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(54) **APPARATUS FOR HEATING HYDROCARBONS WITH RF ANTENNA ASSEMBLY HAVING SEGMENTED DIPOLE ELEMENTS AND RELATED METHODS**

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H01Q 9/16 (2006.01)

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(58) **Field of Classification Search**
CPC E21B 36/04; E21B 36/00; E21B 43/2401
See application file for complete search history.

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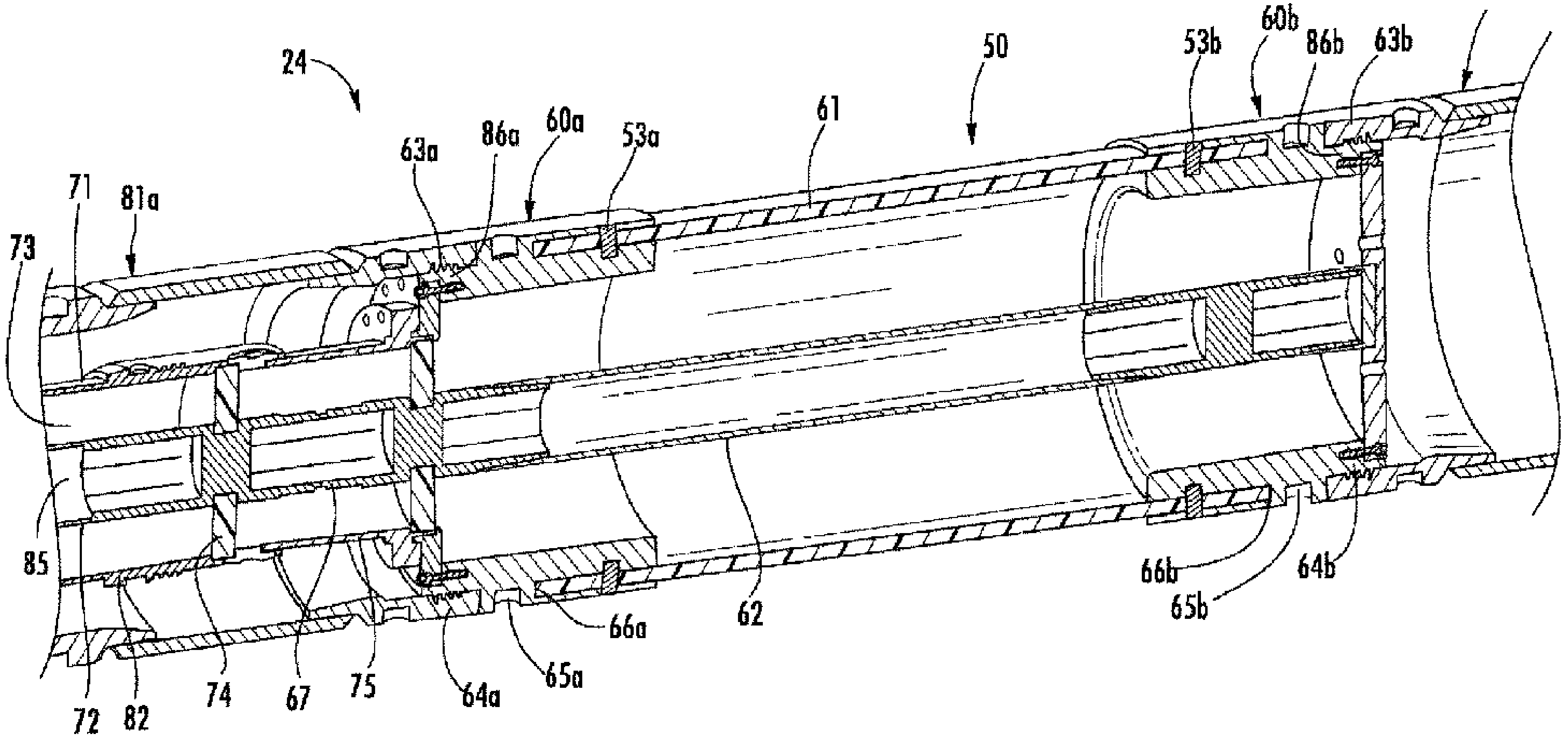
(57) **ABSTRACT**

The apparatus includes an RF antenna assembly to be positioned within a wellbore and coupled to an RF source. The RF antenna assembly includes a first tubular dipole element having opposing proximal and distal ends, an RF transmission line extending through the proximal end of the first tubular dipole element and including an inner conductor, an outer conductor, and a dielectric therebetween. The inner conductor extends outwardly beyond the distal end of the first tubular dipole element. The outer conductor is coupled to the distal end of the first tubular dipole element. The RF antenna assembly includes a second tubular dipole element having opposing proximal and distal ends, with the proximal end being adjacent the distal end of the first tubular dipole element and being coupled to the inner conductor, and a tubular balun.

10 Claims, 8 Drawing Sheets



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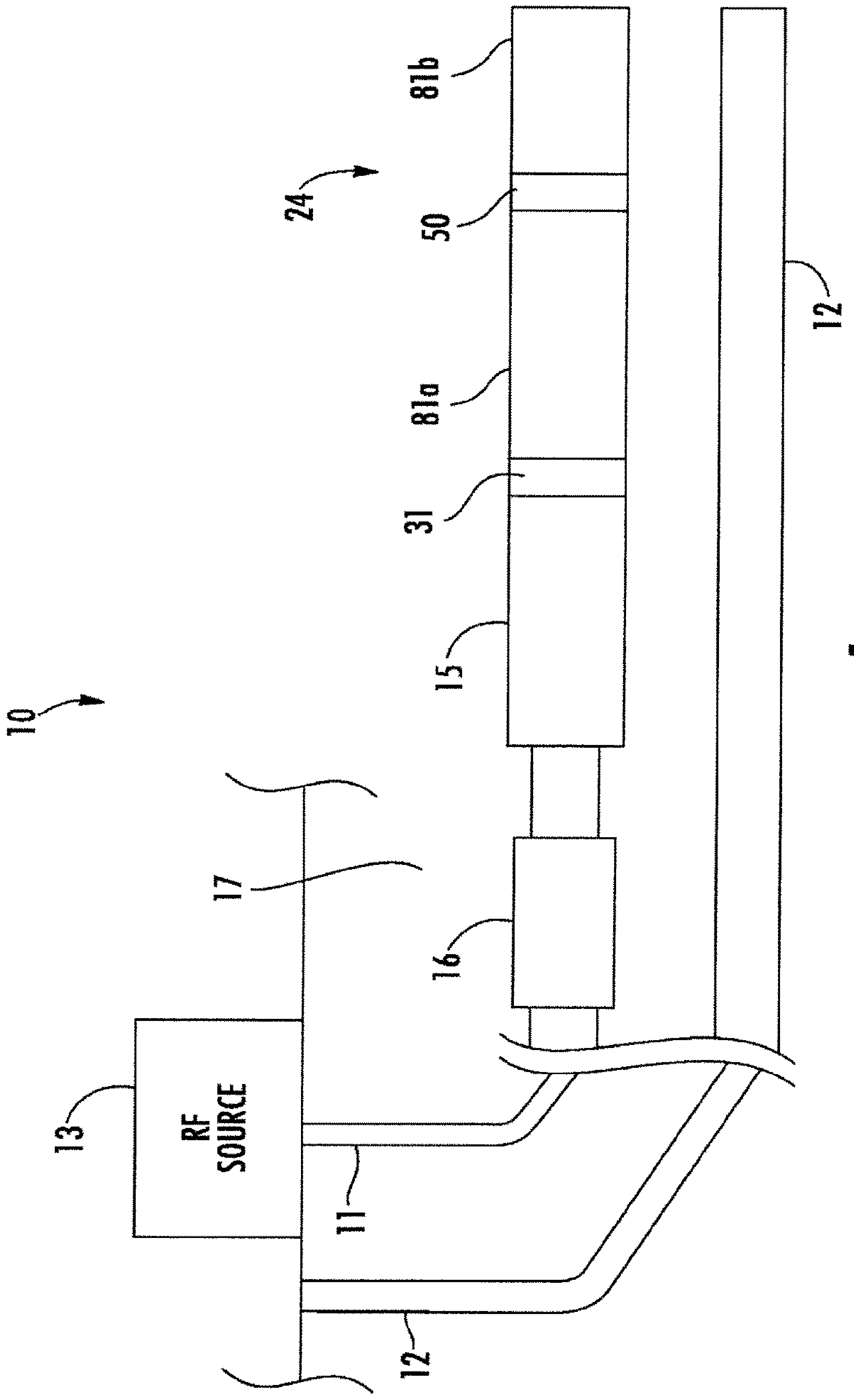

