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(54) **MICROWAVE ABLATION ANTENNA SYSTEM WITH REFLECTOR AND SLOT**

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(71) Applicant: **Wisconsin Alumni Research Foundation, Madison, WI (US)**

(72) Inventors: **Nader Behdad, Oregon, WI (US); Susan C. Hagness, Madison, WI (US); Yahya Mohtashami, Madison, WI (US)**

(73) Assignee: **Wisconsin Alumni Research Foundation, Madison, WI (US)**

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CPC **A61B 18/1815; A61B 2018/00577; A61B 2018/00785; A61B 2018/1853**
See application file for complete search history.

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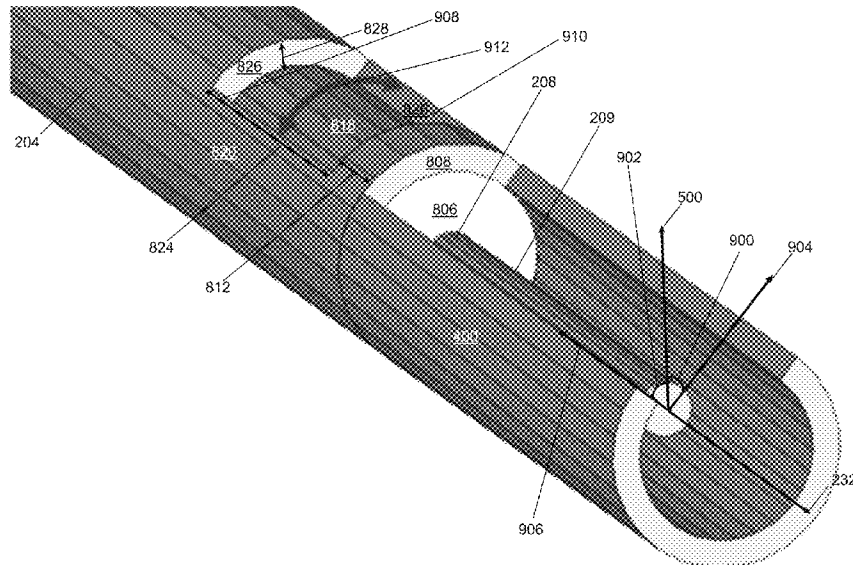
Primary Examiner — Daniel W Fowler

(74) *Attorney, Agent, or Firm* — Bell & Manning, LLC

(57) **ABSTRACT**

An antenna system is provided that includes a coaxial cable, an antenna, a reflector wall, and a slot wall. The reflector wall is formed of a conductive material connected to a conductive shield to extend in an axial direction, is separated from an antenna conductor by a second dielectric material in a radial direction relative to the antenna conductor, and partially surrounds the antenna conductor in the radial direction from a first angle to a second angle when projected into a radial plane. The slot wall is formed through a portion of the conductive shield to expose a dielectric material from a third angle to a fourth angle when projected into the radial plane, is formed on a first side relative to a base. The first angle, the second angle, the third angle, and the fourth angle are defined relative to a common axis parallel to the radial plane.

20 Claims, 18 Drawing Sheets



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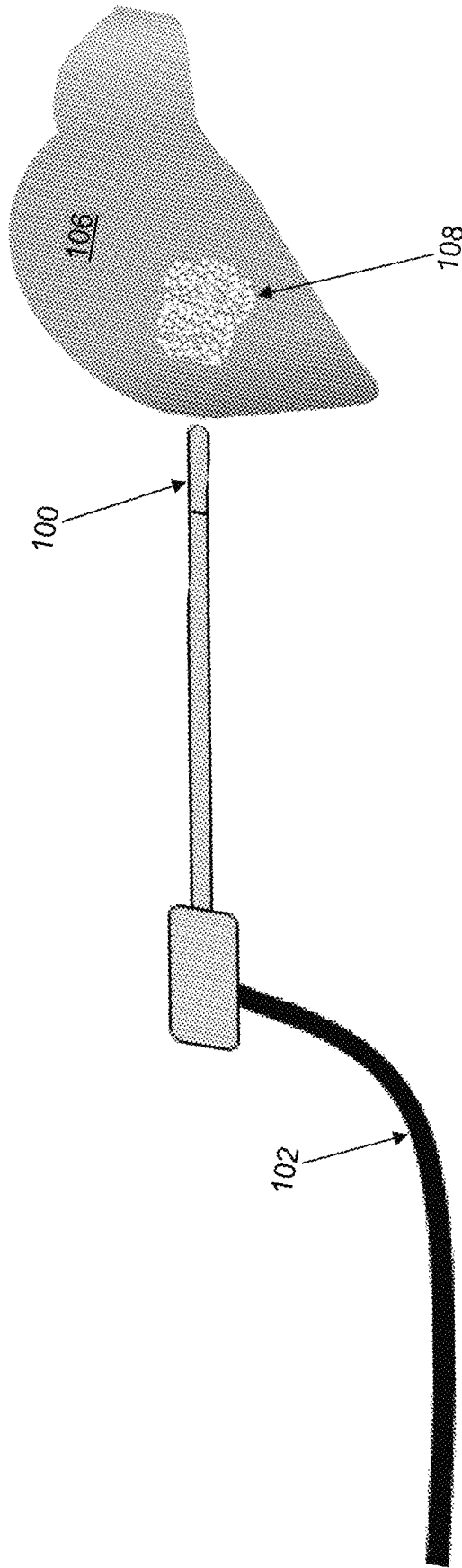


