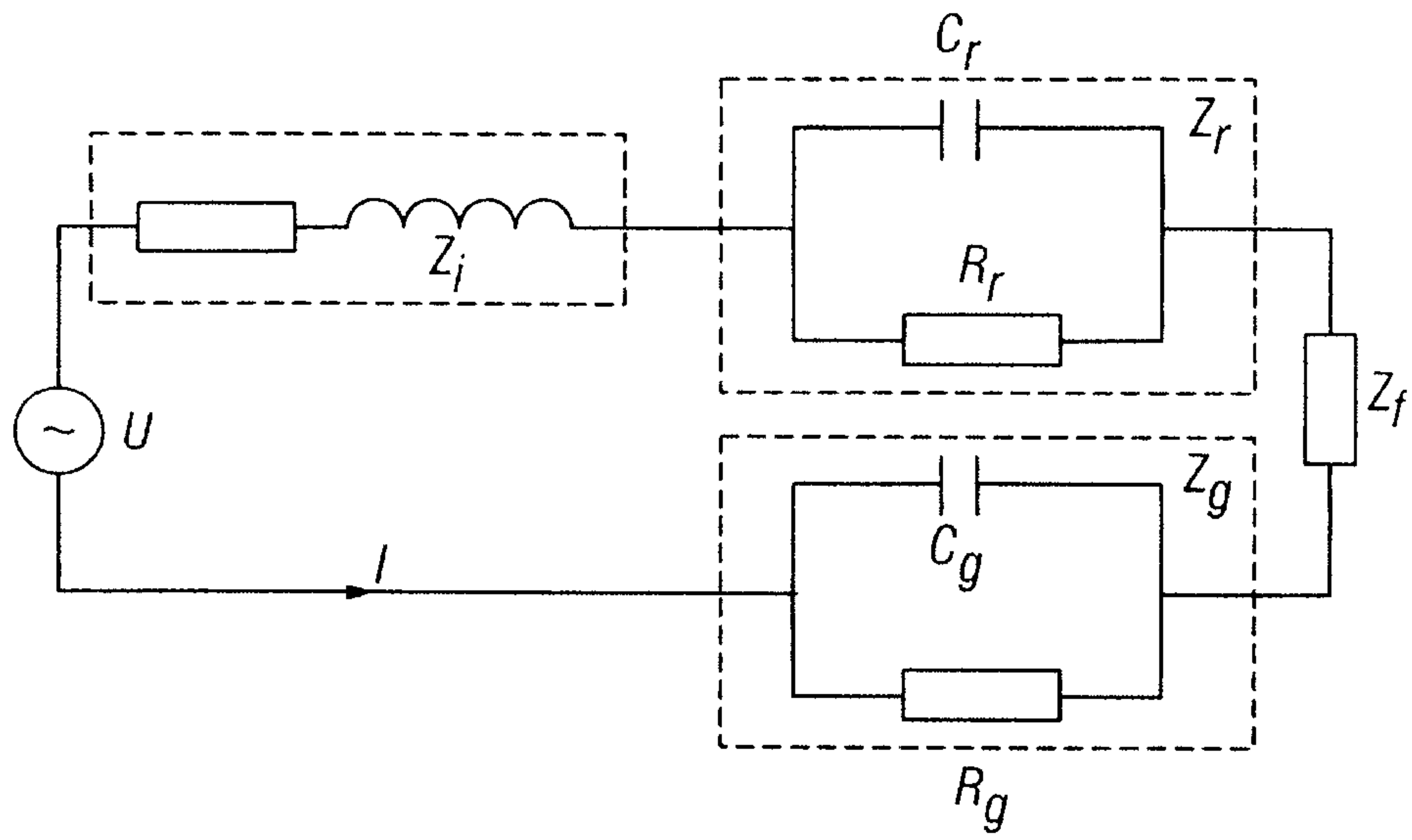


FIG. 2B
(Prior Art)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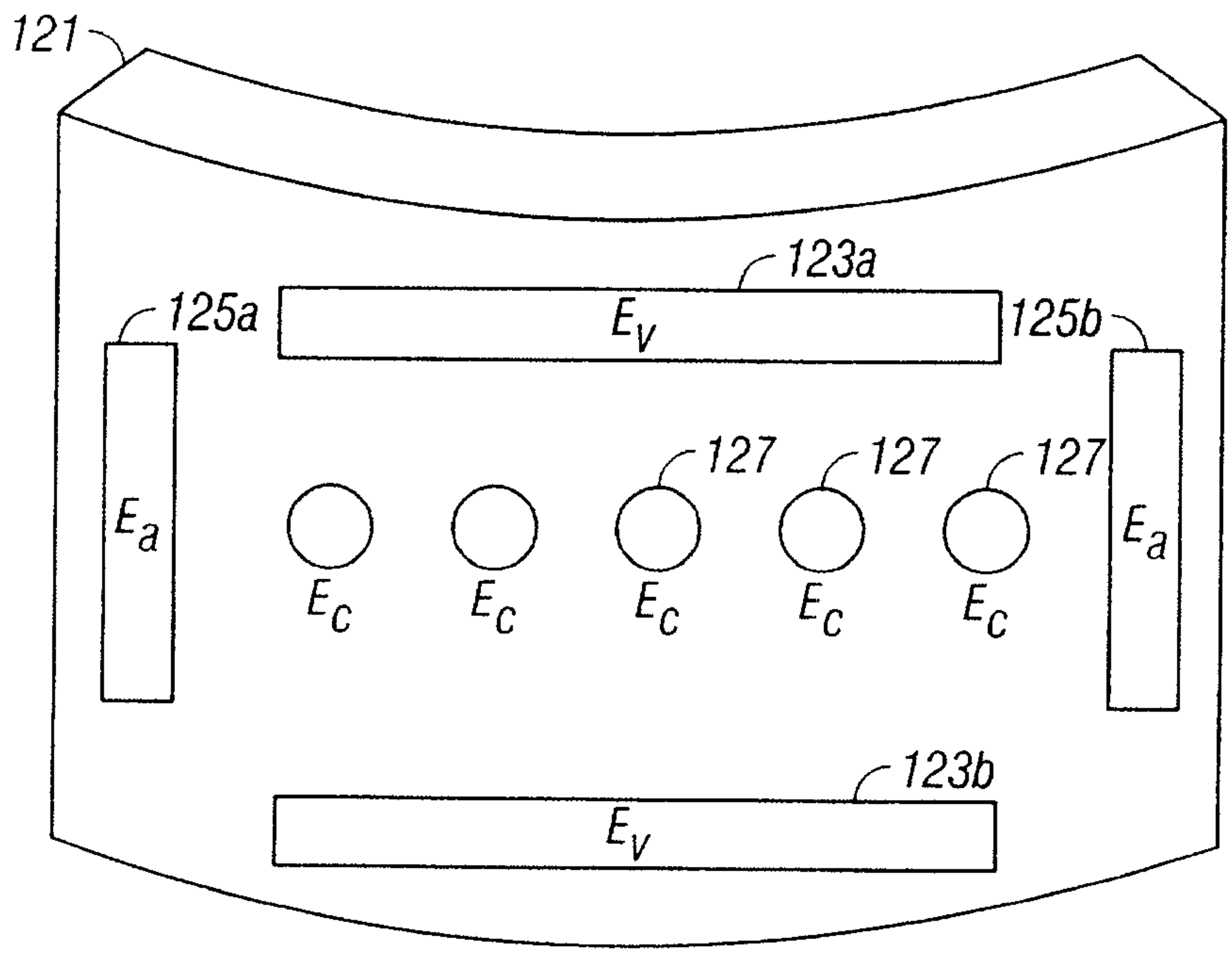
Z_i
R_r
U
Z_f
Z_g
C_g
I
R_g

FIG. 3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125a
125b
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E_a
E_c
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E_c
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123b
E_V

