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(54) **DIPOLE ANTENNA FOR MICROWAVE ABLATION**

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H01Q 9/20 (2006.01)
H01Q 9/18 (2006.01)
H01Q 11/08 (2006.01)
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(58) **Field of Classification Search**

CPC H01Q 9/20; H01Q 9/14; H01Q 1/526
See application file for complete search history.

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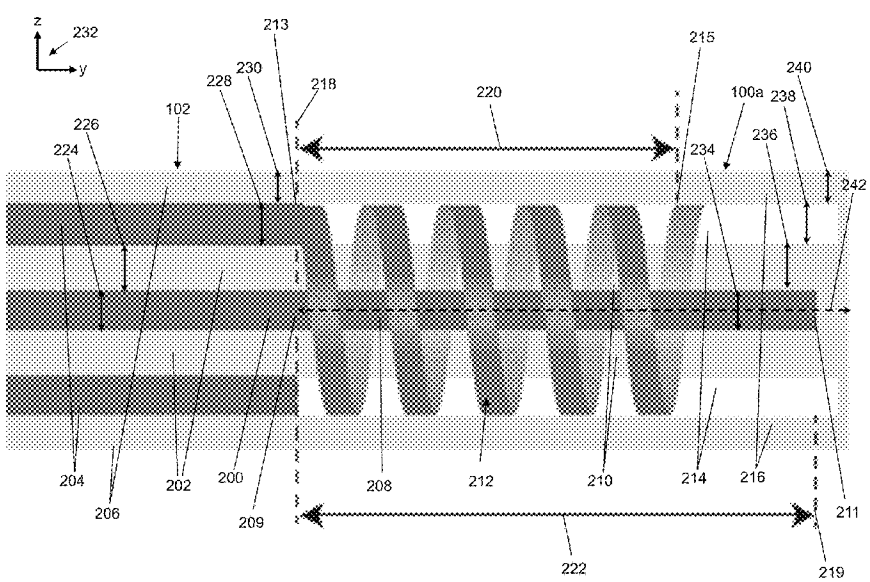
(57) **ABSTRACT**

An antenna includes a first dipole arm and a second dipole arm. The first dipole arm is connected to a first conductor and is formed of a first conducting material. The first dipole arm extends in an axial direction from the first conductor. The second dipole arm is connected to a second conductor that is distinct from the first conductor and is formed of a second conducting material. The second dipole arm extends in the axial direction from the second conductor and is wound around the first dipole arm to form a number of loops. The second dipole arm does not contact the first dipole arm. An axial length of the second dipole arm in the axial direction is less than 90% of an axial length of the first dipole arm in the axial direction.