FIG. 1

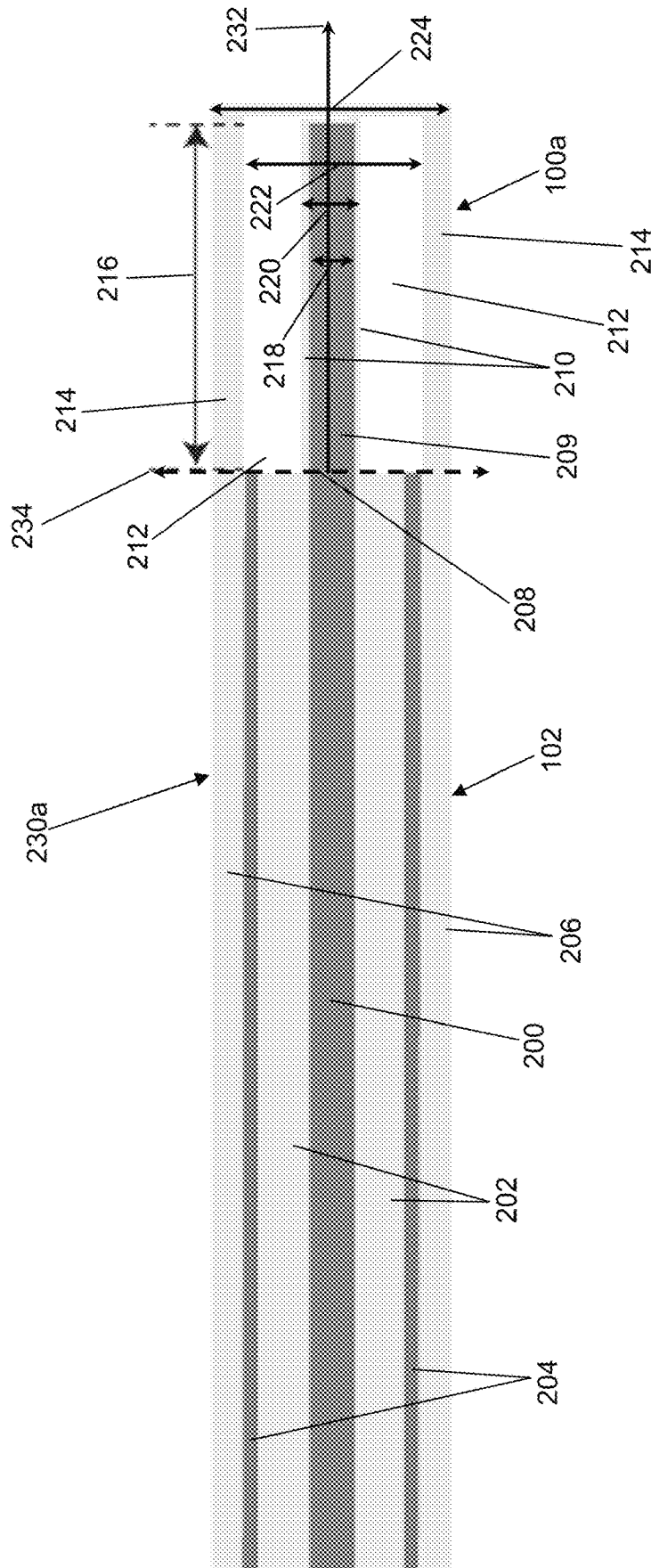


FIG. 2

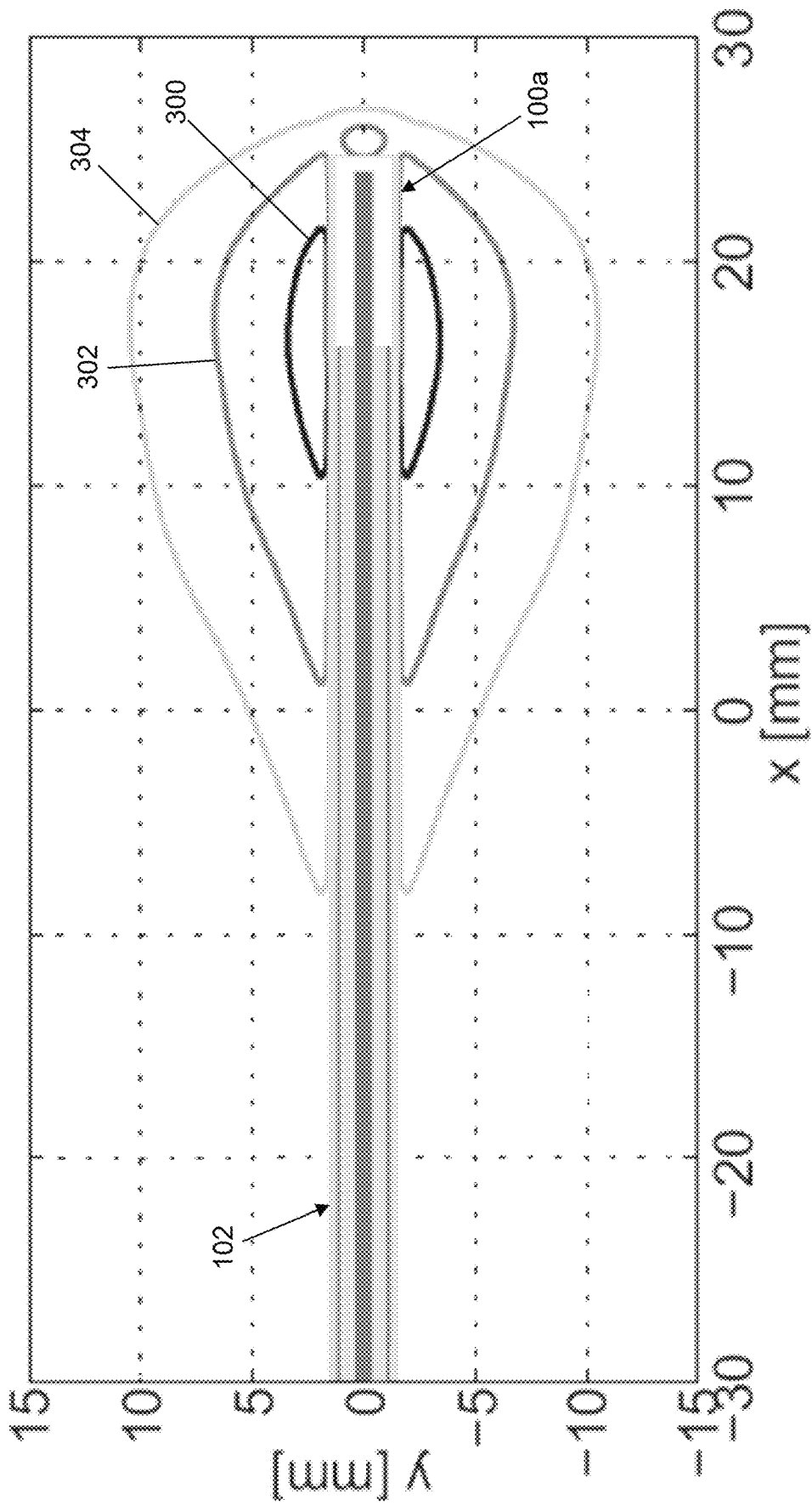


FIG. 3

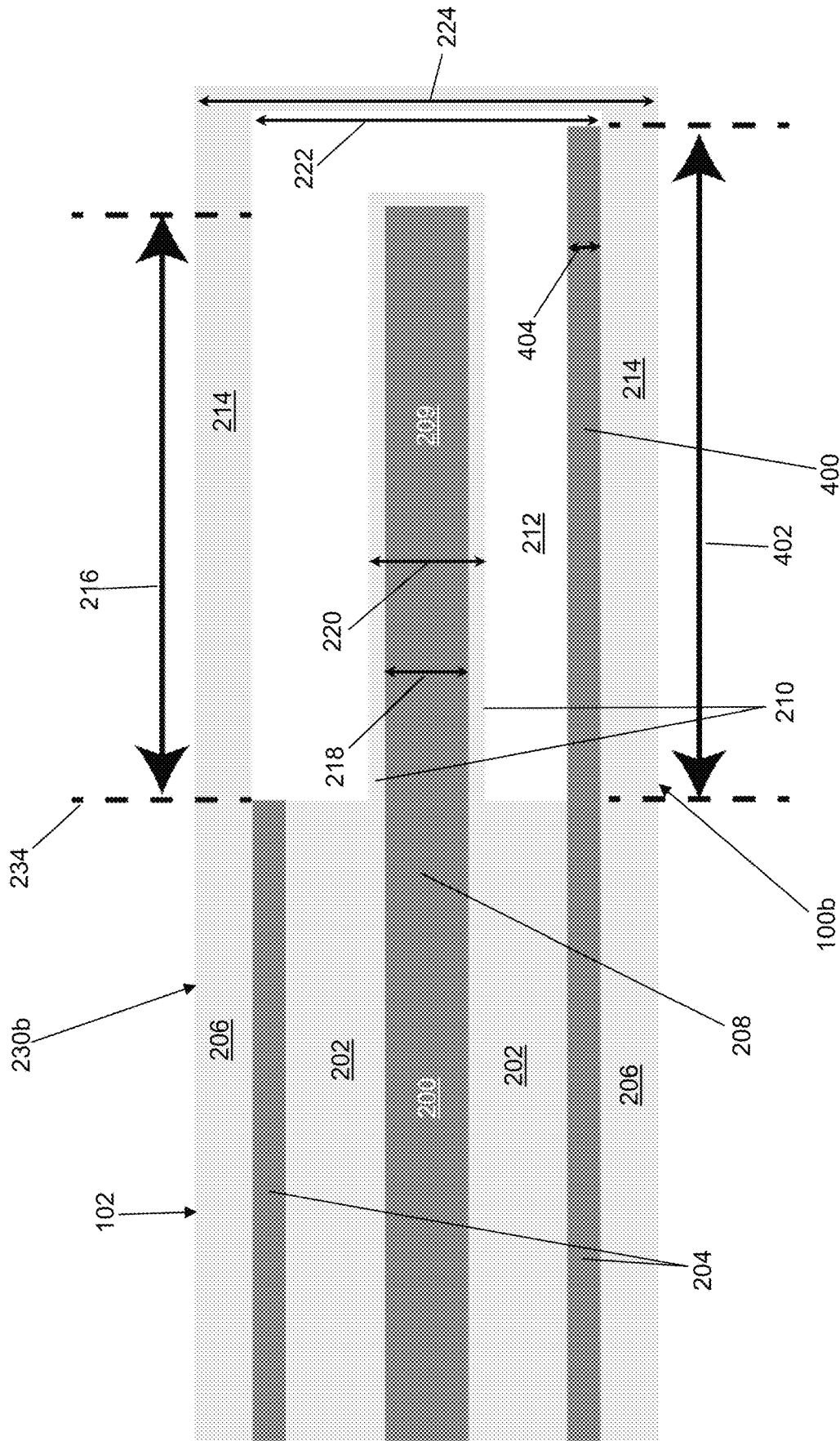


FIG. 4

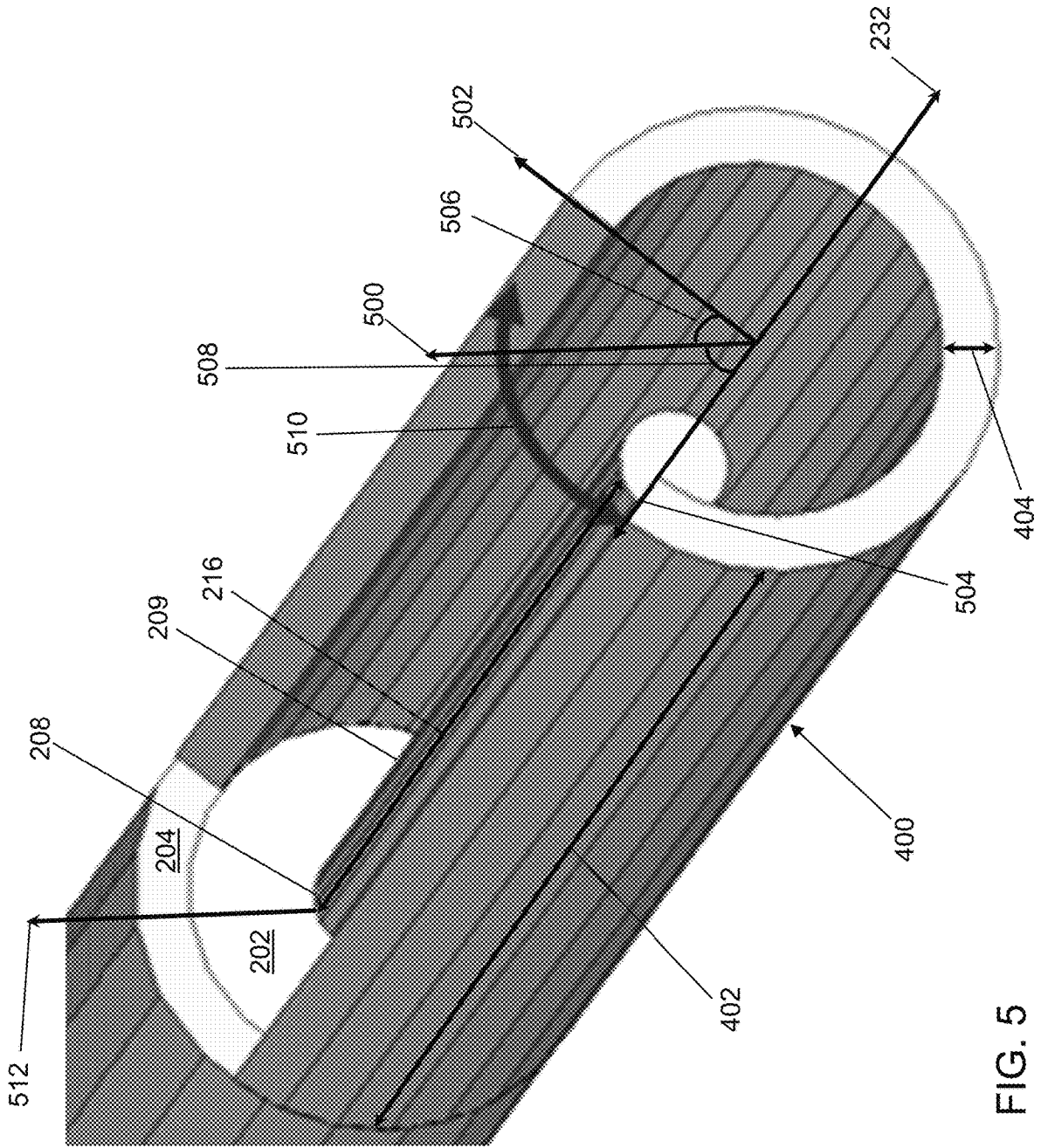


FIG. 5

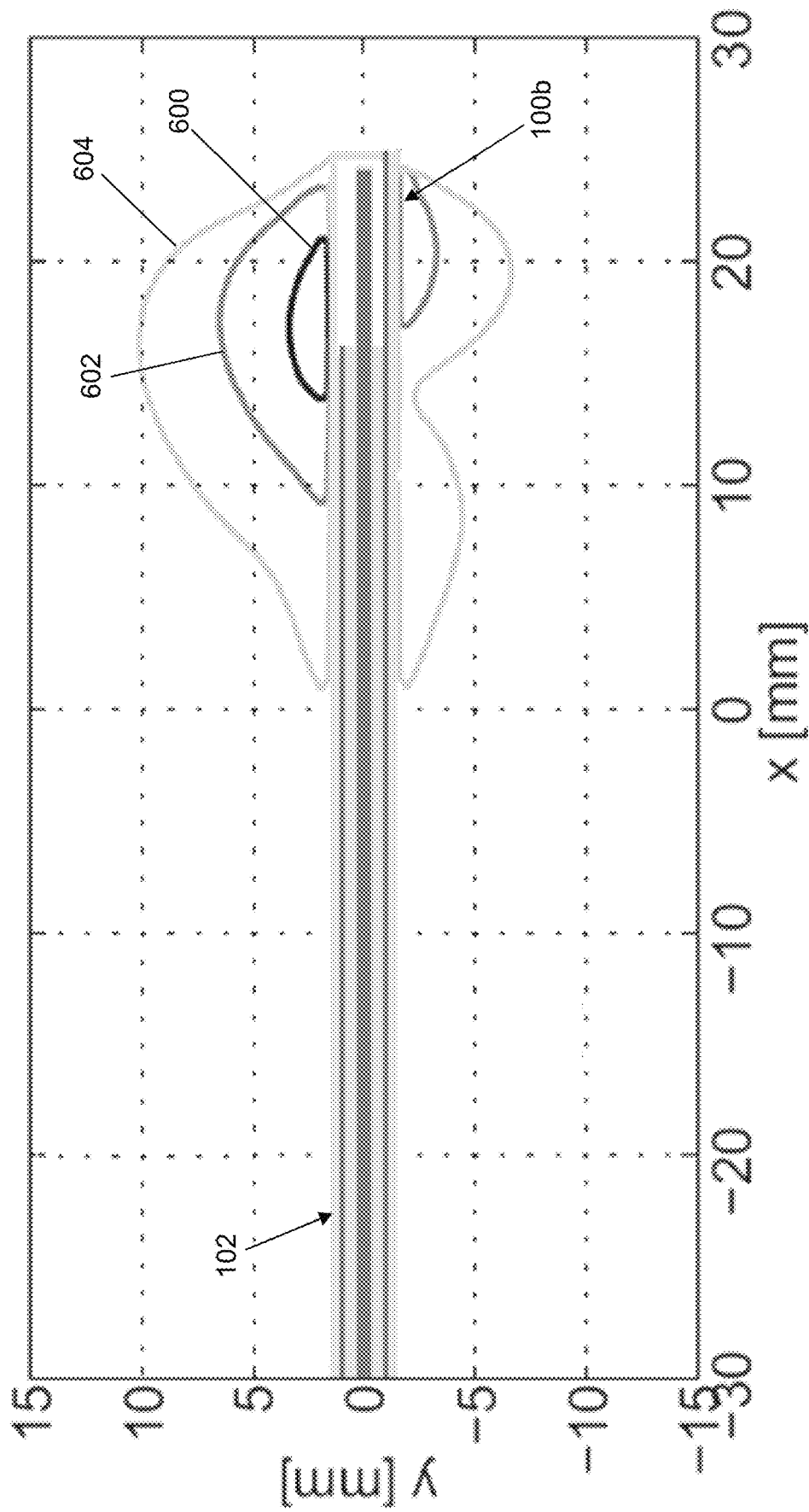


FIG. 6

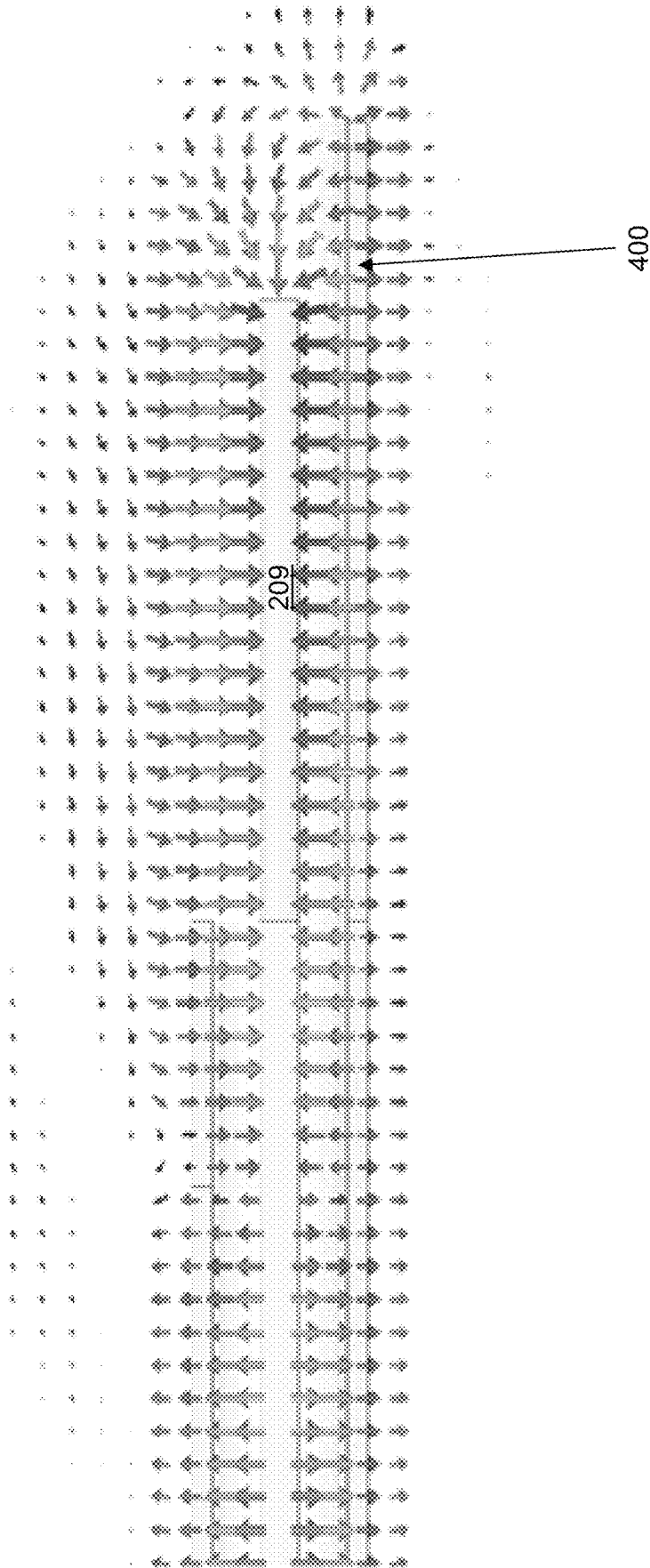


FIG. 7

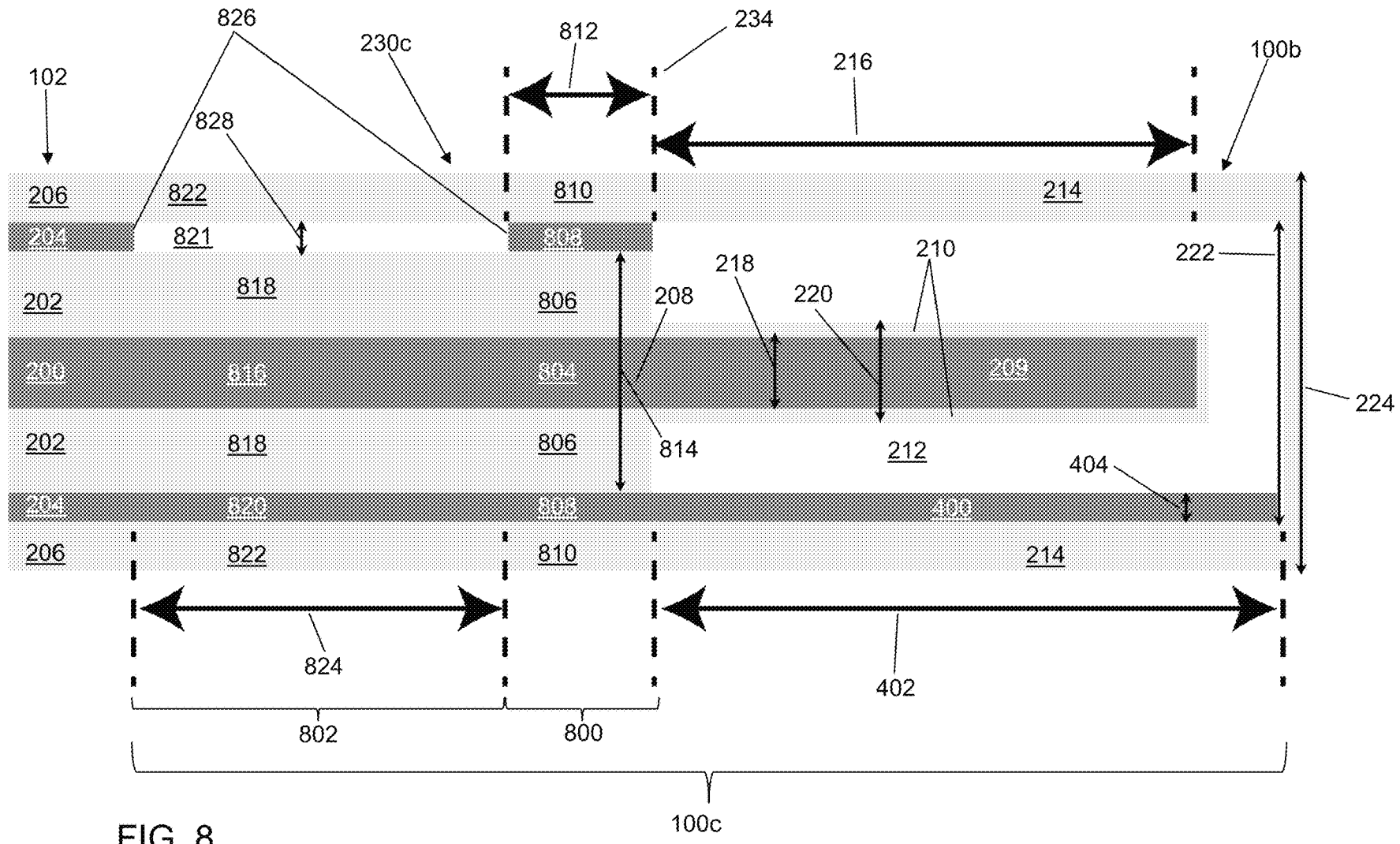


FIG. 8

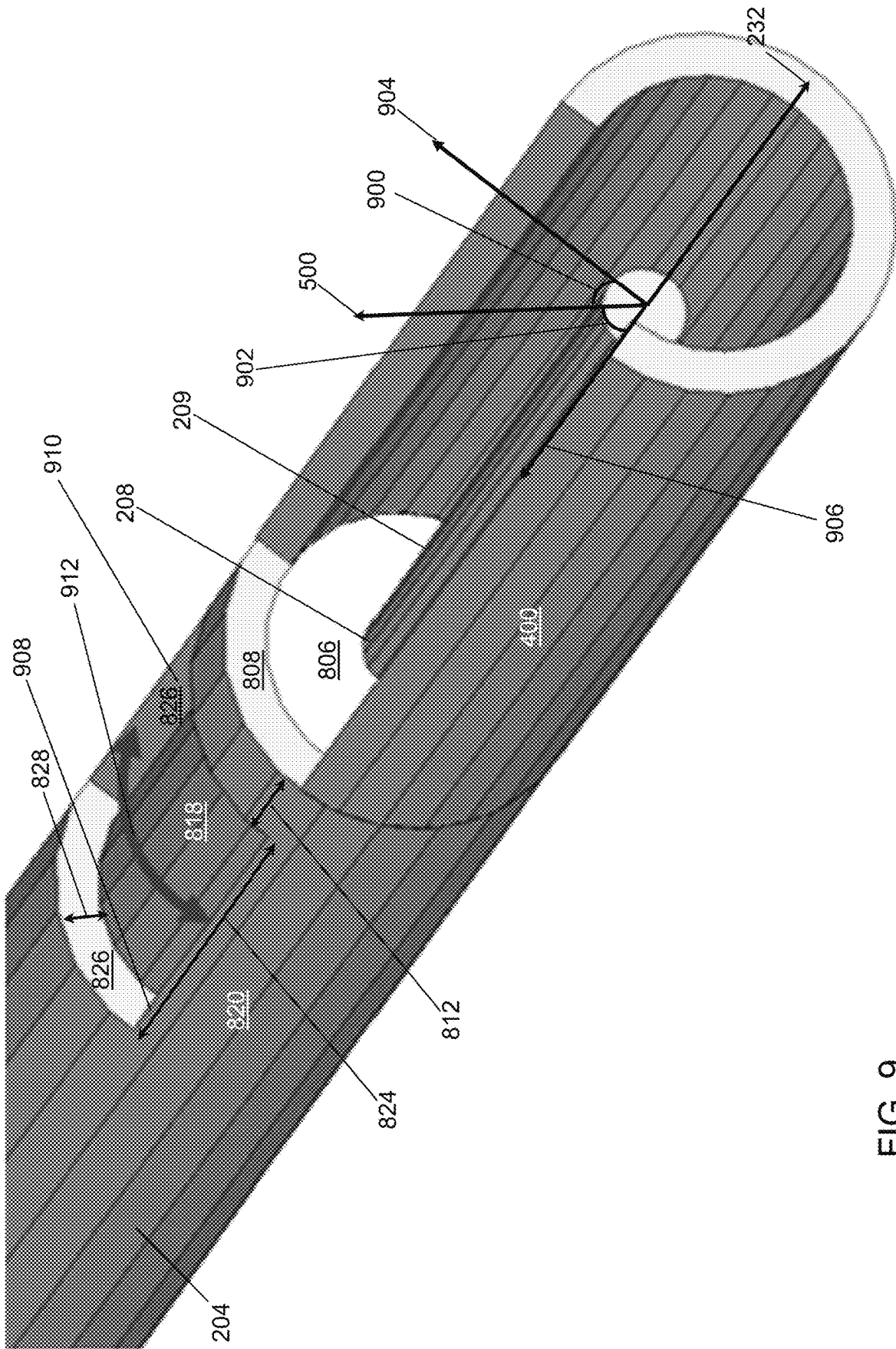


FIG. 9

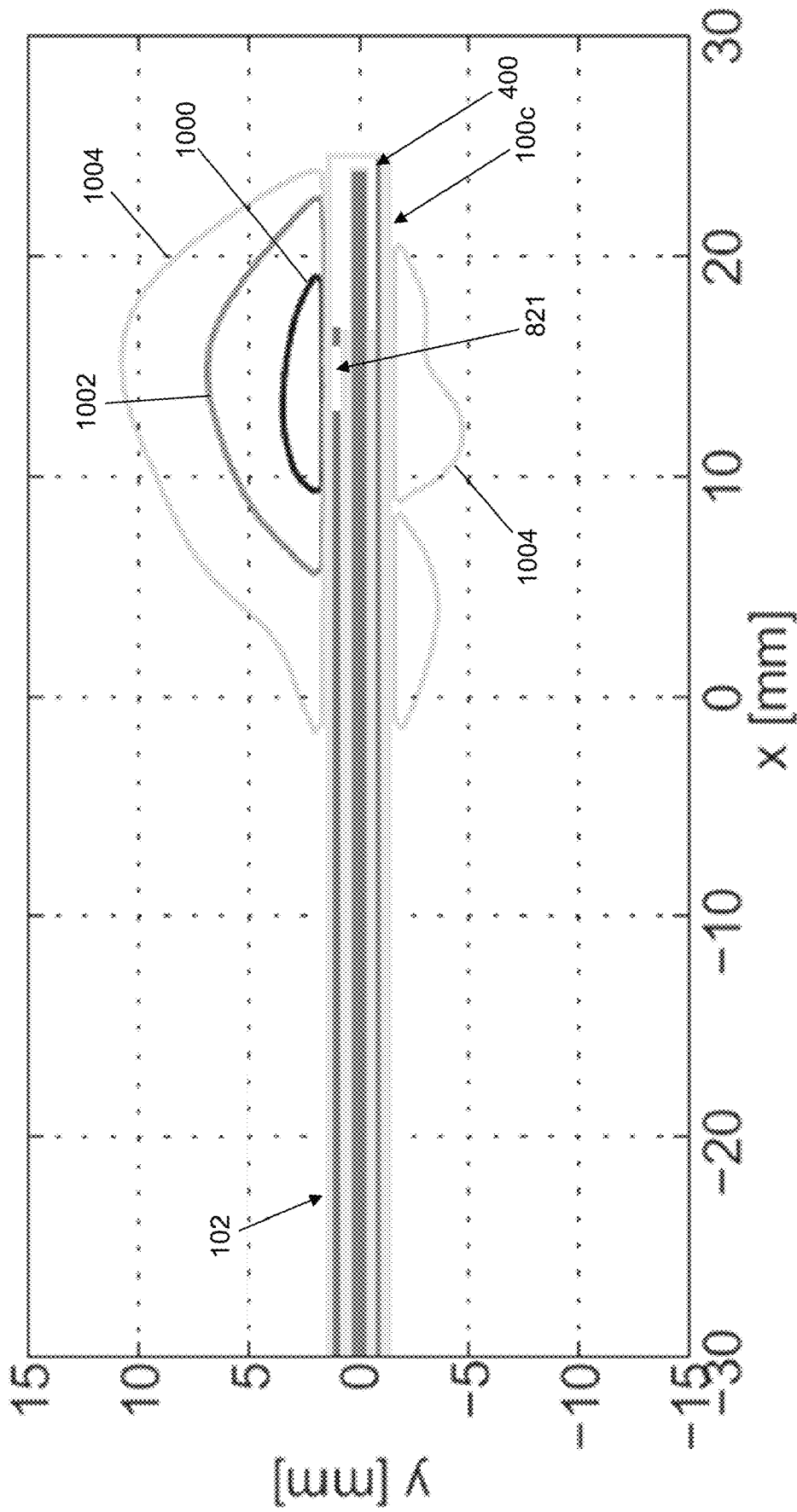


FIG. 10

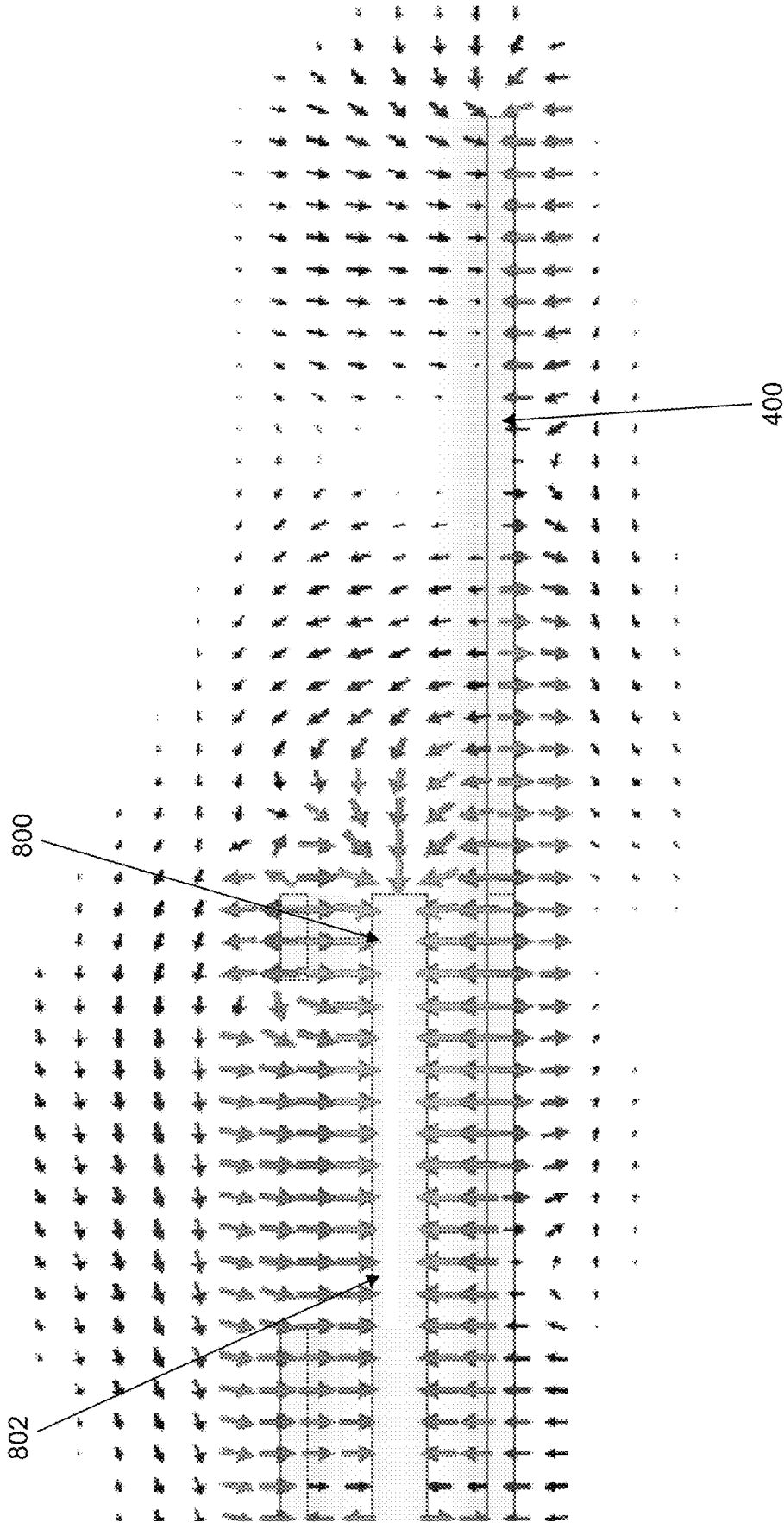


FIG. 11

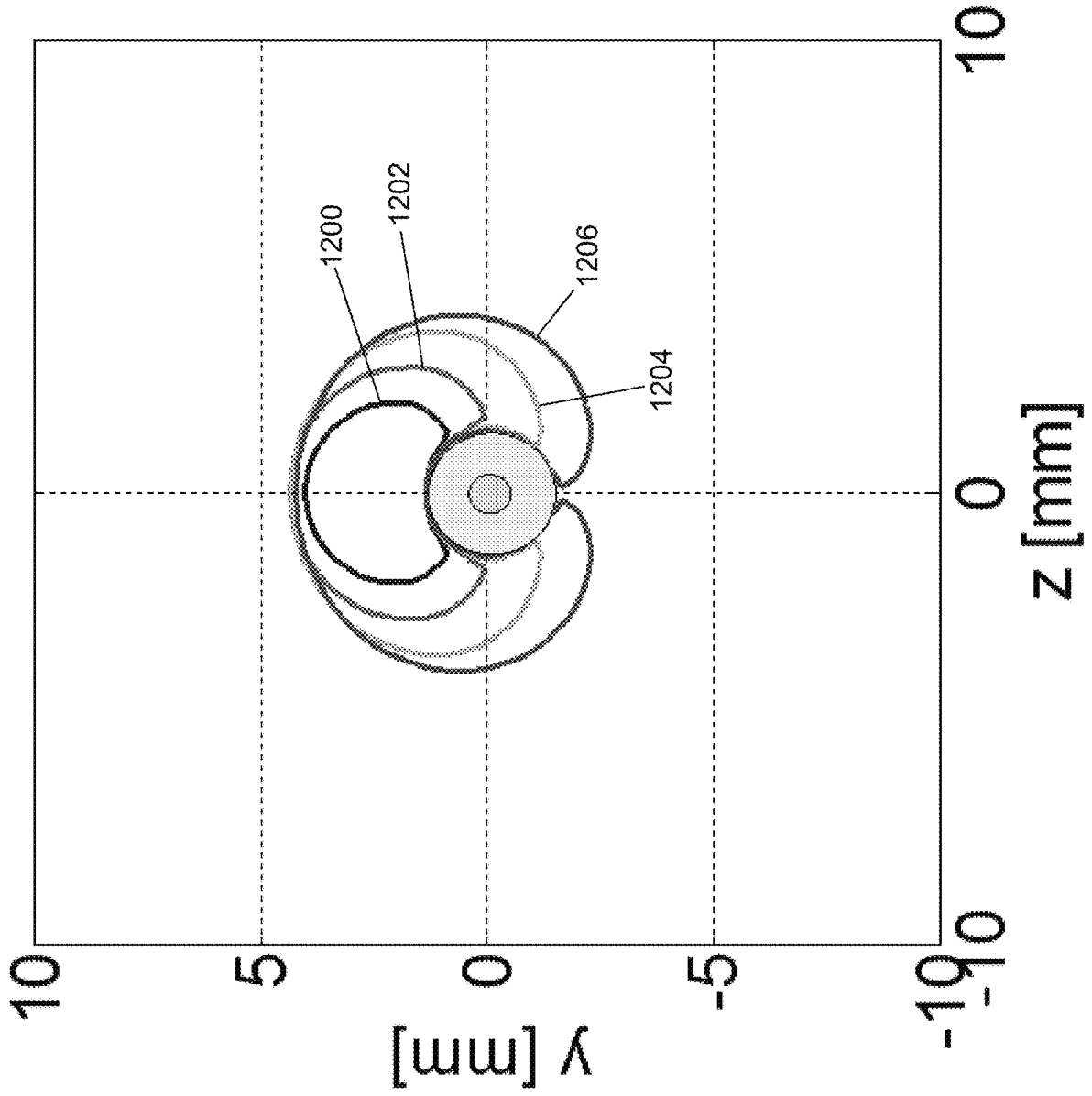


FIG. 12

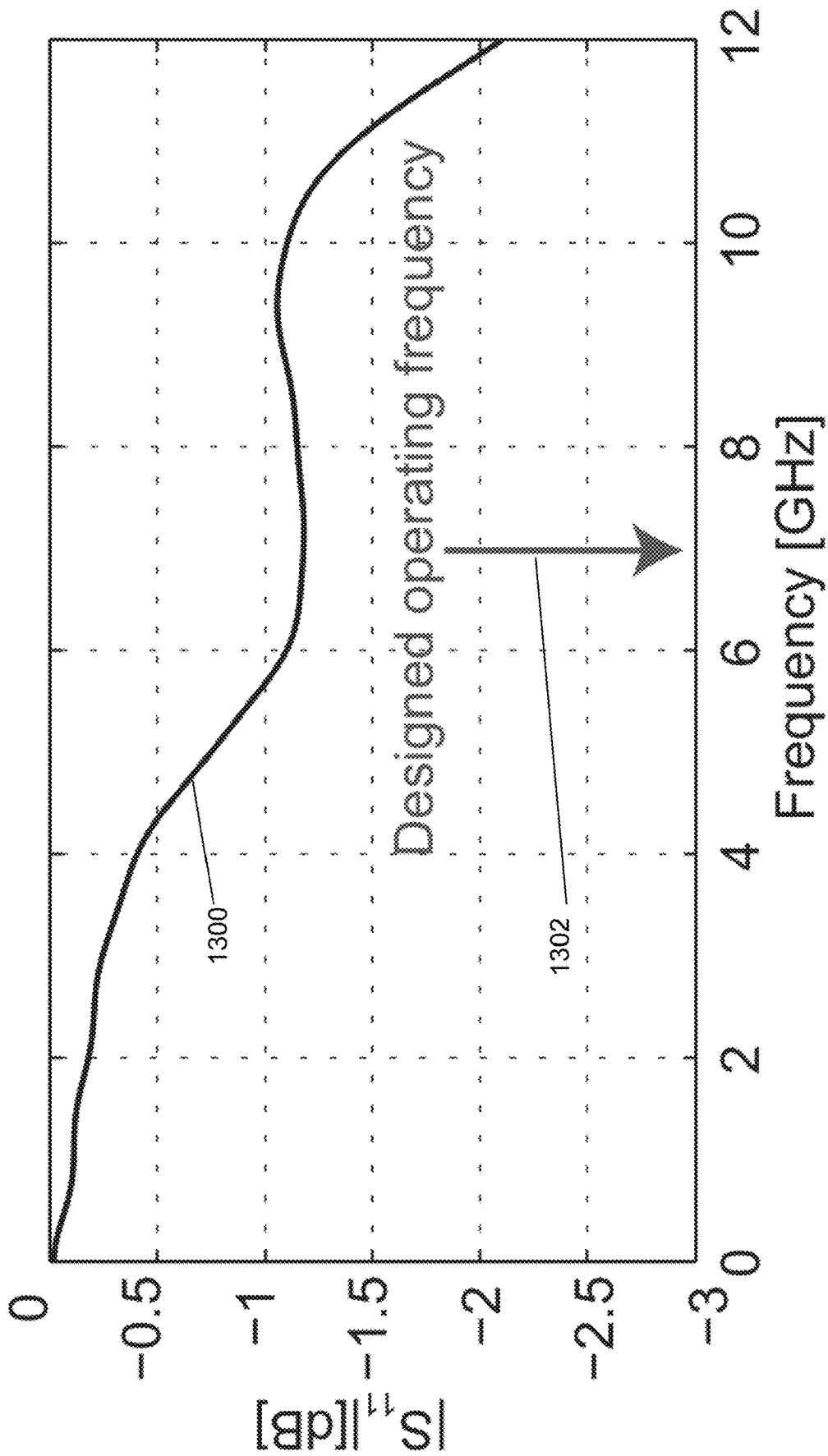


FIG. 13

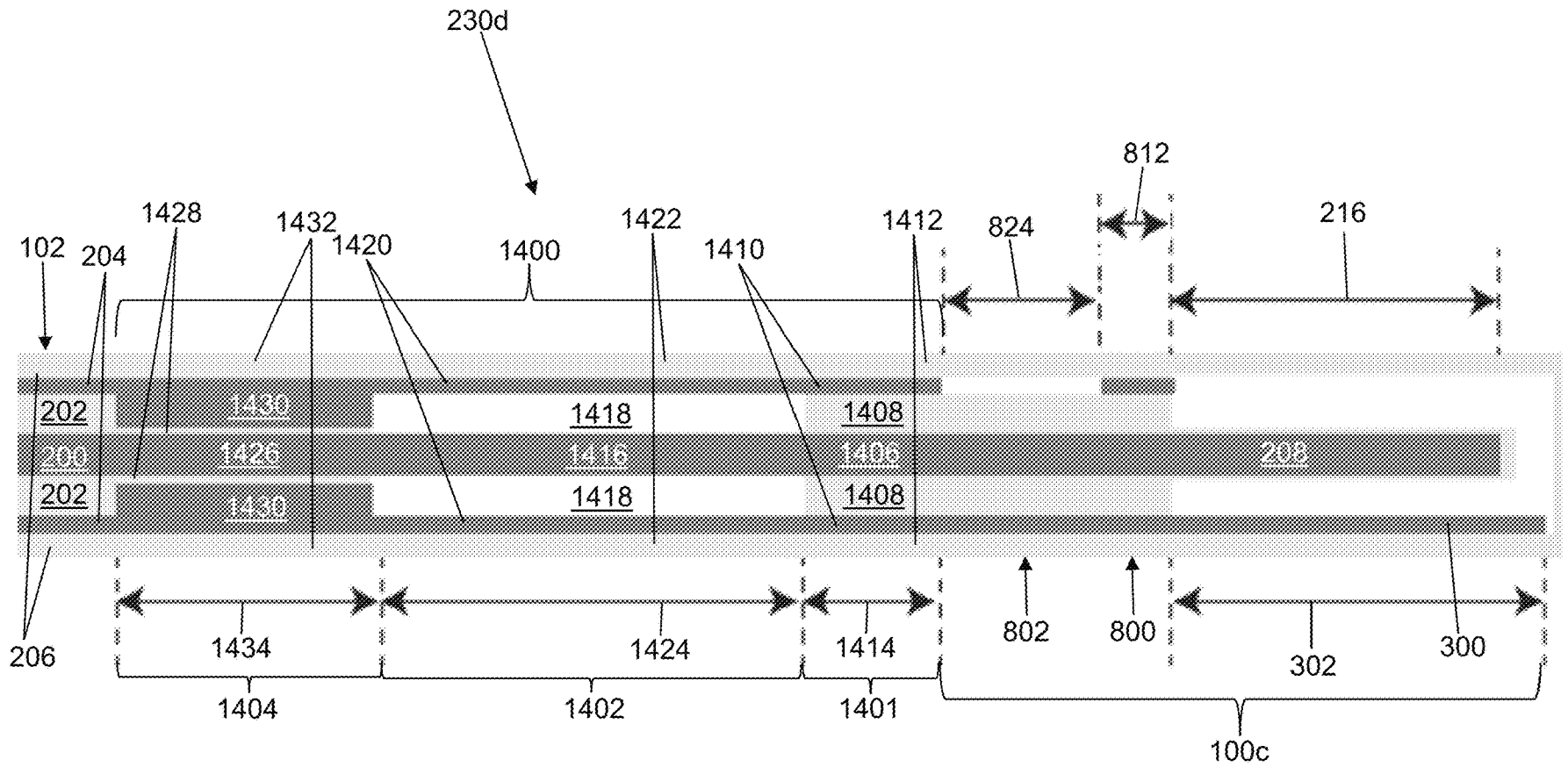


FIG. 14A

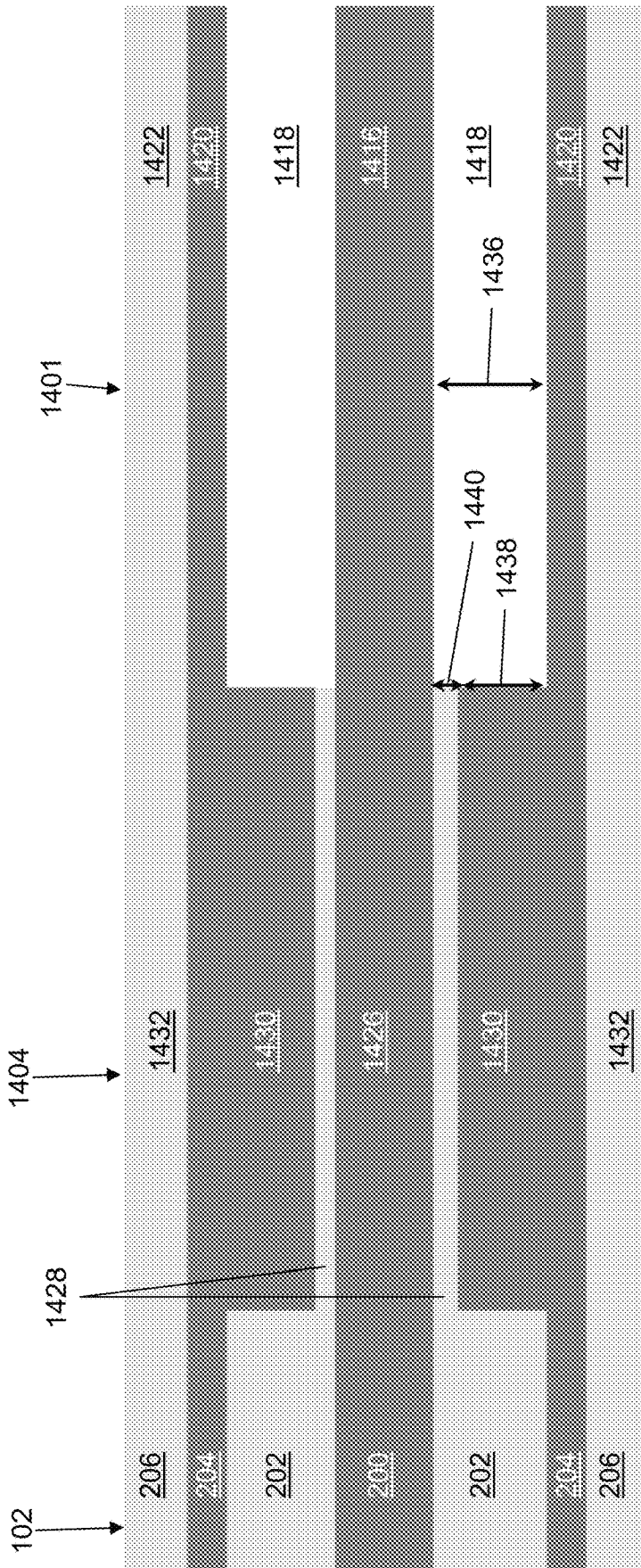


FIG. 14B

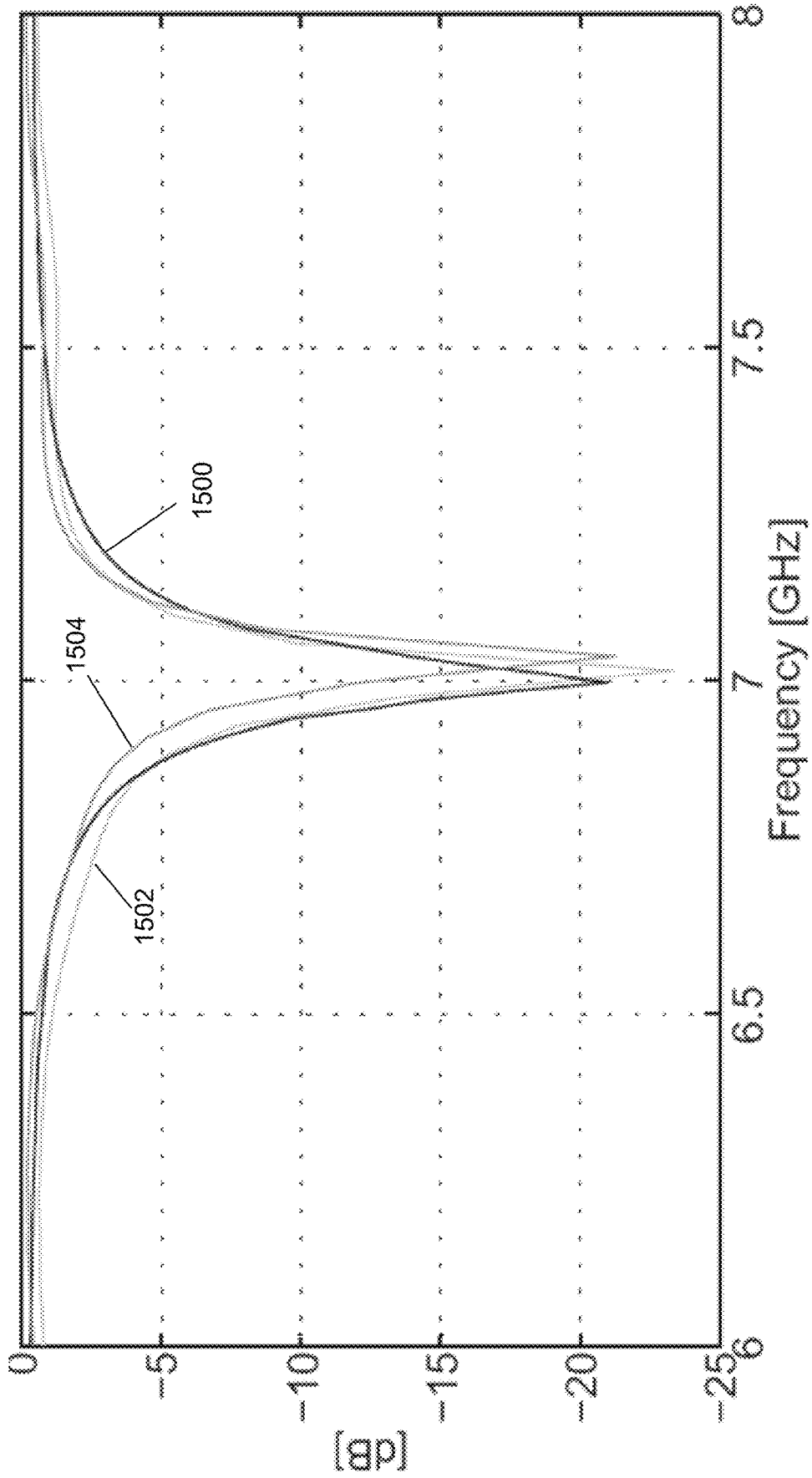


FIG. 15

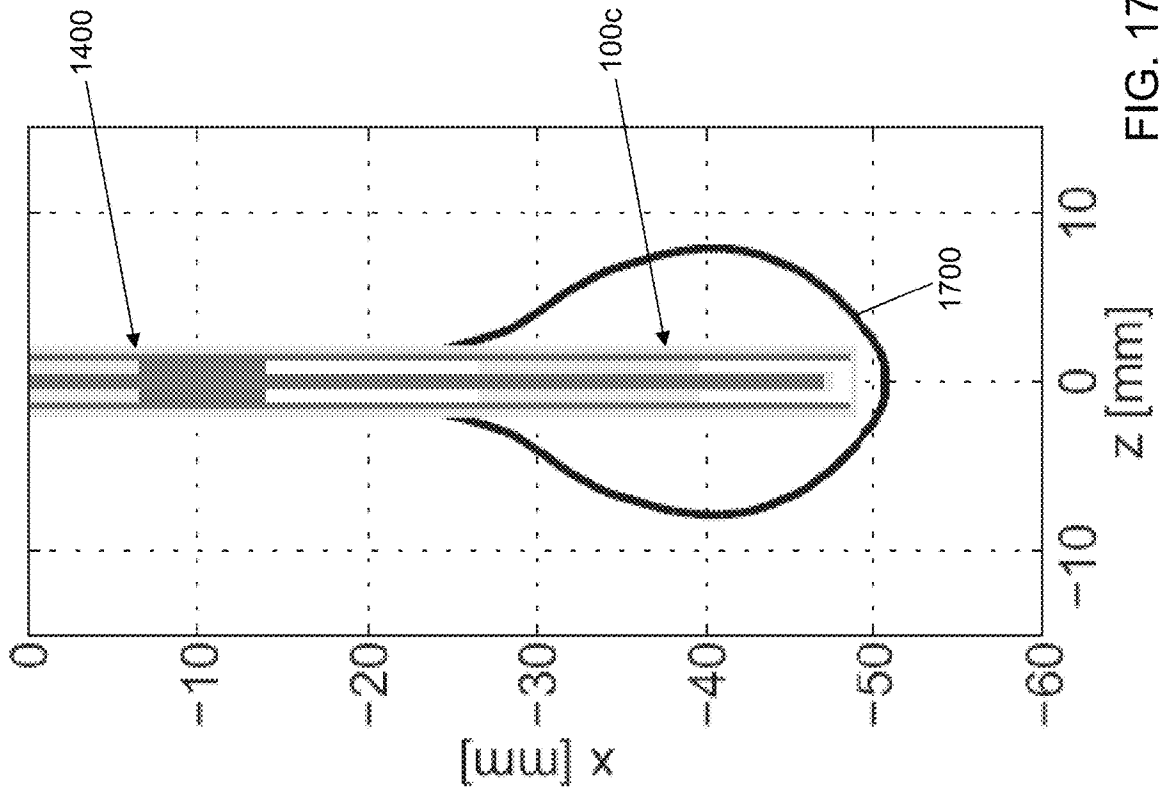


FIG. 17

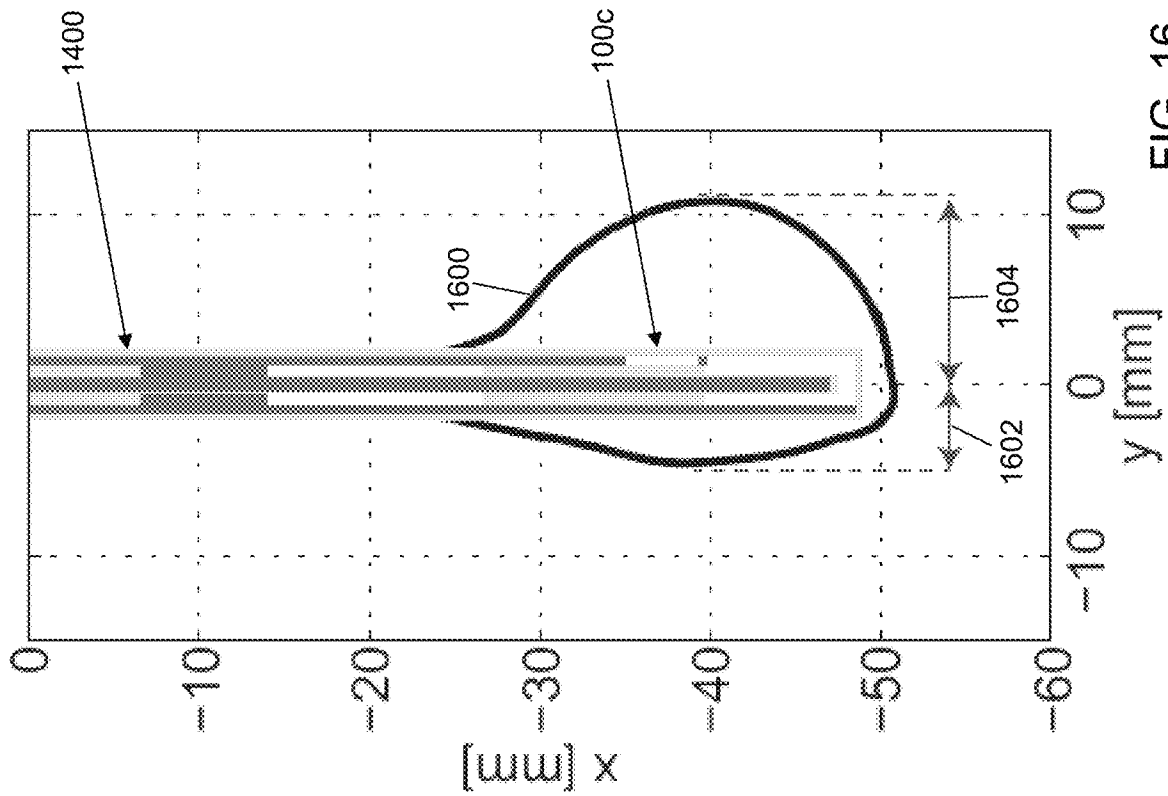


FIG. 16

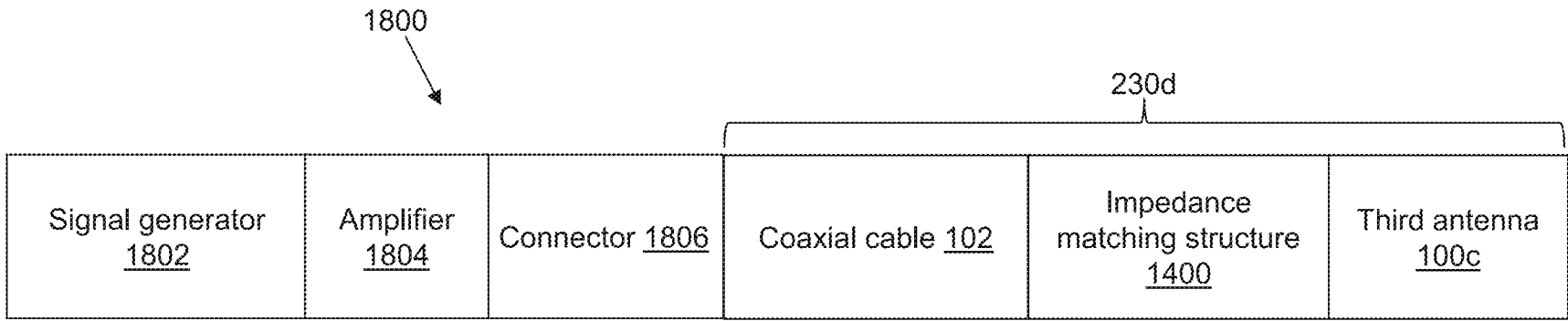


FIG. 18

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MICROWAVE ABLATION ANTENNA SYSTEM WITH REFLECTOR AND SLOT

REFERENCE TO GOVERNMENT RIGHTS

This invention was made with government support under ECCS1406090 awarded by the National Science Foundation. The government has certain rights in the invention.