FIG. 1

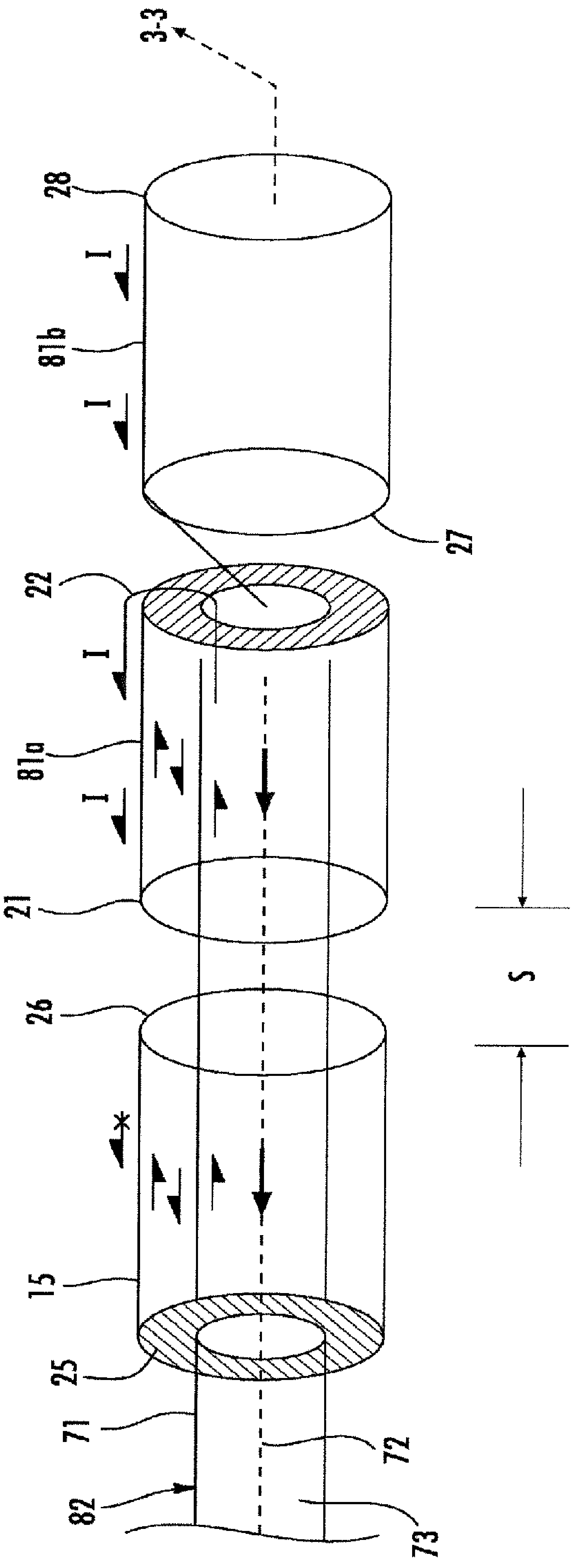

FIG. 2

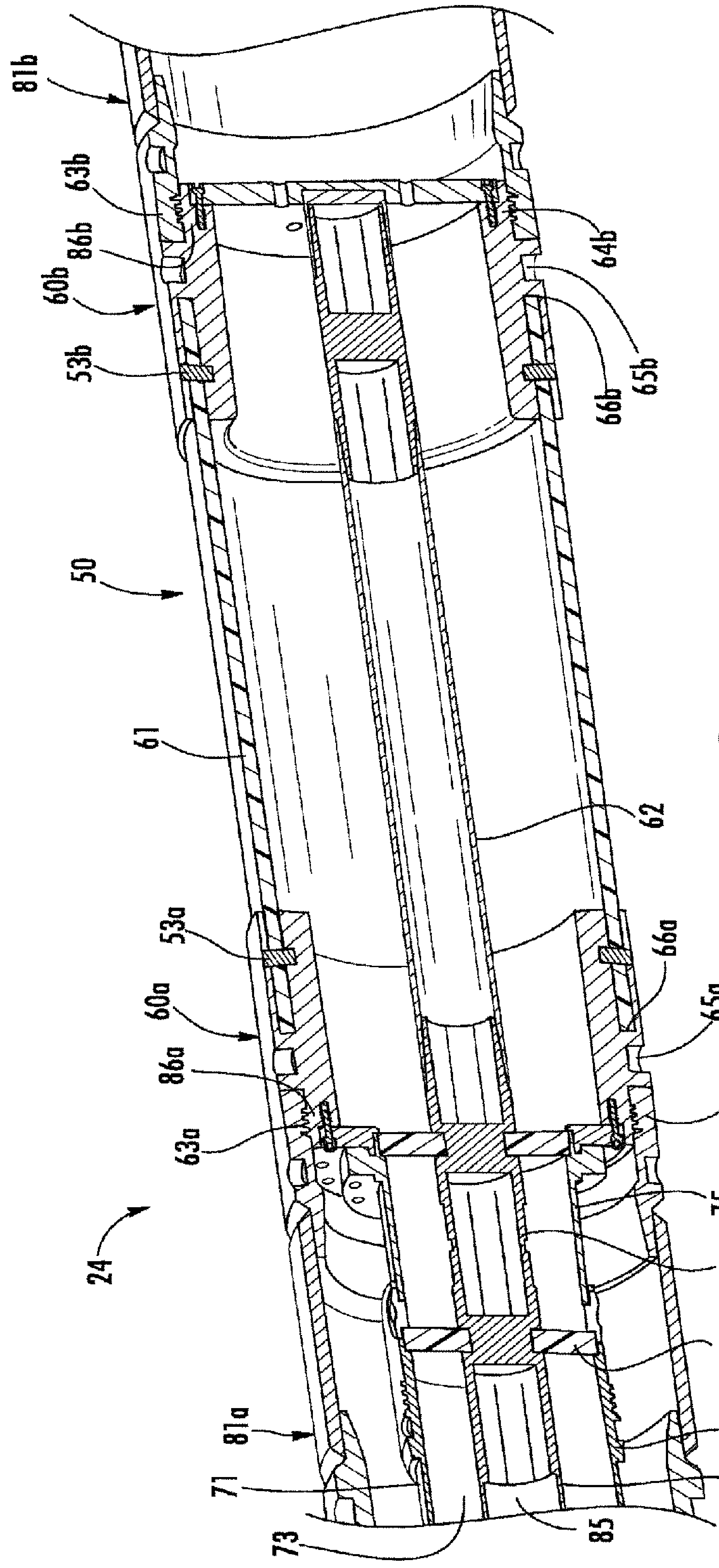
81b
63b
86b
60b
53b
64b
65b
66b
50
61
62
53a
60a
86a
63a
66a
65a
64a
75
67
74
82
72
24
81a
71
73
85

FIG. 3

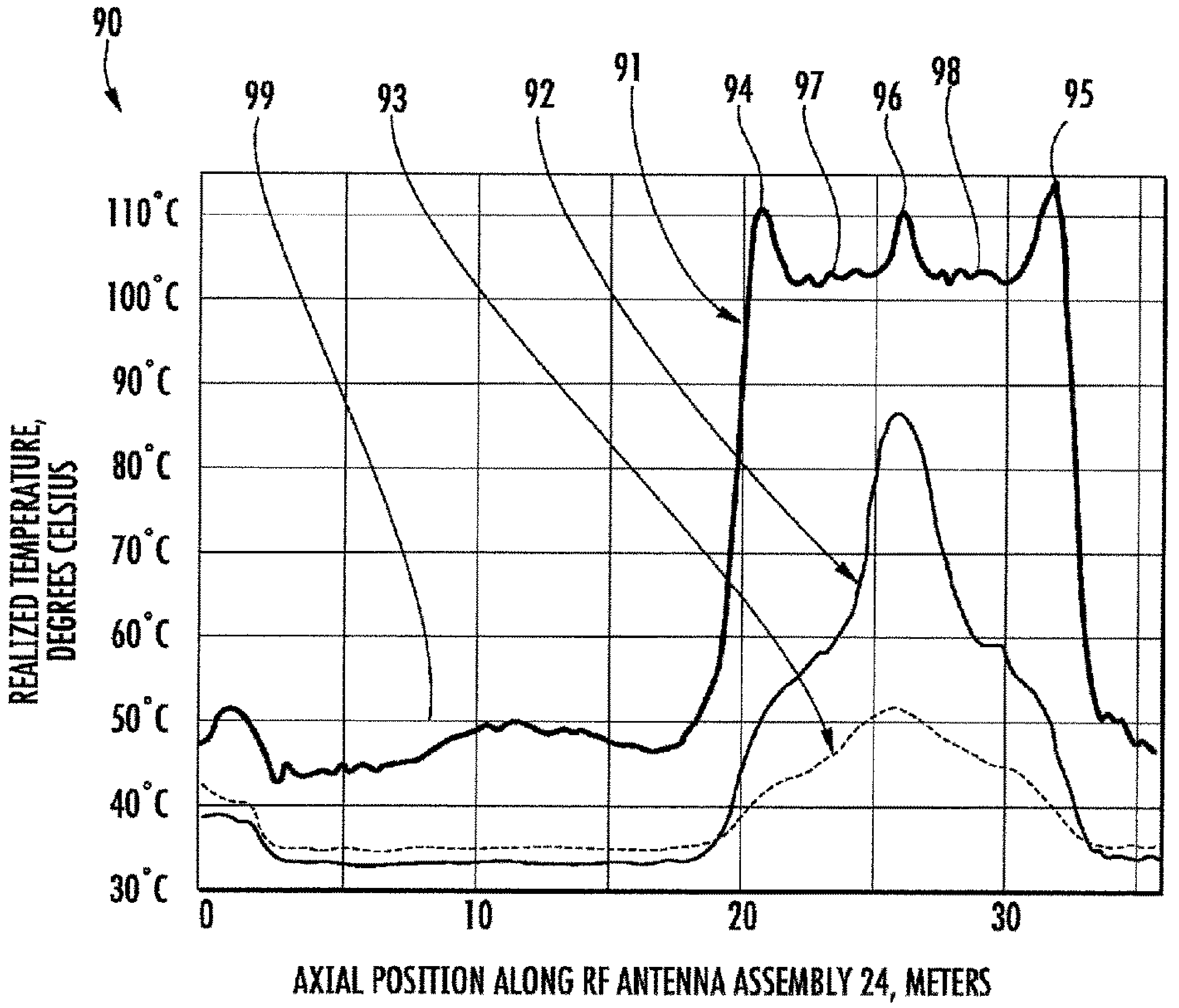
90
99
93
92
91
94
97
96
98
95
110°C
100°C
90°C
80°C
70°C
60°C
50°C
40°C
30°C
REALIZED TEMPERATURE, DEGREES CELSIUS
0
10
20
30
AXIAL POSITION ALONG RF ANTENNA ASSEMBLY 24, METERS