20 Claims, 16 Drawing Sheets



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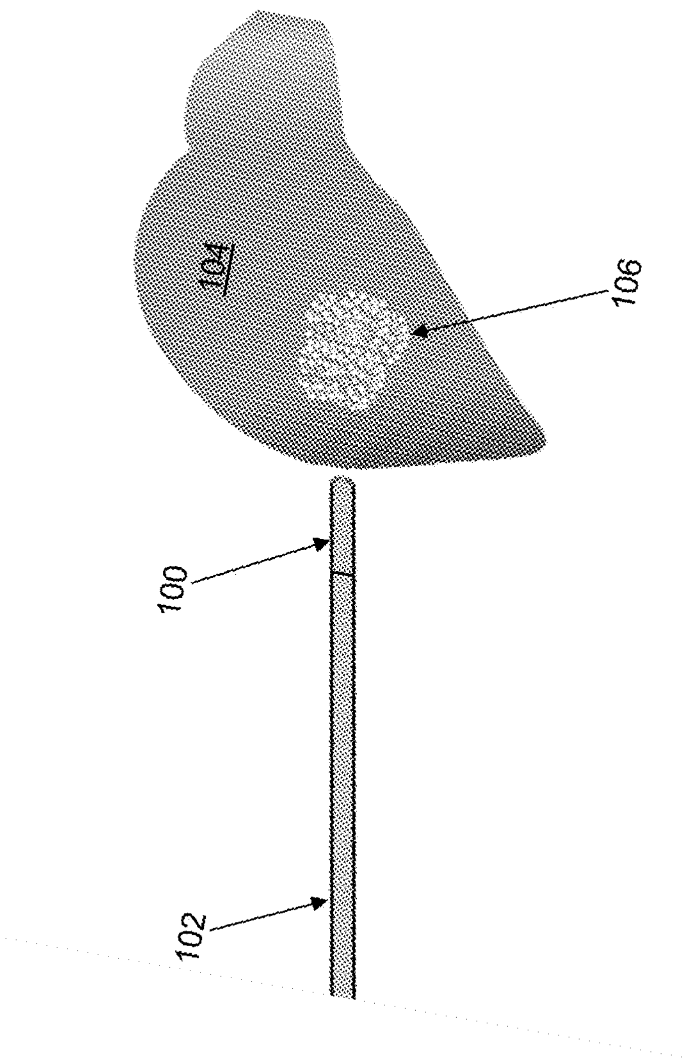
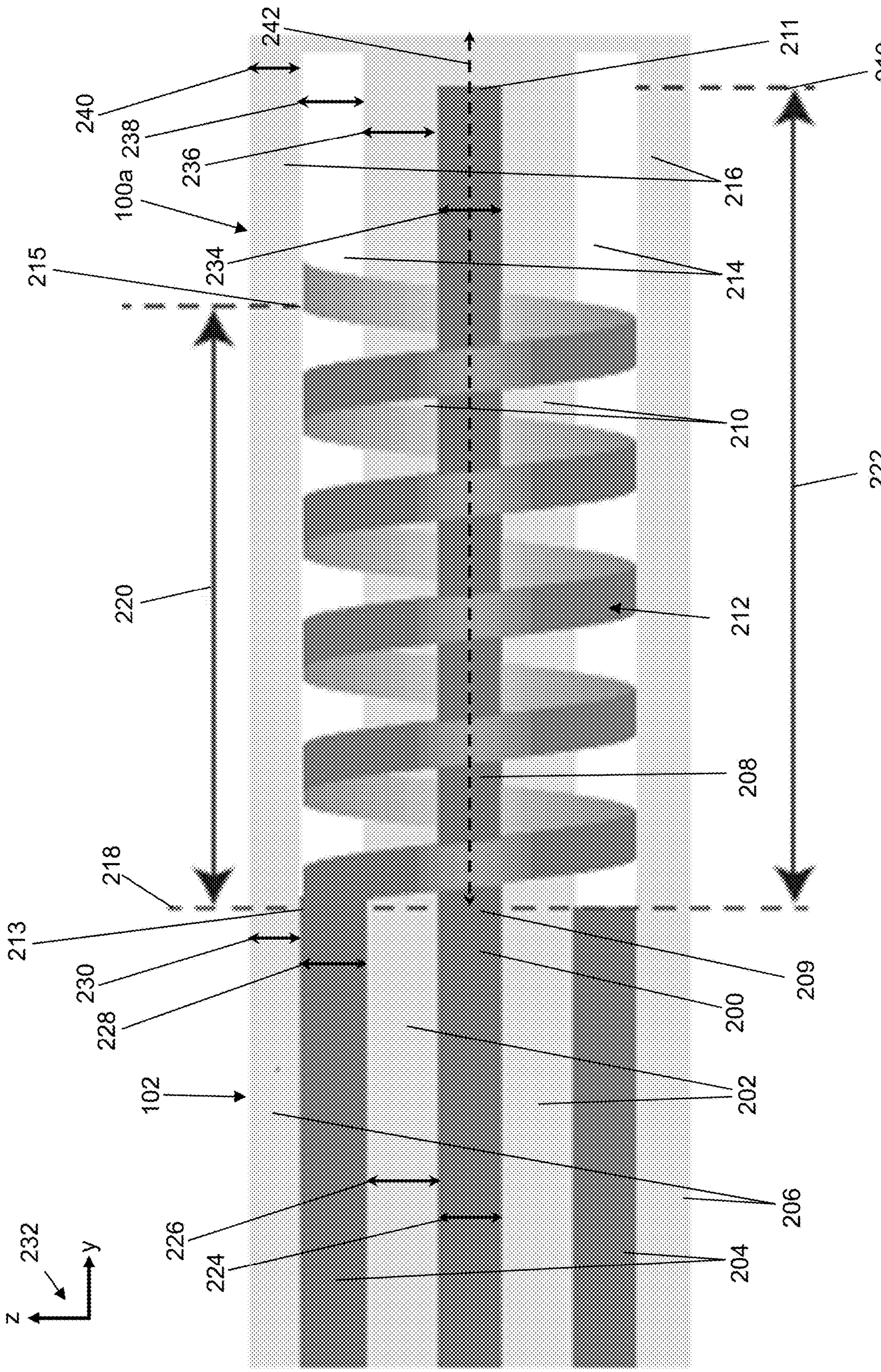