BACKGROUND

Microwave ablation (MWA) is a form of thermal ablation used in interventional radiology to treat cancer. MWA uses electromagnetic waves in the microwave energy spectrum (300 megahertz to 300 gigahertz) to produce tissue-heating effects, i.e., to heat tumors to cytotoxic temperatures. MWA is generally used for minimally invasive treatment and/or palliation of solid tumors in patients. MWA offers several advantages over other ablation technologies such as radiofrequency (RF) and cryoablation including higher temperatures than RF, larger ablation zone volumes, shorter ablation times, and better ablation performance near arteries, which act as heat sinks. Selective delivery of energy to the prescribed tissue volume (i.e. the tumor and its margins) is achieved by means of interstitial placement of a microwave antenna directly into the tumor. Current MWA technology may be employed either laparoscopically or percutaneously, and thus, is considered to be minimally invasive. However, the extent to which MWA is minimally invasive depends on a length and a diameter of the interstitial microwave antenna.

Most MWA antennas are axisymmetric in nature and as a result, produce axisymmetric ablation zones in homogenous tissue. However, these rotationally symmetric ablation zones prevent successful ablation of tumors in certain scenarios. For example, a direct access path to a target tumor may be blocked by a vital organ or a vital organ that should not be ablated may be in proximity to the targeted ablation zone. Clinical examples of these cases are hepatic tumors close to the bowel or diaphragm, tumors on the periphery of lungs, renal tumors in the vicinity of bowel, breast tumors close to the chest wall, etc.

SUMMARY

An antenna system is provided that includes, but is not limited to, a coaxial cable, an antenna, a reflector wall, and a slot wall. The coaxial cable includes, but is not limited to, a center conductor extending a length of the coaxial cable, a dielectric material surrounding the center conductor along the length of the coaxial cable, and a conductive shield surrounding the dielectric material along the length of the coaxial cable. The antenna includes, but is not limited to, a base connected to the center conductor on a first side and an antenna conductor connected to the base on a second side opposite the first side. The antenna conductor extends in an axial direction from the second side of the base, wherein a radial plane through the base is perpendicular to the axial direction. The reflector wall is formed of a conductive material connected to the conductive shield to extend in the axial direction. The reflector wall is separated from the antenna conductor by a second dielectric material in a radial direction relative to the antenna conductor, wherein the reflector wall partially surrounds the antenna conductor in the radial direction from a first angle to a second angle when projected into the radial plane. The slot wall is formed through a portion of the conductive shield to expose the

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dielectric material from a third angle to a fourth angle when projected into the radial plane, wherein the slot wall is formed on the first side relative to the base. The first angle, the second angle, the third angle, and the fourth angle are defined relative to a common axis parallel to the radial plane.