FIG. 4

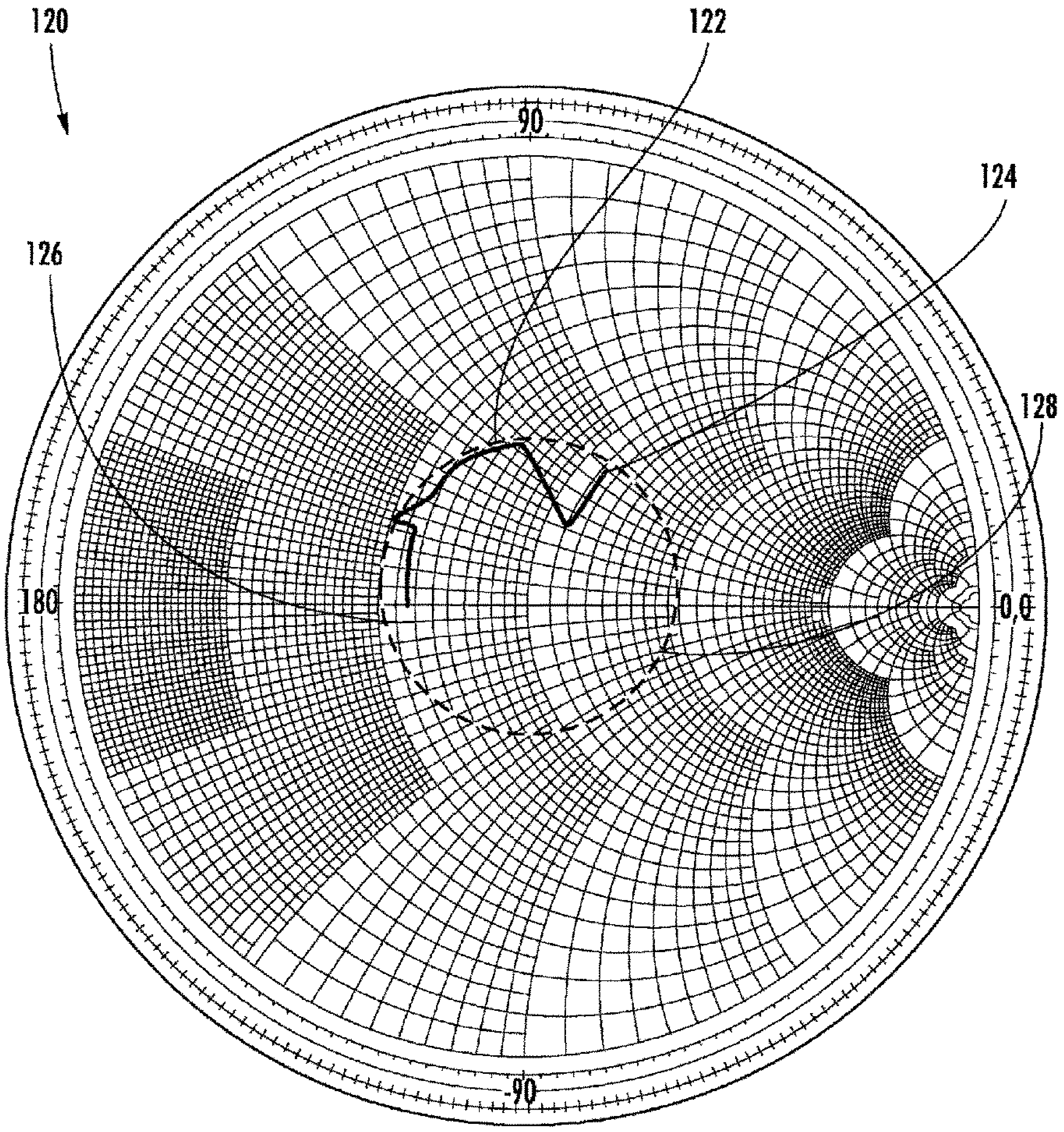

FIG. 5

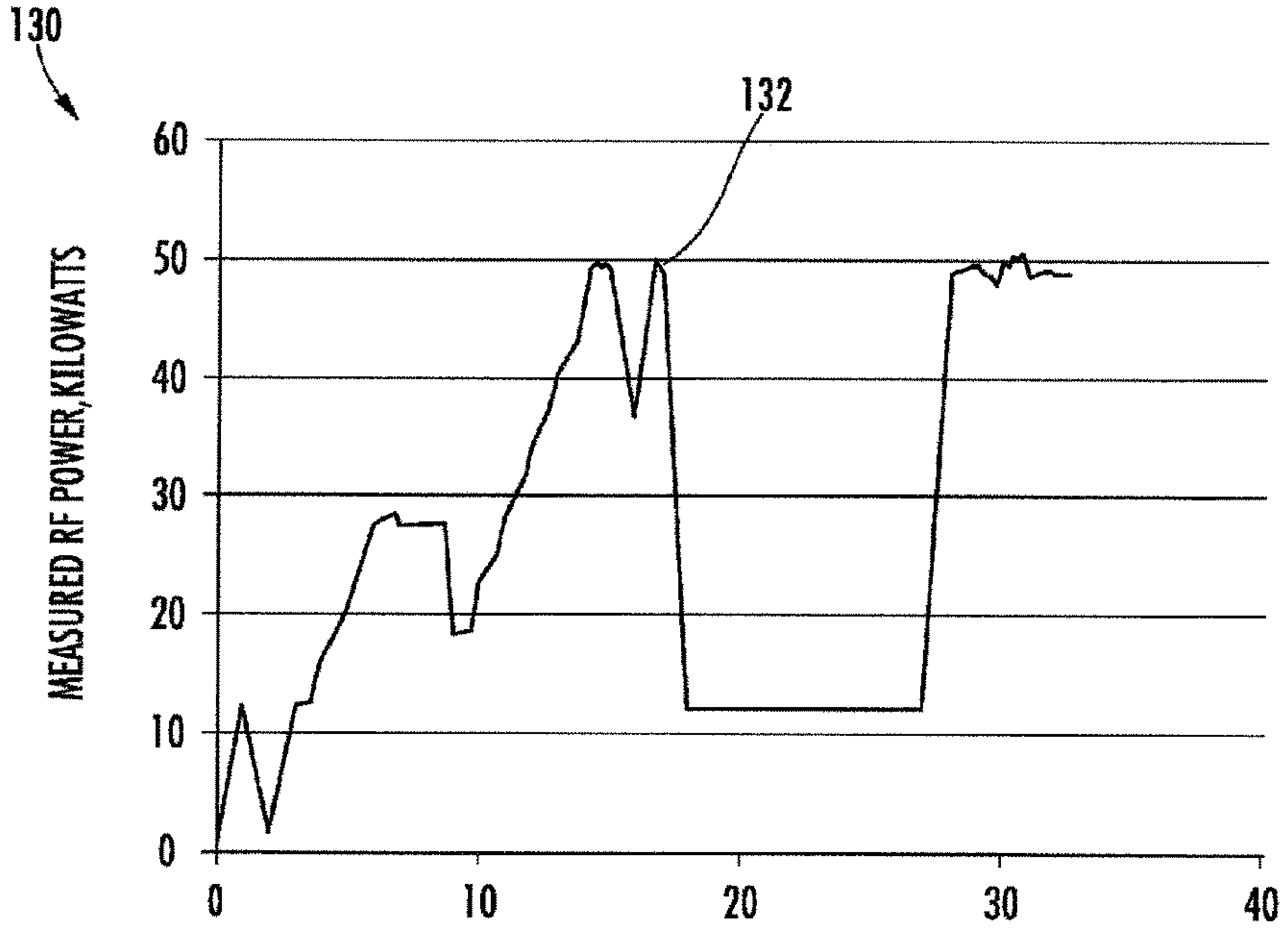
130
132
MEASURED RF POWER, KILOWATTS
60
50
40
30
20
10
0
0
10
20
30
40
TIME, DAYS

FIG. 6

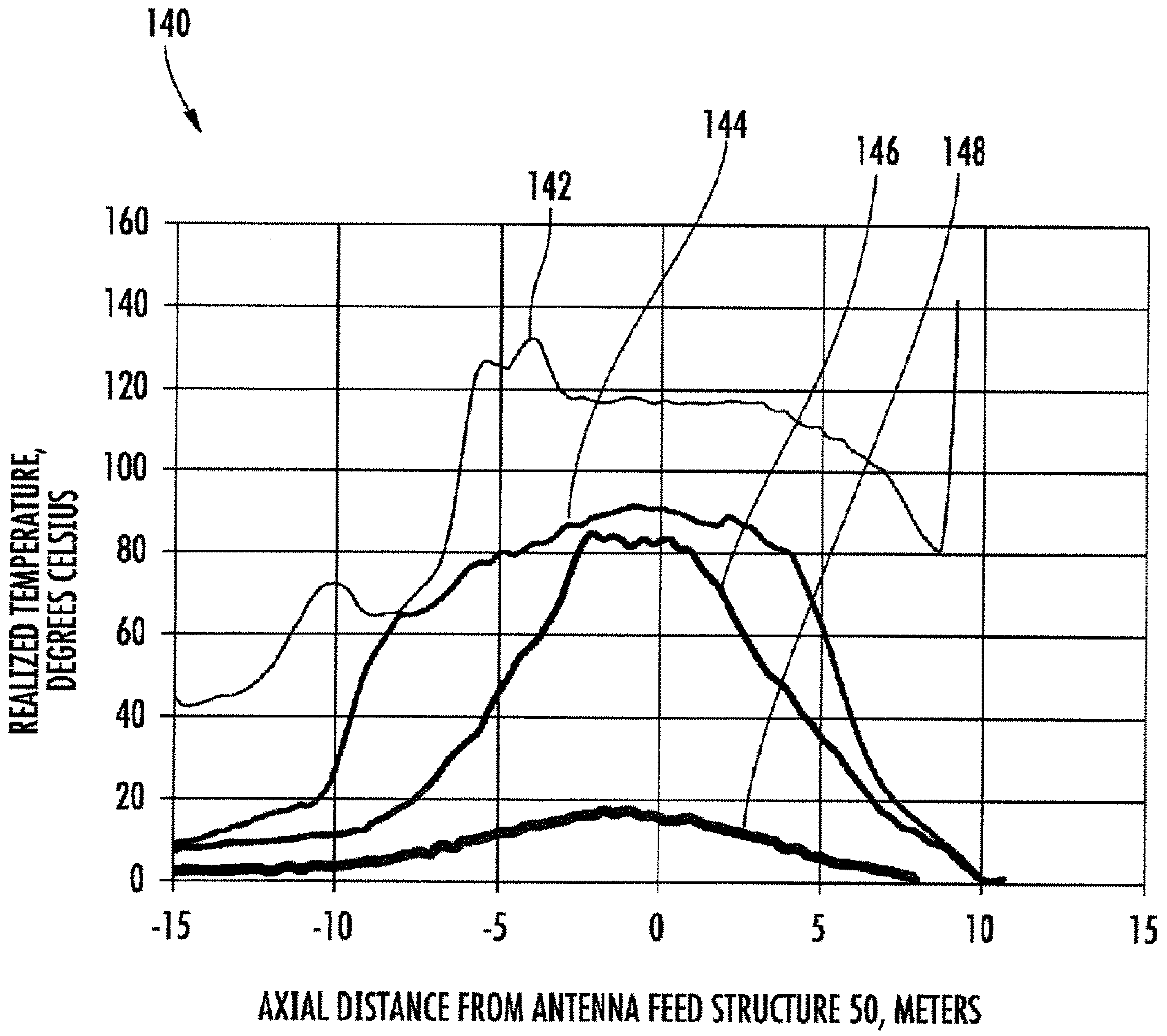
140
142
144
146
148
REALIZED TEMPERATURE, DEGREES CELSIUS
160
140
120
100
80
60
40
20
0
-15
-10
-5
0
5
10
15
AXIAL DISTANCE FROM ANTENNA FEED STRUCTURE 50, METERS