FIG. 4

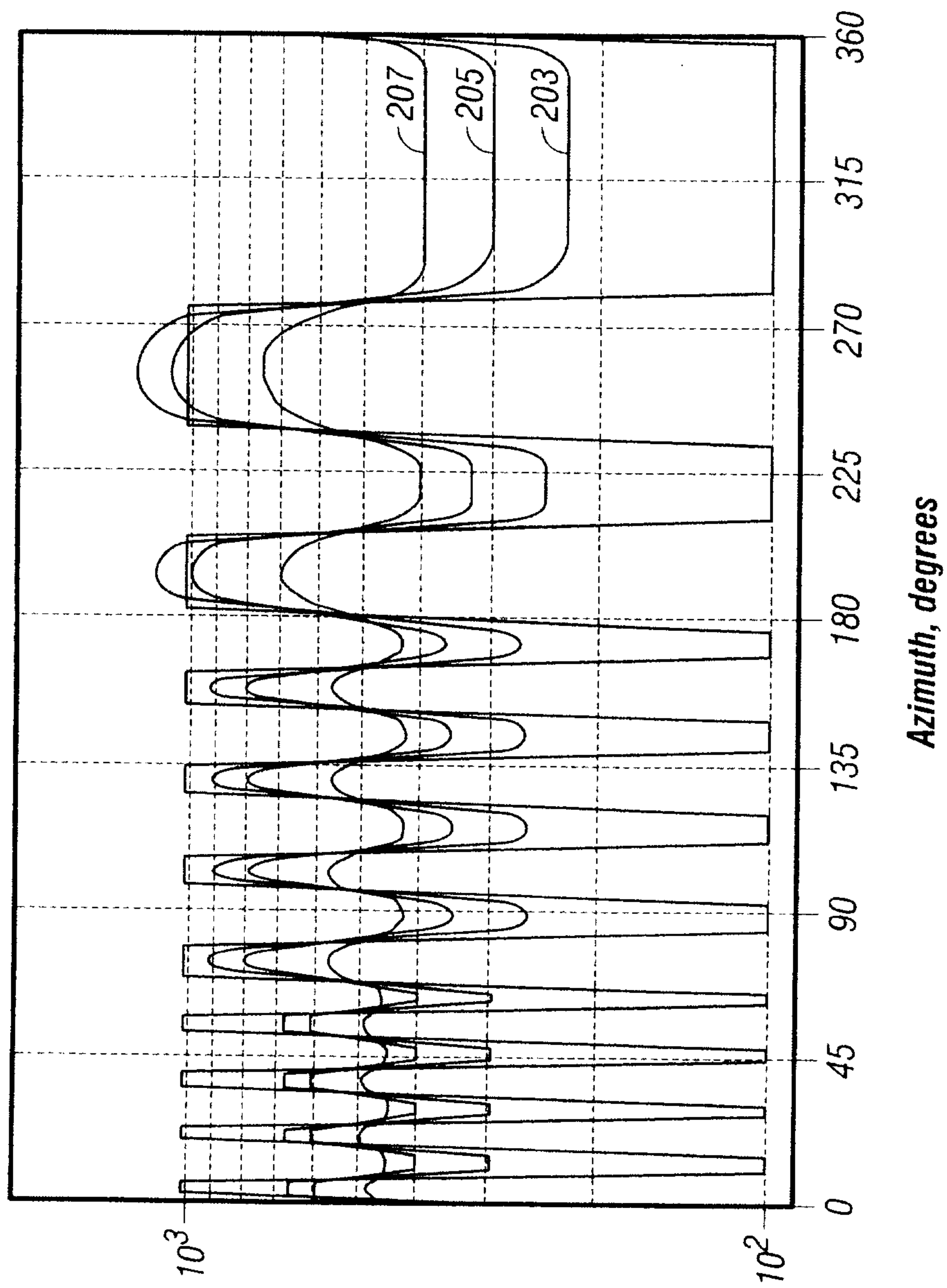
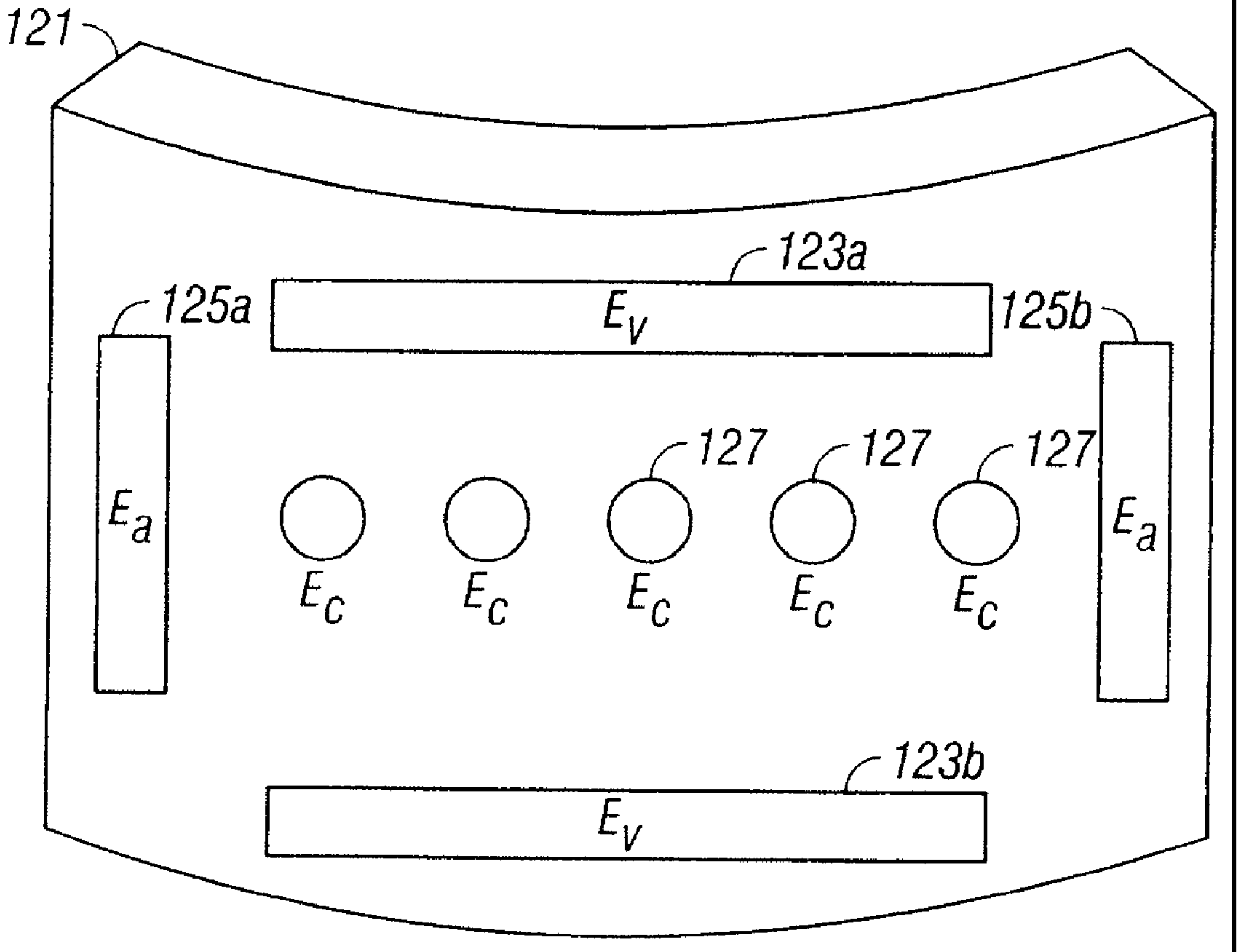

10^3
10^2
0
45
90
135
180
225
270
315
360
207
205
203
Azimuth, degrees

FIG. 5



121
123a
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