A microwave ablation system is provided that includes, but is not limited to, an antenna system, a signal generator, and a connector. The antenna system includes, but is not limited to, a coaxial cable, an antenna, a reflector, and a slot wall. The coaxial cable includes, but is not limited to, a center conductor extending a length of the coaxial cable, a dielectric material surrounding the center conductor along the length of the coaxial cable, and a conductive shield surrounding the dielectric material along the length of the coaxial cable. The antenna includes, but is not limited to, a base connected to the center conductor on a first side and an antenna conductor connected to the base on a second side opposite the first side. The antenna conductor extends in an axial direction from the second side of the base, wherein a radial plane through the base is perpendicular to the axial direction. The reflector is formed of a conductive material connected to the conductive shield to extend in the axial direction. The reflector is separated from the antenna conductor by a second dielectric material in a radial direction relative to the antenna conductor. The reflector partially surrounds the antenna conductor in the radial direction from a first angle to a second angle when projected into the radial plane. The slot wall is formed through a portion of the conductive shield to expose the dielectric material from a third angle to a fourth angle when projected into the radial plane. The slot wall is formed on the first side relative to the base. The first angle, the second angle, the third angle, and the fourth angle are defined relative to a common axis parallel to the radial plane. The signal generator is configured to generate a signal at a selected operating frequency. The connector is configured to connect a second end of the coaxial cable opposite the base of the antenna to the signal generator to receive the generated signal.

Other principal features of the disclosed subject matter will become apparent to those skilled in the art upon review of the following drawings, the detailed description, and the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Illustrative embodiments of the disclosed subject matter will hereafter be described referring to the accompanying drawings, wherein like numerals denote like elements.

FIG. 1 depicts a microwave ablation (MWA) antenna system in accordance with an illustrative embodiment.

FIG. 2 depicts a side cross sectional view of a first MWA antenna for use in the MWA antenna system of FIG. 1 in accordance with an illustrative embodiment.

FIG. 3 shows a normalized specific absorption rate (SAR) pattern of the first MWA antenna of FIG. 2 in the x-y plane in accordance with an illustrative embodiment.

FIG. 4 depicts a side cross sectional view of a second MWA antenna for use in the MWA antenna system of FIG. 1 in accordance with an illustrative embodiment.

FIG. 5 depicts a perspective view of the second MWA antenna of FIG. 4 in accordance with an illustrative embodiment.

FIG. 6 shows a normalized SAR pattern of the MWA antenna of FIGS. 4 and 5 in the x-y plane in accordance with an illustrative embodiment.

FIG. 7 shows a simulated electric field pattern of the MWA antenna system of FIGS. 4 and 5 in the x-y plane in accordance with an illustrative embodiment.

FIG. 8 depicts a side cross sectional view of a third MWA antenna for use in the MWA antenna system of FIG. 1 in accordance with an illustrative embodiment.

FIG. 9 depicts a perspective view of the third MWA antenna of FIG. 8 in accordance with an illustrative embodiment.

FIG. 10 shows a normalized SAR pattern of the third MWA antenna of FIGS. 8 and 9 in the x-y plane in accordance with an illustrative embodiment.

FIG. 11 shows a simulated electric field pattern of the third MWA antenna of FIGS. 8 and 9 in the x-y plane in accordance with an illustrative embodiment.

FIG. 12 shows -10 dB SAR patterns at a feed point to the third MWA antenna of FIGS. 8 and 9 in the x-z plane for slot arc lengths of 90°, 180°, 270°, and 350° in accordance with an illustrative embodiment.

FIG. 13 shows a simulated reflection coefficient, $|S_{11}|$, of the third MWA antenna of FIGS. 8 and 9 without a matching network in accordance with an illustrative embodiment.

FIG. 14A depicts a side cross sectional view of the third MWA antenna of FIGS. 8 and 9 with a matching network in accordance with an illustrative embodiment.

FIG. 14B depicts a zoomed, side cross sectional view of the matching network of FIG. 14A in accordance with an illustrative embodiment.

FIG. 15 shows a simulated and a measured reflection coefficient, $|S_{11}|$, pre-ablation and post-ablation of the third MWA antenna with the matching network of FIGS. 14A and 14B in accordance with an illustrative embodiment.

FIG. 16 shows a simulated ablation zone of the third MWA antenna of FIGS. 8 and 9 in the x-y plane in accordance with an illustrative embodiment.

FIG. 17 shows a simulated ablation zone of the third MWA antenna of FIGS. 8 and 9 in the x-z plane in accordance with an illustrative embodiment.

FIG. 18 depicts a block diagram of a MWA system incorporating the MWA antenna system of FIG. 1 in accordance with an illustrative embodiment.

DETAILED DESCRIPTION

With reference to FIG. 1, a microwave ablation (MWA) antenna 100 is connected to and fed by a coaxial cable 102 that provides electromagnetic energy to antenna 100 at a selected operating frequency f_0 . MWA can be used to provide thermal therapy for treatment of various types of cancer 108 in various tissue/organs 106. Tissue/organs 106 may include liver, kidney, lung, bone, etc. MWA uses microwave frequency in the range 300 megahertz (MHz) to 300 gigahertz (GHz), though the range from 915 MHz to 2.45 GHz is most commonly used. MWA can be used to elevate the temperature of cancerous tissues to cytotoxic levels (e.g. >50° Celsius (C)) that quickly results in cell death. Electromagnetic waves are introduced into cancerous tissues by inserting antenna 100 interstitially into the tumor or other cancerous tissue.

With reference to FIG. 2, a side cross-sectional view of a first antenna system 230a is shown in accordance with an illustrative embodiment. First antenna system 230a may include coaxial cable 102 and a first antenna 100a.

Coaxial cable 102 may include a center conductor 200 extending a length of coaxial cable 102, a dielectric material 202 surrounding center conductor 200 along the length of coaxial cable 102, a conductive shield 204 surrounding

dielectric material 202 along the length of coaxial cable 102, and an insulating jacket 206 surrounding conductive shield 204 along the length of coaxial cable 102. Center conductor 200 is generally circular and may be formed of a solid conductive material such as copper plated steel wire, silver plated steel wire, silver plated copper wire, silver plated copper clad steel wire, copper wire, copper clad aluminum wire, steel wire, etc. Coaxial cable 102 may have a variety of diameters. Dielectric material 102 may include foamed polyethylene, solid polyethylene, polyethylene foam, polytetrafluoroethylene, air, air space polyethylene, vacuum, etc. Conductive shield 204 may be formed of a solid or braided conductive material such as copper, steel, aluminum, silver plated copper, silver plated copper clad steel, etc. Insulating jacket 206 can be made from many different insulating materials such as polyvinyl chloride or another plastic material.

Coaxial cable 102 may be rigid, semi-rigid, or flexible. The characteristic impedance may be off the shelf and range between approximately 20 and approximately 125 ohms or be designed to have a selected characteristic impedance within, above, or below this range as understood by a person of skill in the art using various dielectric and conductive materials, diameters, and thicknesses.

First antenna 100a may be a monopole antenna. First antenna 100a may include a base 208 and an antenna conductor 209. Base 208 is connected to center conductor 200 on a first side and is a feed end of first antenna 100a. Antenna conductor 209 connects to base 208 on a second side opposite the first side. Antenna conductor 209 extends in an axial direction from the second side of base 208. A radial plane 234 can be defined through base 208 that is perpendicular to an axial direction 232. Axial direction 232 extends from a center of antenna conductor 209.

First antenna 100a is formed of a conductive material that may be the same material as and/or may be an extension of center conductor 200 of coaxial cable 102. As understood by a person of skill in the art, the wavelength of operation, λ_0 , of first antenna 100a is defined as $\lambda_2=c/f_0$, where c is the speed of light in an environment in which antenna 100 is used, such as a body tissue, and f_0 is a selected operating frequency of a signal carried by center conductor 200 of coaxial cable 102. For illustration, f_0 may be between 500 MHz and 30 GHz. The wavelength of operation, λ_0 , is a wavelength at the selected operating frequency in a medium in which first antenna 100a is selected to operate. For example, the medium includes first antenna dielectric material 210, second antenna dielectric material 212, and third antenna dielectric material 214 and the body tissue in which first antenna 100a is used to perform MWA.

First antenna 100a may be formed of a straight section of conducting wire, of a plurality of helical turns, of a bent wire, etc. A cross section of first antenna 100a may be circular, square, elliptical, rectangular, etc. though it is typically circular when formed as an extension of center conductor 200 of coaxial cable 102. First antenna 100a has an antenna length 216 of approximately $0.252\lambda_0$ defined from radial plane 234. For example, antenna length 216 was selected as 9 millimeters (mm) to operate at 7 GHz in egg white. First antenna 100a has an antenna width 218 equal to 0.515 mm for coaxial cable 102 selected as 50-ohm (Ω) UT-085C semi-rigid cable. For illustration, antenna width 218 may be selected as $\leq 0.10\lambda_0$.

A first antenna dielectric material 210 may surround antenna conductor 209 along a length of antenna conductor 209. First antenna dielectric material 210 may be the same material as and/or may be an extension of dielectric material

202. A first antenna dielectric width **220** defines a cross section width of first antenna dielectric material **210** surrounding antenna conductor **209**. A depth of first antenna dielectric material **210** is half of first antenna dielectric width **220** minus half of antenna width **218**. For illustration, the depth of first antenna dielectric material **210** is 0.05 mm computed using $0.5 \cdot (0.615 - 0.515)$. For illustration, first antenna dielectric width **220** may be selected as $\leq 0.12\lambda_0$. The depth of first antenna dielectric material **210** may be selected as $\leq 0.01\lambda_0$.

A second antenna dielectric material **212** may surround first antenna dielectric material **210**. A second antenna dielectric width **222** defines a cross section width of second antenna dielectric material **212** surrounding first antenna dielectric material **210**. A depth of second antenna dielectric material **212** is half of second antenna dielectric width **222** minus half of first antenna dielectric width **220**. For illustration, the depth of second antenna dielectric material **212** is 0.791 mm computed using $0.5 \cdot (2.197 - 0.615)$, and second antenna dielectric width **222** is 2.197 mm. The depth of second antenna dielectric material **212** may be selected as $\leq 0.16\lambda_0$, and second antenna dielectric width **222** may be selected as $\leq 0.45\lambda_0$.

A third antenna dielectric material **214** may surround second antenna dielectric material **212**. Third antenna dielectric material **214** may be the same material as and/or may be an extension of insulating jacket **206**. A third antenna dielectric width **224** defines a cross section width of third antenna dielectric material **214** surrounding second antenna dielectric material **212**. A depth of third antenna dielectric material **214** is half of third antenna dielectric width **224** minus half of second antenna dielectric width **222**. For illustration, the depth of third antenna dielectric material **214** is 0.3515 mm and third antenna dielectric width **224** is 2.9 mm. The depth of third antenna dielectric material **214** may be selected as $\leq 0.07\lambda_0$, and third antenna dielectric width **224** may be selected as $\leq 0.6\lambda_0$.

For example, first antenna dielectric material **210**, second antenna dielectric material **212**, and third antenna dielectric material **214** may include foamed polyethylene, solid polyethylene, polyethylene foam, polytetrafluoroethylene, air, air space polyethylene, vacuum, alumina, etc. For illustration, the dielectric materials may include any low loss dielectric materials having a permittivity relative to a vacuum within the range of 1-30. For illustration, first antenna dielectric material **210** and third antenna dielectric material **214** are polytetrafluoroethylene, and second antenna dielectric material **212** is air.

Referring to FIG. 3, a simulated specific absorption rate (SAR) pattern formed by first antenna **100a** operating at 7 GHz is shown in accordance with an illustrative embodiment x-y plane, where y is in radial plane **234** and x is in axial direction **232**. The SAR pattern was normalized to its associated maximum value. The simulated results assumed egg white. A -5 decibel (dB) curve **300** shows a SAR level reduced by 5 dB. A -15 dB curve **302** shows a SAR level reduced by 15 dB. A -25 dB curve **304** shows a SAR level reduced by 25 dB. First antenna **100a** and coaxial cable **102** are shown for reference. First antenna **100a** and coaxial cable **102** have an axisymmetric SAR pattern as is typical in MWA systems.

With reference to FIG. 4, a side cross-sectional view of a second antenna system **230b** is shown in accordance with an illustrative embodiment. With reference to FIG. 5, a perspective view of second antenna system **230b** is shown in accordance with an illustrative embodiment. Second antenna system **230b** may include coaxial cable **102** and a second

antenna **100b**. Second antenna **100b** includes first antenna **100a** and a reflector wall **400**.

Reflector wall **400** is formed of a conductive material that may be the same material as and/or may be an extension of conductive shield **204** of coaxial cable **102**. Reflector wall **400** has a reflector length **402** of between approximately $0.25\lambda_0$ and approximately $0.4\lambda_0$ relative to radial plane **234** defined through base **208** of first antenna **100a**. Reflector wall **400** has a reflector width **404** in radial plane **234**. A y-axis **512** is perpendicular to axial direction **232** and is in radial plane **234**. A z-axis (not shown) is perpendicular to y-axis **512** and to axial direction **232**. Reflector length **402** in axial direction **232** is greater than or equal to antenna length **216** in axial direction **232**. The z-axis and y-axis **512** define radial plane **234**.

Reflector wall **400** is separated from antenna conductor **209** by second dielectric material **212** in a radial direction relative to a center of antenna conductor **209**. Reflector wall **400** partially surrounds antenna conductor **209** in a radial direction from a first angle **506** to a second angle **508** when projected into radial plane **234**. An up direction **500** is parallel to radial plane **234** and more specifically to y-axis **512** and extends from and is perpendicular to axial direction **232**. First angle **506** is defined between up direction **500** and a first vector **502** that extends from axial direction **232** in radial plane **234** to a first edge wall of reflector wall **400**. Second angle **508** is defined between up direction **500** and a second vector **504** that extends from axial direction **232** in radial plane **234** to a second edge wall of reflector wall **400**. Up direction **500** is centered between first angle **502** and second angle **504**. Reflector slot angle **510** defines an angle between first vector **502** and second vector **504**. Reflector wall **400** forms a wall between first vector **502** and second vector **504** and defines a total angle of 360° minus reflector slot angle **510**. In the illustrative embodiment of FIG. 5, reflector slot angle **510** is 90° and the total angle of reflector wall **400** is 270° .