FIG. 7

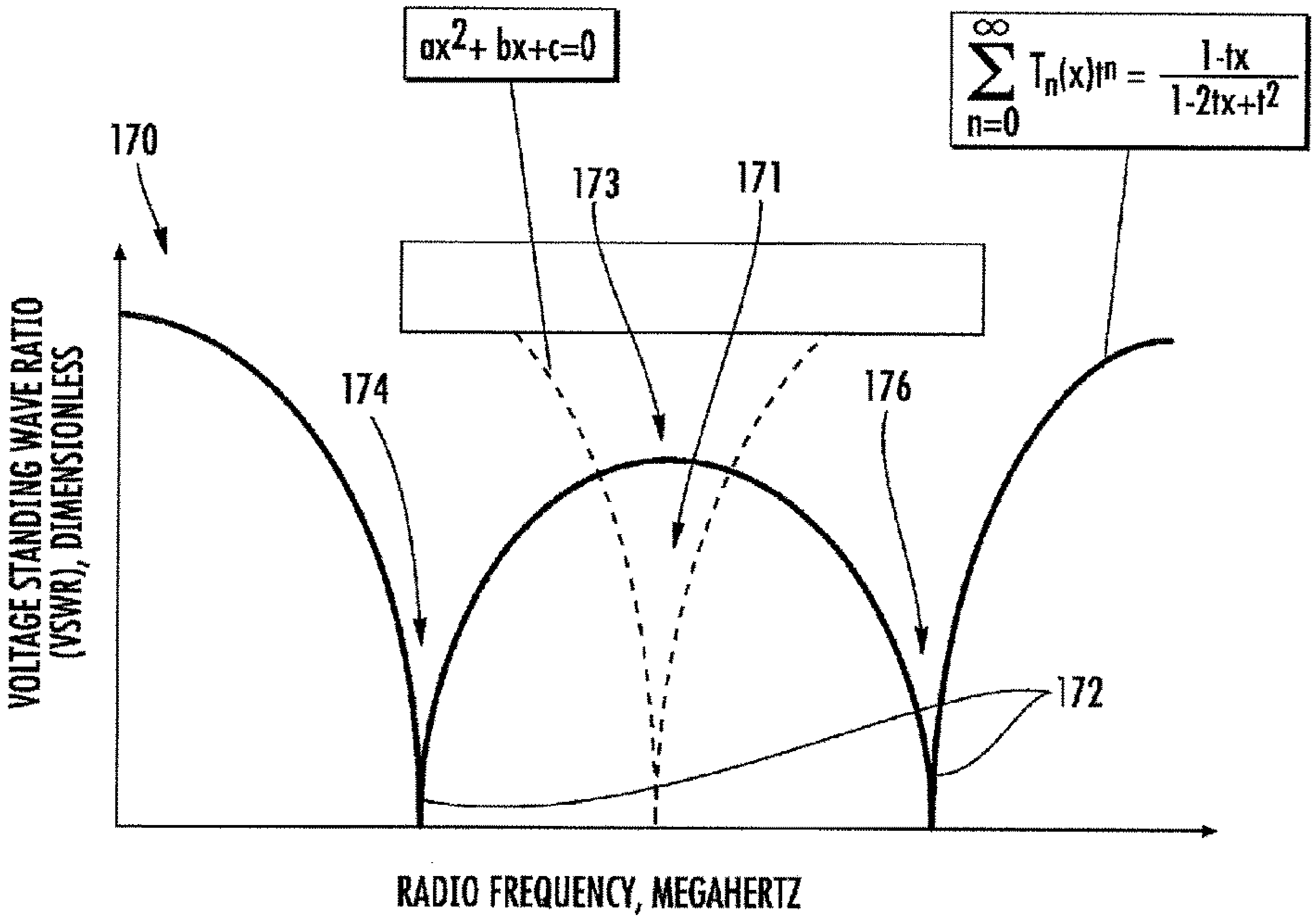
$ax^2+bx+c=0$
$\sum_{n=0}^{\infty} T_n(x)t^n = \frac{1-tx}{1-2tx+t^2}$
170
173
171
174
176
172
VOLTAGE STANDING WAVE RATIO (VSWR), DIMENSIONLESS
RADIO FREQUENCY, MEGAHERTZ

FIG. 8

APPARATUS FOR HEATING HYDROCARBONS WITH RF ANTENNA ASSEMBLY HAVING SEGMENTED DIPOLE ELEMENTS AND RELATED METHODS

Matter enclosed in heavy brackets [ ] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue; a claim printed with strikethrough indicates that the claim was canceled, disclaimed, or held invalid by a prior post-patent action or proceeding.

FIELD OF THE INVENTION

The present invention relates to the field of hydrocarbon resource recovery, and, more particularly, to hydrocarbon resource recovery using radio frequency (RF) heating.

BACKGROUND OF THE INVENTION

Energy consumption worldwide is generally increasing, and conventional hydrocarbon resources are being consumed. In an attempt to meet demand, the exploitation of unconventional resources may be desired. For example, highly viscous hydrocarbon resources, such as heavy oils, may be trapped in tar sands where their viscous nature does not permit conventional oil well production. Estimates are that trillions of barrels of oil reserves may be found in such tar sand formations.

In some instances these tar sand deposits are currently extracted via open-pit mining. Another approach for in situ extraction for deeper deposits is known as Steam-Assisted Gravity Drainage (SAGD). The heavy oil is immobile at reservoir temperatures and therefore the oil is typically heated to reduce its viscosity and mobilize the oil flow. In SAGD, pairs of injector and producer wells are formed to be laterally extending in the ground. Each pair of injector/producer wells includes a lower producer well and an upper injector well. The injector/production wells are typically located in the pay zone of the subterranean formation between an underburden layer and an overburden layer.

The upper injector well is used to typically inject steam, and the lower producer well collects the heated crude oil or bitumen that flows out of the formation, along with any water from the condensation of injected steam. The injected steam forms a steam chamber that expands vertically and horizontally in the formation. The heat from the steam reduces the viscosity of the heavy crude oil or bitumen which allows it to flow down into the lower producer well where it is collected and recovered. The steam and gases rise due to their lower density so that steam is not produced at the lower producer well and steam trap control is used to the same affect. Gases, such as methane, carbon dioxide, and hydrogen sulfide, for example, may tend to rise in the steam chamber and fill the void space left by the oil defining an insulating layer above the steam. Oil and water flow is by gravity driven drainage urged into the lower producer well.

Operating the injection and production wells at approximately reservoir pressure may address the instability problems that adversely affect high-pressure steam processes. SAGD may produce a smooth, even production that can be as high as 70% to 80% of the original oil in place (OOIP) in suitable reservoirs. The SAGD process may be relatively sensitive to shale streaks and other vertical barriers since, as the rock is heated, differential thermal expansion causes fractures in it, allowing steam and fluids to flow through. SAGD may be twice as efficient as the older cyclic steam stimulation (CSS) process.

Many countries in the world have large deposits of oil sands, including the United States, Russia, and various countries in the Middle East. Oil sands may represent as much as two-thirds of the world's total petroleum resource, with at least 1.7 trillion barrels in the Canadian Athabasca Oil Sands, for example. At the present time, only Canada has a large-scale commercial oil sands industry, though a small amount of oil from oil sands is also produced in Venezuela. Because of increasing oil sands production, Canada has become the largest single supplier of oil and products to the United States. Oil sands now are the source of almost half of Canada's oil production, although due to the 2008 economic downturn work on new projects has been deferred, while Venezuelan production has been declining in recent years. Oil is not yet produced from oil sands on a significant level in other countries.

According to the Alberta Research Council, a typical Athabasca oil sand may contain 10 to 13 percent bitumen by weight, 3.5 to 8% percent water by weight, with remainder sand and clay. The electrical conductivity at 1 MHz may be 50 to 80 millimhos per meter, and the relative dielectric permittivity may be 9 to 20 (i.e. dimensionless). The connate water and its associated electrical conductivity makes oil sand an excellent electromagnetic heating susceptor, meaning it can heated with electric and magnetic fields at radio and microwave frequencies. U.S. Published Patent Application No. 2010/0078163 to Banerjee et al. discloses a hydrocarbon recovery process whereby three wells are provided, namely an uppermost well used to inject water, a middle well used to introduce microwaves into the reservoir, and a lowermost well for production. A microwave generator generates microwaves which are directed into a zone above the middle well through a series of waveguides. The frequency of the microwaves is at a frequency substantially equivalent to the resonant frequency of the water so that the water is heated.

Along these lines, U.S. Published Patent Application No. 2010/0294489 to Dreher, Jr. et al. discloses using microwaves to provide heating. An activator is injected below the surface and is heated by the microwaves, and the activator then heats the heavy oil in the production well. U.S. Published Patent Application No. 2010/0294488 to Wheeler et al. discloses a similar approach.

U.S. Pat. No. 7,441,597 to Kasevich discloses using a radio frequency generator to apply RF energy to a horizontal portion of an RF well positioned above a horizontal portion of an oil/gas producing well. The viscosity of the oil is reduced as a result of the RF energy, which causes the oil to drain due to gravity. The oil is recovered through the oil/gas producing well.

Unfortunately, long production times, for example, due to a failed start-up, to extract oil using SAGD may lead to significant heat loss to the adjacent soil, excessive consumption of steam, and a high cost for recovery. Significant water resources are also typically used to recover oil using SAGD, which impacts the environment. Limited water resources may also limit oil recovery. SAGD is also not an available process in permafrost regions, for example. Slow, conducted heating may be necessary initially to soften the formation in order to permit the convective flow of steam heat.

Moreover, despite the existence of systems that utilize RF energy to provide heating, such systems may suffer from inefficiencies as a result of impedance mismatches between the RF source, transmission line, and/or antenna. These mismatches become particularly acute with increased heating of the subterranean formation. Moreover, such applications may require high power levels that result in relatively high transmission line temperatures that may result in transmission failures. High common mode currents may also be generated on an outer conductor of a coaxial transmission line that is unbalanced and that feeds a balanced antenna, such as a dipole, for example. For example, common mode currents may lead to unwanted heating in the overburden or at the surface.

SUMMARY OF THE INVENTION

In view of the foregoing background, it is therefore an object of the present invention to provide a RF heating apparatus that is efficient and robust.

This and other objects, features, and advantages in accordance with the present invention are provided by an apparatus for heating a hydrocarbon resource in a subterranean formation having a wellbore extending therein. The apparatus comprises an RF source, and an RF antenna assembly configured to be positioned within the wellbore and coupled to the RF source. The RF antenna assembly comprises a first tubular dipole element having opposing proximal and distal ends, an RF transmission line extending through the proximal end of the first tubular dipole element and comprising an inner conductor, an outer conductor, and a dielectric therebetween. The inner conductor extends outwardly beyond the distal end of the first tubular dipole element. The outer conductor is coupled to the distal end of the first tubular dipole element. The RF antenna assembly includes a second tubular dipole element having opposing proximal and distal ends, with the proximal end being adjacent the distal end of the first tubular dipole element and being coupled to the inner conductor, and a tubular balun having the RF transmission line extending therethrough and opposing proximal and distal ends, with the distal end being adjacent the proximal end of the first tubular dipole element and the proximal end being coupled to the outer conductor. Advantageously, the apparatus may efficiently heat the hydrocarbon resources in the subterranean formation.

In some embodiments, the RF antenna assembly may comprise a tubular isolator having the RF transmission line extending therethrough and configured to couple together the tubular balun and the first tubular dipole antenna element. For example, the tubular isolator may comprise a cyanate ester composite material.

Additionally, the RF antenna assembly may further comprise a feed structure comprising a dielectric tube between the first and second tubular dipole antenna elements, a first connector coupling the outer conductor to the first tubular dipole element, and a second connector coupling the inner conductor to the second tubular dipole element. Another aspect is directed to a method for making an RF antenna assembly for heating a hydrocarbon resource in a subterranean formation having a wellbore extending therein. The method comprises providing a first tubular dipole element having opposing proximal and distal ends, and positioning an RF transmission line to extend through the proximal end of the first tubular dipole element. The RF transmission line comprises an inner conductor, an outer conductor, and a dielectric therebetween. The inner conductor extends outwardly beyond the distal end of the first tubular dipole element, the outer conductor to be coupled to the distal end of the first tubular dipole element. The method includes providing a second tubular dipole element having opposing proximal and distal ends, with the proximal end being adjacent the distal end of the first tubular dipole element and coupled to the inner conductor, and positioning a tubular balun to have the RF transmission line extending therethrough, the tubular balun having opposing proximal and distal ends, with the distal end being adjacent the proximal end of the first tubular dipole element and the proximal end to be coupled to the outer conductor.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic diagram of an apparatus, according to the present invention.

FIG. **2** is a schematic diagram of a portion of the RF antenna assembly from the apparatus of FIG. **1**.

FIG. **3** is a cross-section view of a portion of one embodiment of the feed structure from the apparatus of FIG. **1** along line **3-3**.

FIG. **4** is a diagram showing the measured heating performance of an example embodiment of the apparatus from FIG. **1**, in sandy soil.

FIG. **5** is a Smith diagram illustrating the measured load impedance of an example embodiment of the apparatus from FIG. **1**.

FIG. **6** is a diagram showing the measured RF power applied to an example embodiment of the apparatus of FIG. **1**.

FIG. **7** is a diagram showing the realized subterranean temperatures produced by an example embodiment of the apparatus of FIG. **1** while heating oil sand.

FIG. **8** is a diagram showing a double tuning method for the apparatus of FIG. **1**.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention will now be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout.

Referring initially to FIGS. **1-2**, an apparatus **10** according to the present invention is now described. The apparatus **10** is for heating a hydrocarbon resource in a subterranean formation **17** having wellbores extending therein. The apparatus includes an injector well **11**, and a producer well **12** extending into respective wellbores in the subterranean formation **17**. The apparatus **10** comprises an RF source **13** coupled to the injector well **11**, and the injector comprises an RF antenna assembly **24** to be positioned within the wellbore.

The RF antenna assembly **24** comprises a first tubular (sleeve) dipole element **81**a having opposing proximal **21** and distal **22** ends. As used herein, distal means deeper into the wellbore while proximal means towards the surface. The RF antenna assembly **24** comprises an RF transmission line **82**, such as a shielded RF transmission line or a coaxial RF transmission line, extending through the proximal end **21** of the first tubular dipole element **81**a and comprising an inner conductor **72**, an outer conductor **71**, and a dielectric **73** therebetween. The inner conductor **72** extends outwardly beyond the distal end **22** of the first tubular dipole element **81**a. The outer conductor **71** is coupled to the distal end **22** of the first tubular dipole element **81**a, illustratively shown as a closed end connection, i.e., this end of the tube is capped. The RF antenna assembly **24** includes a second tubular (sleeve) dipole element **81**b having opposing proximal **27** and distal **28** ends. The proximal end **27** of the second tubular dipole element **81**b is adjacent the distal end **22** of the first tubular dipole element **81**a and is coupled to the inner conductor **72**. The RF antenna assembly **24** includes a tubular (sleeve) balun **15** having the RF transmission line **82** extending therethrough and opposing proximal **25** and distal **26** ends. The distal end **26** of the tubular balun **15** is adjacent the proximal end **21** of the first tubular dipole element **81**a, and the proximal end **25** of the tubular balun **15** is coupled to the outer conductor **71**, illustratively shown as a closed end connection.

In the illustrated embodiment, the RF antenna assembly **24** comprises a tubular isolator **31** having the RF transmission line **82** extending therethrough and configured to couple together the tubular balun **15** and the first tubular dipole antenna element **81**a. The tubular isolator **31** provides an electrical discontinuity in the RF antenna assembly **24**, at which RF electrical currents are supplied to the first and second tubular (sleeve) dipole elements **81**a, **81**b. For example, the tubular isolator **31** may comprise a cyanate ester composite material (e.g. quartz enhanced), polyimide, or to another suitable dielectric composite that has mechanical strength for structural integrity, and absorbs minimal amounts of radiated energy.

Advantageously, the tubular balun **15** is tuned to prevent RF energy from penetrating uphole to the overburden and to concentrate heating downhole towards the hydrocarbon resources. As the subterranean formation **17** heats, its electrical properties may change. So, the dipole tuning may drift away from balun tuning. The overburden may not heat, so the balun **15** tuning may not drift all. Separate tubular balun **15** and first tubular dipole antenna element **81**a allow independent tuning to manage this tuning drift, i.e. there is a split of the tuning of the tubular balun and the antenna to deal with the different behavior of the overburden and the hydrocarbon resources. In short, the region between the first tubular dipole antenna element **81**a and the tubular balun **15** is not heated.

So a method of the invention is the split tuning of the balun and the antenna to deal with the different behavior of the overburden. In the split tuning method: 1) the resonance of the first and second tubular dipole elements **81**a, **81**b is allowed to drift with heating; 2) RF source **13** frequency is varied to track the drilling resonant frequency of the first and second tubular dipole elements **81**a, **81**b; and 3) tubular balun **15** resonant frequency is adjusted by a tubular balun **15** tuning system, such as that described in co-pending patent application titled: "SYSTEM INCLUDING TUNABLE CHOKE FOR HYDROCARBON RESOURCE HEATING AND ASSOCIATED METHODS," U.S. patent application Ser. No. 13/657,172 filed Oct. 22, 2012, the contents of which are hereby incorporated by reference in their entirety.

Additionally, the apparatus **10** comprises a tubular ferrite choke **16** surrounding the RF transmission line **82** and spaced apart from the proximal end **25** of the tubular balun **15**. The first and second tubular dipole elements **81**a-**81**b have a desired operating frequency, and each of the first tubular dipole element, the second tubular dipole element, and the tubular balun **15** may have a length corresponding to +/−10% of a quarter of a wavelength of the desired operating frequency, i.e. the first and second tubular dipole elements form a half-wave dipole antenna, as illustratively noted in FIG. **2**. Moreover, as also illustrated in FIG. **2**, the current flows in the RF antenna assembly **24** are shown with arrows. Advantageously, the current from the outer conductor **71** does not penetrate the tubular balun **15**.

In FIG. **2**, the arrows I denote the flows of RF current at an instant in time, at a preferred electrical size, where the first tubular dipole element **81**a is one quarter wavelength ($\lambda/4$) in length and the second tubular dipole element **81**b is also one quarter wavelength ($\lambda/4$) in length. The tubular dipole elements **81**a-**81**b carry a sinusoidal electric current that converges and diverges from tubular isolator **31**. The internal surfaces of the tubular balun **15** and the first tubular dipole element **81**a both comprise coaxial stubs, which carry internal currents that do not provide subterranean formation **17** heating, but are otherwise useful to provide common mode current suppression and underground tuning components. The present embodiments are not so limited however as to only be operated at ¼ wavelength electrical dimensions for the first and second tubular dipole elements **81**a, **81**b.

Referring now additionally to FIG. **3**, the RF antenna assembly **24** further comprises a feed structure **50** coupling together the first and second tubular dipole antenna elements **81**a-**81**b and electrically coupling the RF transmission line **82** and the first and second tubular dipole antenna elements. The feed structure **50** includes a dielectric tube **61** between the first and second tubular dipole antenna elements **81**a-**81**b, a first connector **60**a coupling the outer conductor **71** to the first tubular dipole element, and a second connector **60**b coupling the inner conductor **72** to the second tubular dipole element. For example, the dielectric tube **61** may comprise a cyanate ester composite material (e.g. quartz enhanced) or another suitable dielectric composite that has mechanical strength for structural integrity, and absorbs minimal amounts of radiated energy.

In the illustrated embodiment, the first and second connectors **60**a-**60**b include a plurality of tool-receiving recesses **65**a-**65**b on an outer surface thereof. The tool-receiving recesses **65**a-**65**b are illustratively circular in shape, but in other embodiments, may comprise other shapes, such as a hexagonal shape. The tool-receiving recesses **65**a-**65**b are provided to aid in using torque wrenches in assembling the antenna assembly **24**. The RF transmission line **82** is affixed to the first connector **60**a with a plurality of bolts **53**a-**53**b. Of course, other fasteners may be used.

In the illustrated embodiment, the inner conductor **72** comprises a tube defining a first fluid passageway **85** therein. The outer conductor **71** is illustratively spaced from the inner conductor **72** to define a second fluid passageway **73**. The passageways **85**, **73** permit the flow of selective gases and fluids that aid in the hydrocarbon recovery process.

The feed structure **50** includes an intermediate conductor **62** extending within the dielectric tube **61** and coupling the inner conductor **72** to the second connector **60**b. For example, the intermediate conductor **62** illustratively comprises a conductive tube of a material comprising, e.g., copper, aluminium. Moreover, the RF transmission line **82** includes an inner conductor coupler **67** for coupling the inner conductor **72** to the intermediate conductor **62**, and first and second dielectric spacers **74**-**75**, each comprising a bore therein for receiving the inner conductor coupler. Additionally, the first and second tubular dipole elements **81**a-**81**b each comprises a threaded end **63**a-**63**b, and the first and second connectors **60**a-**60**b each comprises a threaded end **86**a-**86**b engaging a respective threaded end of the first and second tubular dipole elements for defining overlapping mechanical threaded joints **64**a-**64**b. The threaded ends **63**a-**63**b of the first and second tubular dipole elements **81**a-**81**b each comprises a mating face adjacent the first and second connectors **60**a-**60**b. The mating face includes a threading relief recess to provide good contact at the outer extreme of the first and second connectors **60**a-**60**b. The overlapping mechanical threaded joints **64**a-**64**b provide for a hydraulic seal that seals in fluid and gases within the antenna assembly **24**.

Each of the first and second connectors **60**a-**60**b comprises a recess **66**a-**66**b for receiving adjacent portions of the dielectric tube **61**. In the illustrated embodiment, each recess comprises a circular slot that is circumferential with regards to the first and second connectors **60**a-**60**b. Moreover, all edges in the illustrated embodiment are rounded, which helps to reduce arching in high voltage applications.

Another aspect is directed to a method for making an RF antenna assembly **24** for heating a hydrocarbon resource in a subterranean formation **17** having a wellbore extending therein. The method comprises providing a first tubular dipole element **81**a having opposing proximal and distal ends **21**, **22**, and positioning an RF transmission line **82** to extend through the proximal end of the first tubular dipole element. The RF transmission line **82** comprises an inner conductor **72**, an outer conductor **71**, and a dielectric **73** therebetween. The inner conductor **72** extends outwardly beyond the distal end **22** of the first tubular dipole element **81**a, the outer conductor **71** to be coupled to the distal end **22** of the first tubular dipole element. The method includes providing a second tubular dipole element **81**b having opposing proximal and distal ends **27**-**28**, with the proximal end being adjacent the distal end **22** of the first tubular dipole element **81**a and to be coupled to the inner conductor **72**, and positioning a tubular balun **15** to have the RF transmission line **82** extending therethrough, the tubular balun having opposing proximal and distal ends **25**-**26**, with the distal end being adjacent the proximal end **21** of the first tubular dipole element and the proximal end to be coupled to the outer conductor.