For illustration, reflector length **402** was selected as 9 mm and antenna length **216** was selected as 7 mm to operate at 7 GHz in egg white. First antenna **100a** has an antenna width **218** equal to 0.515 mm for coaxial cable **102** selected as 50-ohm (Ω) UT-085C semi-rigid cable.

Referring to FIG. 6, a simulated SAR pattern formed by second antenna **100b** operating at 7 GHz is shown in accordance with an illustrative embodiment in the x-y plane, where y is in radial plane **234** and x is in axial direction **232**. The SAR pattern was normalized to its associated maximum value. The simulated results assumed egg white. A -5 decibel (dB) curve **600** shows a SAR level reduced by 5 dB. A -15 dB curve **602** shows a SAR level reduced by 15 dB. A -25 dB curve **604** shows a SAR level reduced by 25 dB. Second antenna **100b** and coaxial cable **102** are shown for reference. Second antenna **100b** and coaxial cable **102** create an asymmetric SAR pattern with a decreased radiation in the direction of reflector wall **400**.

Referring to FIG. 7, a simulated electric field direction in a near field region formed by second antenna **100b** operating at 7 GHz is shown in accordance with an illustrative embodiment in the x-y plane. The simulated electric field direction is shown using a normalized dB scale (with respect to its corresponding maximum value) for the electric field.

With reference to FIG. 8, a side cross-sectional view of a third antenna system **230c** is shown in accordance with an illustrative embodiment. With reference to FIG. 9, a perspective view of third antenna system **230c** is shown in accordance with an illustrative embodiment. Third antenna system **230c** may include coaxial cable **102** and a third

antenna **100c**. Third antenna **100c** includes second antenna **100b**, a coaxial cable section **800**, and a slot wall section **802**.

Coaxial cable section **800** may be formed of a section of coaxial cable **102** having a coaxial section length **812**. Coaxial section length **812** may be defined from radial plane **234** to a closest end of slot wall section **802** and may be selected from a range defined between and inclusive of $0.004\lambda_0$ and $0.1\lambda_0$. Coaxial cable section **800** may include a coax section center conductor **804** extending a length of coaxial cable section **800**, a coax section dielectric material **806** surrounding coax section center conductor **804** extending a length of coaxial cable section **800**, a coax section conductive shield **808** surrounding coax section dielectric material **806** along the length of coaxial cable section **800**, and a coax section insulating jacket **810** surrounding coax section conductive shield **808** along the length of coaxial cable section **800**.

A coax section dielectric material width **814** defines a cross section width of coax section dielectric material **806** surrounding coax section center conductor **804**. A depth of coax section dielectric material **806** is half of coax section dielectric material width **814** minus half of first antenna conductor width **218**. For illustration, the depth of second antenna dielectric material **212** is 0.791 mm and second antenna dielectric width **222** is 2.197 mm.

Slot wall section **802** may be formed of a section of coaxial cable **102** having a slot length **824**. Slot wall section **802** may include a slot center conductor **816** extending a length of slot wall section **802**, a slot dielectric material **818** surrounding slot center conductor **816** extending a length of slot wall section **802**, a slot conductive shield **820** surrounding coax section dielectric material **806** along the length of slot wall section **802**, and a slot insulating jacket **822** surrounding slot conductive shield **820** along the length of slot wall section **802**. Slot length **824** may be selected from a range defined between and inclusive of $0.1\lambda_0$ and $0.2\lambda_0$.

In the illustrative embodiment of FIG. 8, base **208** connects to coax section center conductor **804**. First antenna dielectric material **210** connects to and extends from coax section dielectric material **806**. Second antenna dielectric material **212** connects to and may extend from coax section dielectric material **806**. Reflector wall **400** connects to and extends from coax section conductive shield **808**. Third antenna dielectric material **214** connects to and extends from coax section insulating jacket **810**.

In the illustrative embodiment of FIG. 8, slot center conductor **816** connects between coax section center conductor **804** and center conductor **200** of coaxial cable **102**. Slot dielectric material **818** connects between coax section dielectric material **806** and dielectric material **202** of coaxial cable **102**. Slot conductive shield **820** connects between coax section conductive shield **808** and conductive shield **204** of coaxial cable **102**. Slot insulating jacket **822** connects between coax section insulating jacket **810** and insulating jacket **206** of coaxial cable **102**.

A slot wall **826** is formed on a first side of base **208** that is opposite a second side from which reflector wall **400** extends from coax section conductive shield **808**. Slot wall **826** is formed through a portion of slot conductive shield **820** to expose slot dielectric material **818** from a third angle **900** to a fourth angle **902** when projected into radial plane **234** in a manner similar to that described for first angle **506** and for second angle **508** except with reference to a first side wall **908** of slot wall **826** and to a second side wall **910** of

slot wall **826**, respectively. Slot wall **826** forms a slot **821**. Slot **821** may be formed by removing a portion of slot conductive shield **820**.

Third angle **900** is defined between up direction **500** and a third vector **904** that extends from axial direction **232** in radial plane **234** to first side wall **910** (shown referring to the first edge wall of reflector wall **400**, which is parallel in the illustrative embodiment). Fourth angle **902** is defined between up direction **500** and a fourth vector **906** that extends from axial direction **232** in radial plane **234** to second side wall **908** (shown referring to the second edge wall of reflector wall **400**, which is parallel in the illustrative embodiment). Up direction **500** is centered between third angle **900** and fourth angle **902**. Slot angle **912** defines an angle between first vector **502** and second vector **504**. Slot conductive shield **820** forms a wall between third vector **904** and fourth vector **906** and defines a total angle of 360° minus slot angle **912**. In the illustrative embodiment of FIG. 9, slot angle **912** is equal to reflector slot angle **510** and is 90° . The total angle of the wall formed by slot conductive shield **820** is 270° .

Slot wall **826** has a slot wall width **828** between slot dielectric material **818** and slot insulating jacket **822**. Slot wall width **828** may be selected as $\leq 0.1\lambda_0$. First angle **506**, second angle **508**, third angle **900**, and fourth angle **902** are defined relative to a common axis, up direction **500**, that is parallel to radial plane **234**. In the illustrative embodiment of FIGS. 8 and 9, slot angle **912** and reflector slot angle **510** are equal though in an alternative embodiment, slot angle **912** and reflector slot angle **510** may not be equal.

Referring to FIG. 10, a simulated SAR pattern formed by third antenna **100c** is shown in accordance with an illustrative embodiment in the x-y plane, where y is in radial plane **234** and x is in axial direction **232**. The SAR pattern was normalized to its associated maximum value. For operation at 7 GHz, third antenna **100c** was selected to have antenna length **216** equal to 7 mm, reflector length **402** equal to 9 mm, slot length **824** equal to 4 mm, and coaxial section length **812** equal to 1 mm. The simulated results assumed egg white as the medium of operation of third antenna **100c**. The dimensions of third antenna **100c** were optimized in CST Studio to minimize the SAR values behind reflector wall **400**.

A -5 decibel (dB) curve **1000** shows a SAR level reduced by 5 dB. A -15 dB curve **1002** shows a SAR level reduced by 15 dB. A -25 dB curve **1004** shows a SAR level reduced by 25 dB. Third antenna **100c** and coaxial cable **102** are shown for reference. Third antenna **100c** and coaxial cable **102** create a more asymmetric SAR pattern with a radiation that is decreased further behind (negative y-axis values) reflector wall **400** relative to the results shown in FIG. 6 for second antenna **100b**. A -15 dB SAR contour is absent behind reflector wall **400** of third antenna **100c**. A maximum normalized SAR value behind reflector wall **400** of third antenna **100c** is reduced by 5 dB compared to second antenna **100b** showing the efficacy of using slot **821** in enhancing a directionality of third antenna **100c**. Moreover, comparing the SAR pattern of the axisymmetric monopole antenna shown in FIG. 3 for first antenna **100a** and that shown in FIG. 10 for third antenna **100c** reveals two important differences. First, third antenna **100c** is capable of producing a highly directional SAR pattern. Second, third antenna **100c** can suppress the unwanted currents flowing on an outer surface of insulating jacket **206** of coaxial cable **102** without a need for a coaxial balun. This eliminates the need for using a balun and thus, results in a reduction in an overall diameter and invasiveness of third antenna **100c**.

Referring to FIG. 11, a simulated electric field direction in a near field region formed by third antenna **100c** operating at 7 GHz is shown in accordance with an illustrative embodiment in the x-y plane. The simulated electric field is shown for third antenna **100c** with antenna length **216** selected as 0 mm, reflector length **402** selected as 9 mm, slot length **824** selected as 4 mm, coaxial section length **812** selected as 1 mm. The simulated electric field direction is shown using a normalized dB scale (with respect to its corresponding maximum value) for the electric field. A main radiation from third antenna **100c** comes from the slot formed by slot wall section **802**. As can be seen, the direction of the electric field below reflector wall **400** is opposite to that shown in FIG. 7 in a region in a vicinity of a tip of reflector wall **400**.

Referring to FIG. 12, -10 dB SAR patterns at base **208** of third antenna **100c** in the x-z plane are shown in accordance with an illustrative embodiment. A first curve **1200** shows a -10 dB SAR level for slot angle **912** and reflector slot angle **510** equal to 90° (slot wall **820** forming an angle of 270°). A second curve **1202** shows a -10 dB SAR level for slot angle **912** and reflector slot angle **510** equal to 180° (slot wall **820** forming an angle of 180°). A third curve **1204** shows a -10 dB SAR level for slot angle **912** and reflector slot angle **510** equal to 270° (slot wall **820** forming an angle of 90°). A fourth curve **1206** shows a -10 dB SAR level for slot angle **912** and reflector slot angle **510** equal to 350° (slot wall **820** forming an angle of 10°).

Referring to FIG. 13, a simulated reflection coefficient, $|S_{11}|$, curve **1300** of third antenna **100c** without a matching network is shown in accordance with an illustrative embodiment. The presence of reflector wall **400** behind and in close proximity to antenna conductor **209** reduces a feed point impedance of third antenna **100c** degrading the impedance matching. As shown at an operating frequency **1302** of 7 GHz, this low input impedance corresponds to an $|S_{11}|$ value of ~ -1.17 dB. To solve this problem, an internal impedance matching structure can be employed.

For example, referring to FIGS. 14A and 14B, a fourth antenna system **230d** is shown in accordance with an illustrative embodiment. Fourth antenna system **230d** may include coaxial cable **102**, an impedance matching structure **1400**, and third antenna **100c**. Impedance matching structure **1400** is configured to match an impedance of coaxial cable **102** to an impedance of third antenna **100c**. Impedance matching structure **1400** is connected between coaxial cable **102** and a proximal end of third antenna **100c**.

Impedance matching structure **1400** may include a first low impedance section **1401**, a high impedance section **1402**, and a second low impedance section **1404**. In the illustrative embodiment, first low impedance section **1401** is identical to coaxial cable **102**. In another illustrative embodiment, first low impedance section **1401** is identical to second low impedance section **1404**. Impedance matching structure **1400** may be formed from an extension of coaxial cable **102**. High impedance section **1402** is connected between first low impedance section **1401** and second low impedance section **1404**. First low impedance section **1401** is connected between high impedance section **1402** and third antenna **100c**. Second low impedance section **1404** is connected between high impedance section **1402** and coaxial cable **102**.

First low impedance section **1401** may be formed of a section of coaxial cable **102** having a first low impedance section length **1414**. First low impedance section **1401** may include a first low impedance section center conductor **1406** extending a length of first low impedance section length

1414, a first low impedance section dielectric material **1408** surrounding first low impedance section center conductor **1406** extending a length of first low impedance section length **1414**, a first low impedance section conductive shield **1410** surrounding first low impedance section dielectric material **1408** along the length of first low impedance section length **1414**, and a first low impedance section insulating jacket **1412** surrounding first low impedance section conductive shield **1410** along the length of first low impedance section length **1414**.

Second low impedance section **1404** may be formed of a section of coaxial cable **102** having a second low impedance section length **1434**. Second low impedance section **1404** may include a second low impedance section center conductor **1426** extending a length of second low impedance section length **1434**, a second low impedance section dielectric material **1428** surrounding second low impedance section center conductor **1426** extending a length of second low impedance section length **1434**, a second low impedance section conductive shield **1430** surrounding second low impedance section dielectric material **1428** along the length of second low impedance section length **1434**, and a second low impedance section insulating jacket **1432** surrounding second low impedance section conductive shield **1430** along the length of second low impedance section length **1434**. Second low impedance section conductive shield **1430** has a conductor width **1438**. Second low impedance section dielectric material **1428** has a dielectric width **1440**.

High impedance section **1402** may be formed of a section of coaxial cable **102** having a high impedance section length **1424**. High impedance section **1402** may include a high impedance section center conductor **1416** extending a length of high impedance section length **1424**, a high impedance section dielectric material **1418** surrounding high impedance section center conductor **1416** extending a length of high impedance section length **1424**, a high impedance section conductive shield **1420** surrounding high impedance section dielectric material **1418** along the length of high impedance section length **1424**, and a high impedance section insulating jacket **1422** surrounding high impedance section conductive shield **1420** along the length of high impedance section length **1424**.

In an illustrative embodiment, high impedance section **1402** is identical to first low impedance section **1401** except that first low impedance section dielectric material **1408** has been replaced with a different dielectric material that has a lower relative permittivity such as air. Second low impedance section **1404** may be formed by inserting a hollow copper tube in the region between center conductor **200** of coaxial cable **102** and outer conductor **204** of coaxial cable **102**, effectively reducing the width of region **202**. The hollow copper tube forms a new outer conductor with a reduced inner diameter.

High impedance section dielectric material **1418** has a width **1436** that may be equal to a width of first low impedance section dielectric material **1408**. A sum of conductor width **1438** and dielectric width **1440** may be equal to width **1436** of high impedance section dielectric material **1418**.