A theory of operation for the apparatus **10** will now be provided. The first and second tubular dipole elements **81**a, **81**b form the half elements of a dipole antenna that is linear, e.g. line shaped for the divergence of electric current. An inset feed is provided by concentrically locating the RF transmission line **82** inside the first tubular dipole element **81**a, advantageously allowing the RF well heater to be configured in a single hole. Electrical charge is separated across the driving discontinuity of the tubular isolator **31**, which in turns causes a current flow along the first and second tubular dipole elements **81**a, **81**b. Initially, if uninsulated from the subterranean formation **17**, the first and second tubular dipole elements **81**a, **81**b act as electrodes to supply electrical currents to the subterranean formation, which may then be the predominant mode of heating. The initial extension of the RF electric currents axially along the first and second tubular dipole elements **81**a, **81**b may be proportional to the RF skin depth or slightly more than the RF skin depth. The RF skin effect therefore initially concentrates the resistive, Joule effect heating to the vicinity of the tubular isolator **31**. The connate water in the subterranean formation **17** quickly turns to steam, so a steam saturation zone or “steam bubble” forms there. In this steam saturation zone, there may be rock, sand, hydrocarbons and vapor phase water, but no liquid water. The steam bubble may be elongated as it grows from the center outwards following along the first and second tubular dipole elements **81**a, **81**b. In particular, at the steam bubble boundary along the first and second tubular dipole elements **81**a, **81**b, where the liquid water still touches the first and second tubular dipole elements, there are hotspots of heat. Thus, two moving hotspots of heat travel from tubular isolator **31** outwards, the first traveling along the first tubular dipole element **81**a, and the second hotspot traveling along the second tubular dipole element **81**b. Eventually, the moving hotspots reach the ends of the first and second tubular dipole elements **81**a, **81**b, resulting in the first and second tubular dipole elements **81**a, **81**b becoming electrically insulated from the subterranean formation **17** in a steam saturation zone. Steam is an electrical insulator whereas liquid water is an electrical conductor. When insulated from the subterranean formation **17**, the energies delivered to the subterranean formation by the RF antenna assembly **24** automatically shift from conducted electric currents to radiation of electric and magnetic fields. Thus the heating provided by the present embodiments is reliable.

Continuing the theory of operation, the electric fields transduced from the insulated first and second tubular dipole elements **81**a, **81**b capacitively couple the currents from those elements through the steam bubble and into the liquid water regions beyond. In other words, first and second tubular dipole elements **81**a, **81**b are in a sense akin to capacitor plates. When the electric fields reach the connate liquid water, they cause electrons to flow there, and this induced current flow heats the water resistively by Joule effect. Thus, capacitive coupling by transduced and radiated electric fields provides a means of electrical resistance heating in the subterranean formation **17** without the need for electrode like conductive contact. This may be advantageous as electrode contact in hydrocarbon formations may be unreliable.

The diverging and oscillating flow of RF electric currents along the first and second tubular dipole elements **81**a, **81**b also transduce and radiate magnetic fields into the subterranean formation **17**. As the magnetic fields expand through the connate water regions of the subterranean formation **17**, they initiate the flow of Eddy electric currents that heat the subterranean formation **17** by the Joule effect. Thus, magnetic field heating occurs by a compound, inductive process of starting with RF current flow on the first and second tubular dipole elements **81**a, **81**b, followed by magnetic field expansion according to Ampere’s Law, followed by Eddy current flow according to Lent’s Law, and finally formation heating by Joule effect. In a simple sense, induction heating is akin to the RF antenna **24** being a current transformer primary winding and the Eddy currents in the subterranean formation **17** being current transformer secondary windings, although these “windings” do not exist in a traditional sense. It may be typical that a wire coil is necessary to cause magnetic induction heating, but a linear, line shaped electric conductor also provides a useful, curling magnetic field for RF heating. The linear, line-shaped dimensions of the present embodiments are more practical to install in the earth than a large diameter coil.

Continuing the theory of operation, if the first tubular dipole element **81**a is one quarter wavelength (λ/4) in length, and the second tubular dipole element **81**b is also one quarter wavelength (λ/4) in length, magnetic field induction heating may be more prevalent near the center of the RF antenna assembly **24**, and electric field induction heating more prevalent near the ends of the first and second tubular dipole elements **81**a, **82**a. This is because the current and voltage distribution may be sinusoidal with current maxima at the center of the dipole and voltage maxima at the ends of the dipole. The electric and the magnetic fields provided by the RF antenna assembly **24** work together to provide a continuous heated area which may be an oblate spheroid or football shape. At close ranges to the dipole, less than about $\lambda_{media}/2\pi$, the nature of the magnetic and electric fields may be those of reactive near fields, and at extended ranges from the dipole, radii greater that about $\lambda_{media}/2\pi$, the transduced electric and magnetic fields may be those of a radio waves. Advantageously, both reactive near fields and the radio waves provide heating and the radio waves allow the heating to continue to virtually unlimited ranges. RF heating may not rise like steam convection heating, so with RF heating caprock may not be required over the payzone.

Furthermore, realized temperatures underground are a function of the applied RF power in kilowatts (KW), the heating duration in hours H, the heated mass in kg, and the specific heat of the subterranean formation **17** in Joules per kilogram degree Kelvin (J/kg·K) or KW/kg·K. The penetration or radial thermal gradient surrounding the RF antenna assembly **24** is a function of both subterranean electrical conductivity in mhos/meter and of electromagnetic field expansion. Specifically, where r is the radius radially away from the axis of the RF antenna assembly **24**, a $1/r^2$ RF power gradient must occur away from a insulated RF antenna **24** due to the spherical spreading of the RF fields, plus a dissipative RF power gradient must occur due to the RF heating, which may be between $1/r^3$ to $1/r^5$ depending on subterranean formation **17** electrical conductivity. Thus, the combined radial RF power gradient, spreading loss plus dissipative loss, may be $1/r^5$ to $1/r^7$. A practical example is that the instantaneous half depth of penetration of the electromagnetic heating energies radially away from the apparatus **10** in rich oil sand of 0.005 mhos/meter electrical conductivity may be about 20 inches. This is considerably superior to the initial, instantaneous penetration of convected heating, which is zero or nearly zero. An RF heated zone can grow in size much more quickly than a steam injection heated zone. Convective flow is not needed for RF heating to occur, and RF heating can heat impermeable structures, such as shale strata (and even fracture the shale strata). Indeed, speed is a well known attribute of RF heating in general. The realized temperatures T of the RF heating may be any between the formation temperature prior to the commencement of the heating, to the boiling point of the connate subterranean water at reservoir conditions, which may be 200° C. or more depending on depth and pressure. Thus the realized temperatures with the RF heating regulate themselves so as not to exceed the boiling point of water at reservoir conditions. This advantageously avoids hydrocarbon coking which may reduce subterranean formation permeability. RF heating may also prevent the deposit of varnishes on the well apparatus when live oils are produced, as the oils will not be cooling as they drain.

The present embodiments are not so limited to require forming a steam saturation zone underground, nor do they require that the subterranean temperatures reach the boiling point of water. For instance, the realized temperatures may be reduced by reducing RF power levels. Another way to reduce realized temperatures, and a method of the present disclosure, is to inject critical fluids, such as alkane hydrocarbons into the subterranean formation **17** and allow the RF heating to drive them. Injected alkanes may function to thermally regulate the extraction process at lower temperatures and act as a solvent to thin payzone hydrocarbons. Alkane molecules for injection may preferentially include propane, butane, pentane, and hexane, which may boil below the boiling point of water. With alkane injection, the number of carbons in the alkane molecule may adjust the alkane boiling point, which in turn may adjust the underground temperatures necessary to extract the subterranean formation **17** hydrocarbons. The RF antenna assembly **24** may inject the alkane solvent or a separate injector well may be provided, such as an infill well.

Moreover, although an advantageous mode of subterranean heating has been identified as Joule effect, the present embodiments are not so limited, and the introduced electric fields may also cause dielectric heating. Dielectric heating especially occurs due to the interaction of the electric fields with polar molecules, particularly connate water. The combination of Joule effect and the dielectric heating allow the present embodiments to operate effectively over a broad range of radio frequencies, even near the dielectric heating minima frequency for water, which occurs in the radio spectrum near 30 MHz. Preferred radio frequencies for the present embodiments may therefore be between 40 Hertz and 40 Megahertz. The higher frequencies may supply more load resistance while lower frequencies may supply somewhat greater penetration. It may be advantageous to operate the apparatus **10** at a resonance frequency, fundamental or harmonic, of the dipole that is formed by the first and second tubular dipole elements **81**a, **81**b, as resonant operation may avoid a reactive or high power factor load, for instance. Operation at harmonic resonance frequencies may provide resonant operation with alternative load resistances that may advantageously be higher or lower than the fundamental frequency load resistance.

Continuing the theory of operation, hydrocarbons and water often occur together underground. When they do, RF electric and magnetic fields will heat subterranean water much faster than associated hydrocarbons. In the case of oil sand, the connate pore water in oil sand RF generally heats more than 100 times faster than the bitumen. Thus, the pore water becomes hot first and then it conductively heats the bitumen films on the pores. As the sand grains are many, the water pores small, and the bitumen pore films having substantial area and contact with the pore water, the rise in bitumen temperature closely paces the pore water temperature rise. The bitumen may be melted and mobilized from an expanding thermal front surrounding the apparatus **10** and if the underground boiling temperatures are reached, the steam from the RF heated connate water may provide an additional driving to force to mobilize the warmed and thinned bitumen. Thus apparatus **10** may produce hydrocarbons and connate water together at same time. If alkane solvents are injected, they may also provide a driving force to mobilize bitumen. Of course, hot water or injected steam can be provided as a pressure drive on the hydrocarbons, and gravity drainage may also be incorporated. The speed and penetration of RF heating is much greater than that of steam heating, so RF electromagnetic heating provides increased present value.

Electrical start up methods for the apparatus **10** will now be discussed. The RF antenna assembly **24** may be configured to initially provide conductive electrical contact with the subterranean formation **17** or it may be electrically insulated from the formation initially. Both the bare and insulated approaches will be successful due to the many heating modes mentioned previously. However, an uninsulated RF antenna assembly **24** may initially present a low resistance and high voltage standing wave ratio (VSWR) until the connate water boils off, so an electrical start up my be needed. Various methods of start up are anticipated. One exemplary method of startup, winch has been tested, has been to supply RF power into the low load resistance/high VSWR at reduced RF power until the water boiled off the surfaces. Most RF power sources will manage ill conditioned load impedances at low power, and only low power is needed to boil the water off.

Another start up method is to elevate frequency until an increased load resistance/low VSWR is obtained, as raising the frequency increases the load resistance when there is liquid water contact. Another startup method is to initially apply direct current (DC) to the RF antenna assembly **24** to boil the connate water off the antenna surfaces, as VSWR losses do not occur at DC. Of course, the various methods to insulate the RF antenna assembly **24** also exist, such as filling the hole with a nonconductive material, eliminating the need for an electrical startup all together.

The tubular balun **15** may be provided to control or prevent common mode currents. Here, a common mode current is defined as an electrical current flowing on the outside of the RF transmission line **82**. This may occur as the outer conductor **71** can support separate electrical current flows on its inside and outside surfaces due to RF skin effect. Without the tubular balun **15** then, stray capacitance between the uphole end of the first tubular dipole antenna elements **81**a and the outer conductor **71** may convey the RF heating currents uphole, through overburden, and even to the surface. This would be unwanted as heating in overburden may be uneconomic. RF heating at the surface may melt permafrost or even cause a personnel safety hazard. The tubular balun **15** prevents these unwanted conditions by providing a high electrical resistance across its open end at radio frequencies. The high electrical resistance across the open mouth of the tubular balun **15** occurs due to the short circuit at the closed end of the tubular balun **15** being referred to as an open circuit by the ¼ wavelength (or a odd harmonic of ¼ wavelength) length of the tubular balun. The short circuit end is referred as an open circuit (or nearly so) at the open end due the cosine distribution of current and sine distribution of voltage along the inside the tubular balun **15**. A preferred length of the tubular balun **15** is given by:

$$L=0.25n\lambda/\sqrt{\mu_r \in_r};$$

where:

L=the physical length of the tubular balun **15**, in meters;

n=odd integers, e.g. 1, 3, 5 . . . ;

λ=wavelength in meters=speed of light in meters per second/radio frequency in Hertz;

λ_r=relative magnetic permeability of fill inside tubular balun **15**, if any; and

$\in_r$=relative dielectric permittivity of fill inside tubular balun **15**, if any.

Referring now additionally to FIG. **4**, diagram **90** illustrates the measured heating performance of an example embodiment of the apparatus **10** in a hill of sandy, moist soil which corresponded to a subterranean formation **17**. The sandy soil did not contain hydrocarbons but the electrical and thermal characteristics of the sandy soil were similar to those of rich oil sand, and in specific, the sandy soil had an electrical conductivity of between σ=0.003 mhos/meter and 0.0005 mhos/meter. The moist sand test was instrumented with temperature and pressure sensors at different distances from the RF antenna assembly **24**. In particular, the diagram **90** illustrates performance at a time point of 44 hours during a 5 day RF heating staging test.

Curve **91** shows the realized temperature profile immediately aside the RF antenna assembly **24** as a function of axial position along the RF antenna assembly. In the diagram **90**, the RF antenna assembly **24** exited the sand hill at an axial position of 0 meters, and the downhole end of the RF antenna assembly **24** was at 35 meters. Curves **92**-**93** show the temperature profiles at 1 meter and 2.5 meters radial distance away film the RF antenna assembly **24**. During the staging test, the example embodiment of the apparatus **10** radiated 86 kilowatts (KW) of power with a voltage standing wave ratio of 3.06:1. Temperature peaks **94**, **95** were caused by electric fields at the ends of the first and second tubular dipole antenna elements **81**a-**81**b, which capacitively coupled electric currents into the moist sand nearby. Temperature peak **96** corresponded to the location of the tubular isolator **31** as locally increased electric field strengths also existed there. Heating at local minimas **97**, **98** was mostly due to magnetic near fields from the first and second tubular dipole antenna elements **81**a-**81**b causing induced eddy currents in the subterranean formation **17**. Likewise, the longer range heating at the 1 and 2.5 meter radii were also caused by magnetic fields from first and second tubular dipole antenna elements **81**a-**81**b.

In general, magnetic field beating predominated at greater radial distances. Note that unwanted uphole RF heating was effectively prevented by the tubular balun **15**, so the RF heating was concentrated around the first and second tubular dipole antenna elements **81**a, **81**b, located between 5 and 18 meters position. Temperature rise near the surface, between about 0 and 5 meters axial position, was due to the sun and warm rain, which occurred during the test. At the time the test was terminated, the RF heated zone was continuing to grow in size and the heating could have been extended. After the RF heating test, a hole was dug into the top of the sand pile and steam rose there. An infrared/thermal camera clearly showed the heating region of the sand pile from a distance. An RF heated zone of virtually any required size may be created by the RF antenna assembly **24**.

The apparatus **10** was later deployed in an undisturbed bench of rich of oil sand, which contained bitumen. The intent of the oil sand test was to demonstrate RF heating only, so a producer well and injected solvents were not provided. However, the borehole was much larger in diameter than the apparatus **10** and, after RF heating, the free space filled with oil and leakage had to be contained. The driving force to mobilize the produced oil was created by the RF fields, as no steam was injected. The heating due to the electromagnetic fields mobilized the oil radially inwards. Table 1 below describes the measured results of the oil sand heating test with the apparatus **10**.

TABLE 1

Oil Sand Test Results

Parameter	Value
Subterranean formation 17	Undisturbed bench of rich oil sand/bitumen ore.
Ore electrical conductivity	0.002 to 0.01 mhos/meter
RF antenna assembly 24 orientation	Horizontal
RF antenna assembly 24 electrical type	Double tuned half wave dipole
Borehole diameter	0.50 meters
First and second tubular dipole element diameter 81a, 81b	0.15 meters
First and second tubular dipole element length 81a, 81b	10.6 meters each
First and second tubular dipole element length 81a, 81b material	Aluminum
Tubular balun 15 length	10.6 meters
Tubular balun 15 diameter	0.15 meters

TABLE 1-continued

Oil Sand Test Results

Parameter	Value
Tubular balun 15 diameter material	Aluminum
Dielectric conduit diameter	0.33 meters
Outer casing	The apparatus 10 was located inside a nonconductive dielectric conduit
Outer casing material	Isocyanurate polymer with spun glass fibers
RF transmission line 82	Coaxial, formed of concentric tubing
RF transmission line 82 characteristic impedance	50 Ω
RF transmission line 82 cooling and inerting	Recirculated dry nitrogen
Radio frequency	6.78 MHz, held constant throughout the test
Electromagnetic heating mode	Induction of electric currents by application of electric and magnetic fields
Primary heating mechanism	Joule effect in connate water
Secondary heating mechanism	Dielectric heating in connate water
Solvent injection	None
Radiated RF power	0 to 50 kilowatts, varied throughout the test, see FIG. 6
Applied RF waveform	Sinusoid (no modulation or pulses)
RF source 13	Modified shortwave broadcast transmitter
RF source 13 active devices	Tetrode vacuum tube, Eimac 4CV100,000C
Duration of RF heating	35 days
Initial temperature of oil sand	4 to 10 degrees Celsius
Ending temperature of oil sand	120 degrees Celsius near the RF antenna assembly 24, plus radial thermal gradient beyond
Producer well	Not provided
Produced oil quantity	600-1000 gallons, estimated

Of course, more oil could have been produced if producer well were provided, solvents injected, steam introduced, etc.

Continuing the description of the oil sand test of the apparatus **10**, a nonconductive conduit was used to house the RF antenna assembly **24**. The nonconductive dielectric conduit was provided at the oil sand test to easily slide the RF antenna assembly **24** in and out d the earth, especially after heating had occurred. Thus, no electric currents were applied to the hydrocarbon ore by electrode contact. A nonconductive conduit is not required for the operation of the RF antenna assembly **24**.

Furthermore, referring now additionally to FIGS. **5-6**, diagram **120** shows the measured electrical impedance of the RF antenna assembly **24** as the RF heating progressed. The diagram **120** is in a polar format known as a Smith Chart©, and it shows the measured electrical load that the RF antenna assembly **24** presented to the RF source **13** at the RF power source **13**, thus the phase delay of the RF transmission line **82** is included in the measured impedance trace **122**. The data points that make up trace **122** represent different points in time, radio frequency was held constant throughout the test. Point **124** was the initial impedance prior to the start of the RF heating, and it measured to be Z=59+32j ohms or the equivalent of 59 ohms of resistance in series with 32 ohms of inductive reactance. Point **126** is the impedance at the conclusion of the RF heating on day 32, and it was measured to be Z=29−4j ohms or the equivalent of 29 ohms of resistance in series with 4 ohms of capacitive reactance. Circle **128** encloses the region of the Smith Chart having a 2 to 1 VSWR or less.

Thus, the RF antenna assembly **24** advantageously maintained a VSWR of 2 to 1 or less throughout the RF heating, providing a useful load for the RF source **13** whose impedance mismatch loss was 4 percent or less. The RF antenna **24** is a highly efficient RF heating applicator. More than 95 percent of the RF power shown in FIG. **6** was delivered into the oil sand. The RF antenna assembly **24** impedance was measured by momentarily turning off the RF power source **13** and connecting the vector network analyzer to the RF antenna **24**.

Continuing the oil sand test description, FIG. **6** graph **130** and trace **132** depicts the RF power level that was applied to the RF antenna assembly **24** over time. It became necessary to reduce the RF power level to reduce the amount of oil being produced. At the 50 kilowatt power level, the applied power metric was 2.4 kilowatts/meter of well length.

Referring now additionally to FIG. **7**, diagram **140** illustrates the measured realized subterranean temperatures at the completion of the oil sand test of the example embodiment of the apparatus **10**. Curve **142** shows the realized temperature profile immediately aside the RF antenna assembly **24**, curve **144** is for the realized temperature at 1.5 meters radial distance away from the axis of the RF antenna assembly **24**, curve **146** is for 1.75 meters radial distance, and curve **148** is for 3.5 meters radial distance. 0 meters in the X axis corresponds to antenna feed structure **50**, e.g., the center of the dipole.

Continuing the oil sand test description, the nature of the RF produced hydrocarbon was atypical of the bitumen produced in the oil sand by other process, such as the Clark hot water process or SAGD process. Specifically, RF heating produced a paraffinic oil of considerably reduced viscosity. As will be appreciated, higher paraffin content hydrocarbon resources may be considered already upgraded or at or near pipeline grade as they are thinned with respect to hydrocarbon resources with a higher asphalt content, for example. Paraffinic hydrocarbon resources are relatively shiny and transparent or partially so, i.e., a wax. In contrast, bitumen typically produced via strip mining and a hot water bath is jet black and almost solid at −12° C., for example. Higher paraffin content hydrocarbon resources may further be used for refining higher octane gasoline, for example. Thus, increased paraffin content may be valued higher than other types of hydrocarbon resources.

Table 2 compares measured properties of RF produced oil with those of typical of Clark hot water process bitumen.

TABLE 2

Comparison Of RF Produced Oil With Clark Process Bitumen

Method	Mining Process, Typical	RF Process, Measured
Hydrocarbon Ore Production Technique	Rich Oil Sand Mining, followed by Clark Hot Water bath separation	Rich Oil Sand RF stimulated well
Produced Oil Base	Asphalt	Paraffin
API Gravity (hydrocarbon relative density)	~8	~14

TABLE 2-continued

Comparison Of RF Produced Oil With Clark Process Bitumen

Method	Mining Process, Typical	RF Process, Measured
Viscosity in Centipoids, 20° C.	200,000	39,100
Saturates	17%	20%
Aromatics	39%	42%

After the 35 days of RF heating, and a cool down period that followed, a paddle was dipped into the RF produced oil, which had nearly filled the oversized hole containing the antenna assembly **24**. As the oil test was conducted during cold surface conditions, the temperature of the produced oil had by the time of sampling cooled to −12 degrees Celsius. In spite of the low −12 Celsius oil measured temperature, the RF produced oil slowly ran off the paddle. As can be appreciated, the RF produced oil was thinned and may have been near pipeline grade viscosity. Several days had elapsed before the oil sample was analyzed. RF produced oil may thicken over time, so the RF produced oil may have had an even lower viscosity immediately upon completion of the RF heating. Electric and magnetic fields of RF heating cause temporary aggregation of asphaltene or paraffin particles into larger ones, which in turn temporarily modifies the rheological properties of the RF produced oil. The aggregation based thinning may last for a time of hours, and it is repeatable. Realized thinning times were sufficient for extraction during the RF heating. After the test, oil sand surrounding the antenna was lighter in color than unheated oil sand nearby.

In oil sand, RF heating with the apparatus **10** produces oil with 3 to 5 times more C**12** to C**28** range molecules than bitumen produced by the Clark Hot Water Process. The lower molecular mass hydrocarbons produced by the apparatus **10** are produced at bulk temperatures of less than about 130° C.: RF electric fields can cause hydrocarbon cracking, and RF electromagnetic fields (electric and magnetic) are known to cause selective heating of one molecule type over another. Advantageously, the C**12** to C**28** molecules may be in the valuable diesel and lubricating oil range.