Removing low impedance section dielectric material **1408** reduces a capacitance per unit length of impedance matching structure **1400** and increases its characteristic impedance. A short transmission line with a high impedance can be modeled as a series inductor. On the other hand, second low impedance section **1404** may be implemented by decreasing an inner diameter of conductive shield **204** of coaxial cable **102** such that conductor width **1438** is larger

for second low impedance section conductive shield **1430** than for conductive shield **204** of coaxial cable **102**, which increases the capacitance per unit length of the line and decreases its characteristic impedance. A short section of a transmission line with a low characteristic impedance is equivalent to a parallel capacitor. Therefore, impedance matching structure **1400** is equivalent to a series inductor (high impedance section **1402**) sandwiched by two parallel capacitors (first low impedance section **1401** and second low impedance section **1404**). The values of a first capacitance for first low impedance section **1401**, of an inductance for high impedance section **1402**, and second capacitance for second low impedance section **1404** are chosen to provide an impedance match between third antenna **100c** and coaxial cable **102**.

In an illustrative embodiment, first low impedance section length **1414**, high impedance section length **1424**, and second low impedance section length **1434** may be calculated using the parameters defined for third antenna **100c** operating at 7 GHz and finely tuned using full wave EM simulations in CST Microwave Studio® or another EM simulation tool. Referring to FIG. 15, a simulated input impedance, $|S_{11}|$, curve **1500** of third antenna **100c** with impedance matching structure **1400** is shown in accordance with an illustrative embodiment. First low impedance section length **1414** was selected as 4 mm, high impedance section length **1424** was selected as 12 mm, second low impedance section length **1434** was selected as 7 mm, and conductor width **1438** was selected as 0.898 mm computed using $0.5 \cdot (1.678 - 0.78)$.

Third antenna **100c** was fabricated and used to perform ablation experiments in egg white. A signal generator (HP 8350B sweep oscillator) was used to produce a 7.05 GHz continuous-wave signal. The generated signal was fed to a power amplifier (IFI T186-50 TWT amplifier), the output of which was fed to impedance matching structure **1400** using a 40 centimeter (cm) long coaxial cable **102**. Ablation experiments were conducted at a power level of 20 W for a duration of 5 minutes. During the experiments, a reflected power back towards the power amplifier was monitored. The maximum reflected power during the entire ablation procedure was observed to be less than one W indicating that third antenna **100c** maintained a good impedance match throughout the entire ablation process as dielectric constant of the medium (egg white) changed.

A pre-ablation measured reflection coefficient, $|S_{11}|$, curve **1502** of third antenna **100**, and a post-ablation measured reflection coefficient, $|S_{11}|$, curve **1504** of third antenna **100c** are shown in FIG. 15. The small differences between simulated reflection coefficient, $|S_{11}|$, curve **1500**, pre-ablation measured reflection coefficient, $|S_{11}|$, curve **1502**, and post-ablation measured reflection coefficient, $|S_{11}|$, curve **1504** can be attributed to errors that mostly arise in fabrication of impedance matching structure **1400**, as well as uncertainties in a precise value of a dielectric constant of egg white and the changes of the dielectric constant of the egg white that occur during ablation.

The results confirm that third antenna **100c** is well-matched at 7.0 GHz using impedance matching structure **1400** because a low $|S_{11}|$ of ~ 20 dB is obtained. Additionally, third antenna **100c** has a relatively narrow bandwidth of $\sim 1.8\%$, which is a fairly narrow bandwidth due to the large impedance mismatch. This, however, does not pose a practical limitation for using third antenna **100c** in MWA applications because MWA is performed at a single frequency.

Referring to FIG. 16, a simulated x-y ablation zone **1600** of third antenna **100c** in the x-y plane in egg white at a power

level of 20 W after 5 minutes of ablation is shown in accordance with an illustrative embodiment. Referring to FIG. 17, a simulated x-z ablation zone **1700** of third antenna **100c** in the x-z plane in egg white at a power level of 20 W after 5 minutes of ablation in accordance with an illustrative embodiment. As shown in FIG. 16, simulated x-y ablation zone **1600** is highly directional in the x-y plane (the plane of asymmetry) while simulated x-z ablation zone **1700** is symmetric in the x-z plane. To quantify a degree of directionality of simulated x-y ablation zone **1600**, a first distance **1602** is compared to a second distance **1604**. First distance **1602** and second distance **1604** are the distances between the edges of simulated x-y ablation zone **1600** and a center of third antenna **100c** on each side of base **208**. A directionality ratio (DR) of 100% means a completely directional heating pattern while a value of 0% indicates a completely symmetric pattern. For simulated x-y ablation zone **1600**, the DR values are 41% in the x-y plane and 0% and in the x-z plane.

Referring to FIG. 18, a block diagram of a MWA system **1800** is shown in accordance with an illustrative embodiment. MWA system **1800** may include a signal generator **1802**, an amplifier **1804**, a connector **1806**, coaxial cable **102**, and fourth antenna system **230d**. Signal generator **1802** generates an analog signal at the operating frequency selected for third antenna **100c**. A duty cycle of the analog signal may be controlled by signal generator **1802** based, for example, on an ablation zone size and heating rate. The analog signal may be amplified by amplifier **1804**. Connector **1806** connects a second end of coaxial cable **102** opposite impedance matching structure **1400**. The loss through coaxial cable **102** is considered when adjusting the output power level of amplifier **1804** for a desired input power level to third antenna **100c**. Connector **1806** may be a coaxial connector designed to maintain the coaxial form across the connection and having the same impedance as coaxial cable **102**.

Third antenna **100c** exploits a reflector-backed monopole in combination with a semi-annular slot etched in the outer conductor of a feeding coaxial cable **102** to obtain highly directional SAR and heating patterns in which the SAR values in the backward region are 15 dB below the values in the forward region and the lateral expansion of the heating zone in the backward region is approximately 0.4 times that of the forward region. Third antenna **100c** is also capable of producing compact SAR patterns and localized ablation zones without using a coaxial balun. The use of a reflector in close proximity to the radiating monopole deteriorates impedance matching, but can be resolved by using an impedance matching structure.

As understood by a person of skill in the art, at least some of the dimensions described herein are a function of the wavelength and/or characteristics of coaxial cable **102** selected for the MWA antenna system. Additionally, for simplicity of construction some of the width dimensions are illustrated as the same though this is not required. For example, center conductor **200**, slot center conductor **816**, coax section center conductor **804**, and antenna conductor **209** are illustrated in FIG. 8 as having identical widths though this is not required.

Use of directional terms, such as top, bottom, right, left, front, back, upper, lower, horizontal, vertical, behind, etc. are merely intended to facilitate reference to the various surfaces of the described structures relative to the orientations introduced in the drawings and are not intended to be limiting in any manner unless otherwise indicated.

As used in this disclosure, the term "connect" includes join, unite, mount, couple, associate, insert, hang, hold, affix,

attach, fasten, bind, paste, secure, bolt, screw, rivet, pin, nail, clasp, clamp, cement, fuse, solder, weld, glue, form over, slide together, layer, and other like terms. The phrases “connected on” and “connected to” include any interior or exterior portion of the element referenced. Elements referenced as connected to each other herein may further be integrally formed together. As a result, elements described herein as being connected to each other need not be discrete structural elements. The elements may be connected permanently, removably, or releasably.

As used in this disclosure, the term “mount” includes join, unite, connect, couple, associate, insert, hang, hold, affix, attach, fasten, bind, paste, secure, bolt, screw, rivet, pin, nail, clasp, clamp, cement, fuse, solder, weld, glue, form over, slide together, layer, and other like terms. The phrases “mounted on” and “mounted to” include any interior or exterior portion of the element referenced. These phrases also encompass direct connection (in which the referenced elements are in direct contact) and indirect connection (in which the referenced elements are not in direct contact, but are mounted together via intermediate elements). Elements referenced as mounted to each other herein may further be integrally formed together. As a result, elements described herein as being mounted to each other need not be discrete structural elements. The elements may be mounted permanently, removably, or releasably.

The word “illustrative” is used herein to mean serving as an example, instance, or illustration. Any aspect or design described herein as “illustrative” is not necessarily to be construed as preferred or advantageous over other aspects or designs. Further, for the purposes of this disclosure and unless otherwise specified, “a” or “an” means “one or more”. Still further, the use of “and” or “or” is intended to include “and/or” unless specifically indicated otherwise.

The foregoing description of illustrative embodiments of the disclosed subject matter has been presented for purposes of illustration and of description. It is not intended to be exhaustive or to limit the disclosed subject matter to the precise form disclosed, and modifications and variations are possible in light of the above teachings or may be acquired from practice of the disclosed subject matter. The embodiments were chosen and described in order to explain the principles of the disclosed subject matter and as practical applications of the disclosed subject matter to enable one skilled in the art to utilize the disclosed subject matter in various embodiments and with various modifications as suited to the particular use contemplated. It is intended that the scope of the disclosed subject matter be defined by the claims appended hereto and their equivalents.

What is claimed is:

1. An antenna system comprising:

a coaxial cable comprising

a center conductor extending a length of the coaxial cable;

a dielectric material surrounding the center conductor along the length of the coaxial cable; and

a conductive shield surrounding the dielectric material along the length of the coaxial cable;

an antenna comprising

a base connected to the center conductor on a first side of the base; and

an antenna conductor connected to the base on a second side of the base opposite the first side, wherein the antenna conductor extends in an axial direction from the second side of the base, wherein a radial plane through the base is perpendicular to the axial direction;

a reflector wall formed of a conductive material connected to the conductive shield to extend in the axial direction, wherein the reflector wall is separated from the antenna conductor by a second dielectric material in a radial direction relative to the antenna conductor, wherein the reflector wall is curved partially around the antenna conductor in the radial direction between a first angle and a second angle when projected into the radial plane; and

a slot wall formed through a portion of the conductive shield to expose the dielectric material between a third angle and a fourth angle when projected into the radial plane, wherein the slot wall is separated from the center conductor by the dielectric material in the radial direction relative to the center conductor,

wherein the first angle, the second angle, the third angle, and the fourth angle are defined relative to a common axis parallel to the radial plane, wherein the first angle is equal to the third angle, and the second angle is equal to the fourth angle.

2. The antenna system of claim 1, wherein the antenna is a monopole antenna.

3. The antenna system of claim 1, wherein the reflector wall has a reflector length in the axial direction defined from the radial plane that is greater than or equal to an antenna length of the antenna conductor in the axial direction defined from the radial plane.

4. The antenna system of claim 3, wherein the antenna length is 0.25λ , where λ is a wavelength at an operating frequency of a signal carried by the center conductor in a medium in which the antenna is selected to operate.

5. The antenna system of claim 3, wherein the reflector length is selected from a range defined between and inclusive of 0.25λ and 0.4λ , where λ is a wavelength at an operating frequency of a signal carried by the center conductor in a medium in which the antenna is selected to operate.

6. The antenna system of claim 1, wherein a distance defined from the radial plane to a closest end of the slot wall is selected from a range defined between and inclusive of 0.004λ and 0.1λ , where λ is a wavelength at an operating frequency of a signal carried by the center conductor in a medium in which the antenna is selected to operate.

7. The antenna system of claim 6, wherein the operating frequency is greater than or equal to 500 megahertz and less than or equal to 30 gigahertz.

8. The antenna system of claim 1, wherein a length of the slot wall defined parallel to the axial direction is selected from a range defined between and inclusive of 0.01λ and 0.25λ , where λ is a wavelength at an operating frequency of a signal carried by the center conductor in a medium in which the antenna is selected to operate.

9. The antenna system of claim 1, wherein an angular difference between the first angle and the second angle in the radial plane is between 10 degrees and 350 degrees.

10. The antenna system of claim 1, wherein an angular difference between the third angle and the fourth angle in the radial plane is between 10 degrees and 350 degrees.

11. The antenna system of claim 1, wherein the second dielectric material includes a coating on the antenna conductor.

12. The antenna system of claim 11, wherein the second dielectric material further includes air between the coating and the reflector wall.

13. The antenna system of claim 1, wherein an insulating material surrounds the conductive shield along the length of

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the coaxial cable and the reflector wall, covers a slot formed by the slot wall, and covers a reflector slot formed by the reflector wall.

14. The antenna system of claim 1, wherein the base and the antenna conductor are extensions of the center conductor of the coaxial cable.

15. The antenna system of claim 1, wherein the reflector wall is an extension of the conductive shield of the coaxial cable.

16. The antenna system of claim 1, further comprising:
 an impedance matching structure formed in the coaxial cable, the impedance matching structure comprising
 a section of the center conductor along a length of the impedance matching structure;
 a second dielectric material surrounding the section of the center conductor along the length of the impedance matching structure; and
 a second conductive shield surrounding the second dielectric material along the length of the impedance matching structure up to an end of the slot wall farthest from the base;

wherein the impedance matching structure is configured to match an impedance of the coaxial cable to an impedance of the antenna.

17. The antenna system of claim 16, wherein the impedance matching structure includes a first low impedance section, a second low impedance section, and a high impedance section between the first low impedance section and the second low impedance section.

18. The antenna system of claim 17, wherein the dielectric material in the high impedance section is different than the dielectric material in the first low impedance section and the dielectric material in the second low impedance section.

19. The antenna system of claim 17, wherein the first low impedance section is positioned between the high impedance section and the slot wall in the axial direction and is identical to the coaxial cable.

20. A microwave ablation system comprising:

an antenna system comprising
 a coaxial cable comprising
 a center conductor extending a length of the coaxial cable;

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a dielectric material surrounding the center conductor along the length of the coaxial cable; and
 a conductive shield surrounding the dielectric material along the length of the coaxial cable;

an antenna comprising
 a base connected to the center conductor on a first side of the base; and

an antenna conductor connected to the base on a second side of the base opposite the first side, wherein the antenna conductor extends in an axial direction from the second side of the base, wherein a radial plane through the base is perpendicular to the axial direction;

a reflector formed of a conductive material connected to the conductive shield to extend in the axial direction, wherein the reflector is separated from the antenna conductor by a second dielectric material in a radial direction relative to the antenna conductor, wherein the reflector is curved partially around the antenna conductor in the radial direction between a first angle and a second angle when projected into the radial plane; and

a slot wall formed through a portion of the conductive shield to expose the dielectric material between a third angle and a fourth angle when projected into the radial plane, wherein the slot wall is separated from the center conductor by the dielectric material in the radial direction relative to the center conductor,

wherein the first angle, the second angle, the third angle, and the fourth angle are defined relative to a common axis parallel to the radial plane, wherein the first angle is equal to the third angle, and the second angle is equal to the fourth angle;

a signal generator configured to generate a signal at a selected operating frequency; and

a connector configured to connect a second end of the coaxial cable opposite the base of the antenna to the signal generator to receive the generated signal.

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