Referring to FIG. **8**, graph **170**, an additional method of tuning the balun and dipole comprising the RF antenna assembly **24** will now be described, known here as a method of double tuning. The double tuning method may advantageously allow for holding the operating frequency of the RF source **13** constant throughout the RF heating, as the double tuning method provides for increased VSWR bandwidth from the RF antenna assembly **24**. For explanation, trace **171** shows the VSWR response versus frequency of a half wave dipole comprised of the first and second tubular dipole elements **81**a, **81**b if no transmission line or common mode currents were present. This dipole response alone is quadratic or "single dip". In the double tuning method for the RF antenna assembly **24**, the balun **15** is included and the spacing s (see FIG. **2**) between the proximate ends of the first tubular dipole element **81**a and the tubular balun **15** is varied to produce a double tuned VSWR response depicted as trace **172** in the FIG. **8**. The double tuned trace **172** response may comprise a 4th order Chebyschev polynomial response in some embodiments. A closer spacing s results in a spreading apart of the VSWR minima **174**, **176** and an increase in the VSWR bandwidth of the RF antenna assembly **24**. A wider spacing s results in a closer spacing of the VSWR minima **174**, **176** and a smaller VSWR bandwidth. The double tuning may provide a RF antenna assembly **24** VSWR bandwidth that is about 2 to 4 times that of the half wave dipole by itself. VSWR ripple amplitude **173** will vary with spacing s and is traded for with the VSWR bandwidth required.

The double tuning in the RF antenna assembly **24** may result from the controlled coupling of two coaxial resonators that exist in situ: 1) the inside surfaces of the first tubular dipole element **81**a, and 2) the inside surface of the tubular balun **15**. These two structures have the aspects of resonant coaxial stubs that use the outer conductor **71** as their inner conductor. In other words, the first tubular dipole element **81**a and tubular balun **15** are coaxial transmission lines over coaxial transmission lines. Heating a subterranean formation **17** may initially increase formation electrical conductivity due to increased salt concentration and later decrease conductivity as the liquid water content is further eliminated. Changing water content may change heating applicator/RF antenna assembly **24** electrical impedance and cause the need for tunings.

A method of the present embodiments to increase electrical load resistance is provided by adjusting the ratio of the lengths of the first and second tubular dipole elements **81**a, **81**b. The method may also include adjusting the first and second tubular dipole elements **81**a, **81**b in order to make the dipole antenna resistance equal to the transmission line **82** characteristic impedance. When the RF antenna assembly **24** is insulated from the subterranean formation **17**, making the first and second tubular dipole elements **81**a, **81**b equal in length results in a lower or minimum value of electrical resistance. Making the first and second tubular dipole elements **81**a, **81**b unequal in length results in an increased or higher electrical resistance across the tubular isolator **31**.

In general, the more conductive the subterranean formation **17** is, the lower the electrical resistance provided by the RF antenna assembly **24**, so the more unequal in length the first and second tubular dipole elements **81**a, **81**b may be adjusted. Preferred load resistance values provided by the first and second tubular dipole elements **81**a, **81**b may be between about 30 and 70 ohms due to the characteristic impedances required for coaxial transmission lines of lowest loss, highest voltage withstanding, and or greatest current handling. The resistance versus length ratio of the first and second tubular dipole elements **81**a, **81**b may resemble a tangent function as sine shaped voltage and cosine shaped current relationships may exist. The method for controlling the load resistance may include using subterranean formation **17** electrical conductivity obtained a priori from well induction resistivity logs, prior to the apparatus **10** installation and completion.

Advantageously, the method allows the apparatus **10** and the RF antenna assembly **24** to heat subterranean formations having a wide range of electric conductivities, ranging from about 0.00001 mhos/meter conductivity to 10 mhos/meter and to do so without an underground transformer. As typical, the conductivity of subterranean water can be a function of dissolved carbon dioxide, which forms weak carbonic acid, OH^- radical molecules, and especially any dissolved salts.

Other features relating to apparatuses for RF heating are disclosed in co-pending application "RF ANTENNA ASSEMBLY WITH FEED STRUCTURE HAVING DIELECTRIC TUBE AND RELATED METHODS," U.S. patent application Ser. No. 13/804,415 filed Mar. 14, 2013, which is incorporated herein by reference in its entirety.

Many modifications and other embodiments of the invention will come to the mind of one skilled in the art having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is understood that the invention is not to be limited to the specific embodiments disclosed, and that modifications and embodiments are intended to be included within the scope of the appended claims.

That which is claimed is:

1. An apparatus for heating a hydrocarbon resource in a subterranean formation having a wellbore extending therein, the apparatus comprising:

a radio frequency (RF) source; and

an RF antenna assembly configured to be positioned within the wellbore and coupled to said RF source;

said RF antenna assembly comprising

a first tubular dipole element having opposing proximal and distal ends,

an RF transmission line extending through the proximal end of said first tubular dipole element and comprising an inner conductor, an outer conductor, and a dielectric therebetween, said inner conductor extending outwardly beyond the distal end of said first tubular dipole element, said outer conductor coupled to the distal end of said first tubular dipole element,

a second tubular dipole element having opposing proximal and distal ends, with the proximal end of the second tubular dipole element being adjacent the distal end of said first tubular dipole element and being coupled to said inner conductor, and

a tubular balun having said RF transmission line extending therethrough and opposing proximal and distal ends, with the distal end of the tubular balun being adjacent the proximal end of said first tubular dipole element and the proximal end of *the* tubular balun being coupled to said outer conductor.

2. The apparatus of claim **1** wherein said RF antenna assembly comprises a tubular isolator having said RF transmission line extending therethrough and configured to couple together said tubular balun and said first tubular dipole antenna element.

[3. The apparatus of claim **2** wherein said tubular isolator comprises a cyanate ester composite material.**]**

4. The apparatus of claim **1** wherein said RF antenna assembly further comprises a feed structure comprising:

a dielectric tube between said first and second tubular dipole antenna elements;

a first connector coupling said outer conductor to said first tubular dipole element; and

a second connector coupling said inner conductor to said second tubular dipole element.

[5. The apparatus of claim **4** wherein said first and second tubular dipole elements each comprises a threaded end; and wherein said first and second connectors each comprises a threaded end engaging a respective threaded end of said first and second tubular dipole elements for defining overlapping mechanical threaded joints.**]**

[6. The apparatus of claim **4** wherein said first and second connectors each comprises a recess for receiving adjacent portions of said dielectric tube.**]**

[7. The apparatus of claim **4** wherein said dielectric tube comprises a cyanate ester composite material.**]**

[8. The apparatus of claim **1** wherein said inner conductor comprises a tube defining a first fluid passageway therein; and wherein said outer conductor is spaced from said inner conductor to define a second fluid passageway.**]**

9. The apparatus of claim **1** further comprising a tubular ferrite choke surrounding said RF transmission line and spaced apart from the proximal end of said tubular balun.

10. The apparatus according to claim **1** wherein said first and second tubular dipole elements have a desired operating frequency; and wherein each of said first tubular dipole element, said second tubular dipole element, and said tubular balun has a length corresponding to +/−10% of a quarter of a wavelength of the desired operating frequency.

11. An apparatus for heating a hydrocarbon resource in a subterranean formation having a wellbore extending therein, the apparatus comprising:

a radio frequency (RF) source;

an RF antenna assembly configured to be positioned within the wellbore and coupled to said RF source;

said RF antenna assembly comprising

a first tubular dipole element having opposing proximal and distal ends,

an RF transmission line extending through the proximal end of said first tubular dipole element and comprising an inner conductor, an outer conductor, and a dielectric therebetween, said inner conductor extending outwardly beyond the distal end of said first tubular dipole element, said outer conductor coupled to the distal end of said first tubular dipole element,

a second tubular dipole element having opposing proximal and distal ends, with the proximal end of the second tubular dipole element being adjacent the distal end of said first tubular dipole element and being coupled to said inner conductor,

a tubular balun having said RF transmission line extending therethrough and opposing proximal and distal ends, with the distal end of the tubular balun being adjacent the proximal end of said first tubular dipole element and the proximal end of the tubular balun being coupled to said outer conductor,

a tubular isolator having said RF transmission line extending therethrough and configured to couple together said tubular balun and said first tubular dipole antenna element, and

a feed structure comprising

a dielectric tube between said first and second tubular dipole antenna elements,

a first connector having a first circumferential slot for receiving said dielectric tube, and

a second connector having a second circumferential slot for receiving said dielectric tube; and

a tubular ferrite choke surrounding said RF transmission line and spaced apart from the proximal end of said tubular balun.

[12. The apparatus of claim **11** wherein said tubular isolator comprises a cyanate ester composite material.**]**

[13. The apparatus of claim **11** wherein said first and second tubular dipole elements each comprises a threaded end; and wherein said first and second connectors each comprises a threaded end engaging a respective threaded end of said first and second tubular dipole elements for defining overlapping mechanical threaded joints.**]**

[14. The apparatus of claim **11** wherein said dielectric tube comprises a cyanate ester composite material.**]**

[15. The apparatus of claim **11** wherein said inner conductor comprises a tube defining a first fluid passageway therein; and wherein said outer conductor is spaced from said inner conductor to define a second fluid passageway.**]**

16. A method for making a radio frequency (RF) antenna assembly for heating a hydrocarbon resource in a subterranean formation having a wellbore extending therein, the method comprising:

providing a first tubular dipole element having opposing proximal and distal ends;

positioning an RF transmission line to extend through the proximal end of the first tubular dipole element, the RF transmission line comprising an inner conductor, an outer conductor, and a dielectric therebetween, the inner conductor extending outwardly beyond the distal end of the first tubular dipole element, the outer conductor to be coupled to the distal end of the first tubular dipole element;

providing a second tubular dipole element having opposing proximal and distal ends, with the proximal end of the second tubular dipole element being adjacent the distal end of the first tubular dipole element and coupled to the inner conductor; and

positioning a tubular balun to have the RF transmission line extending therethrough, the tubular balun having opposing proximal and distal ends, with the distal end of the tubular balun being adjacent the proximal end of the first tubular dipole element and the proximal end of the tubular balun to be coupled to the outer conductor.

17. The method of claim **16** further comprising coupling together the tubular balun and the first tubular dipole antenna element with a tubular isolator having the RF transmission line extending therethrough.

18. The method of claim **16** further comprising forming a feed structure by at least:

coupling a dielectric tube between the first and second tubular dipole antenna elements;

coupling the outer conductor to the first tubular dipole element using a first connector; and

coupling the inner conductor to the second tubular dipole element using a second connector.

[19. The method of claim **16** further comprising:

forming the inner conductor to comprise a tube defining a first fluid passageway therein; and

forming the outer conductor to be spaced from the inner conductor to define a second fluid passageway.**]**

20. The method of claim **16** further comprising positioning a tubular ferrite choke to surround the RF transmission line and to be spaced apart from the proximal end of the tubular balun.

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