FIG. 1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210
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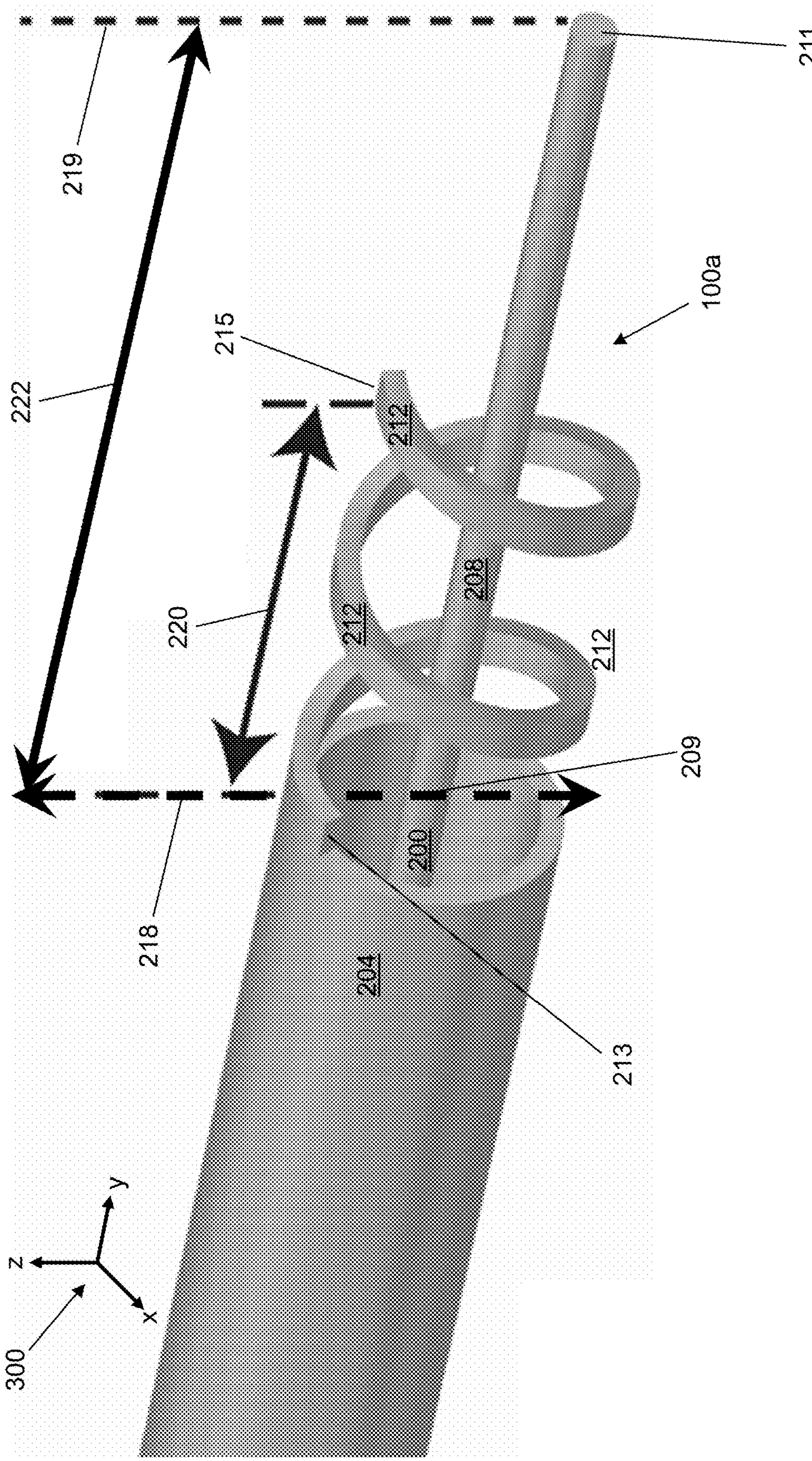
230
200
228
202
102
206
226
224
204
232
z
y

FIG. 2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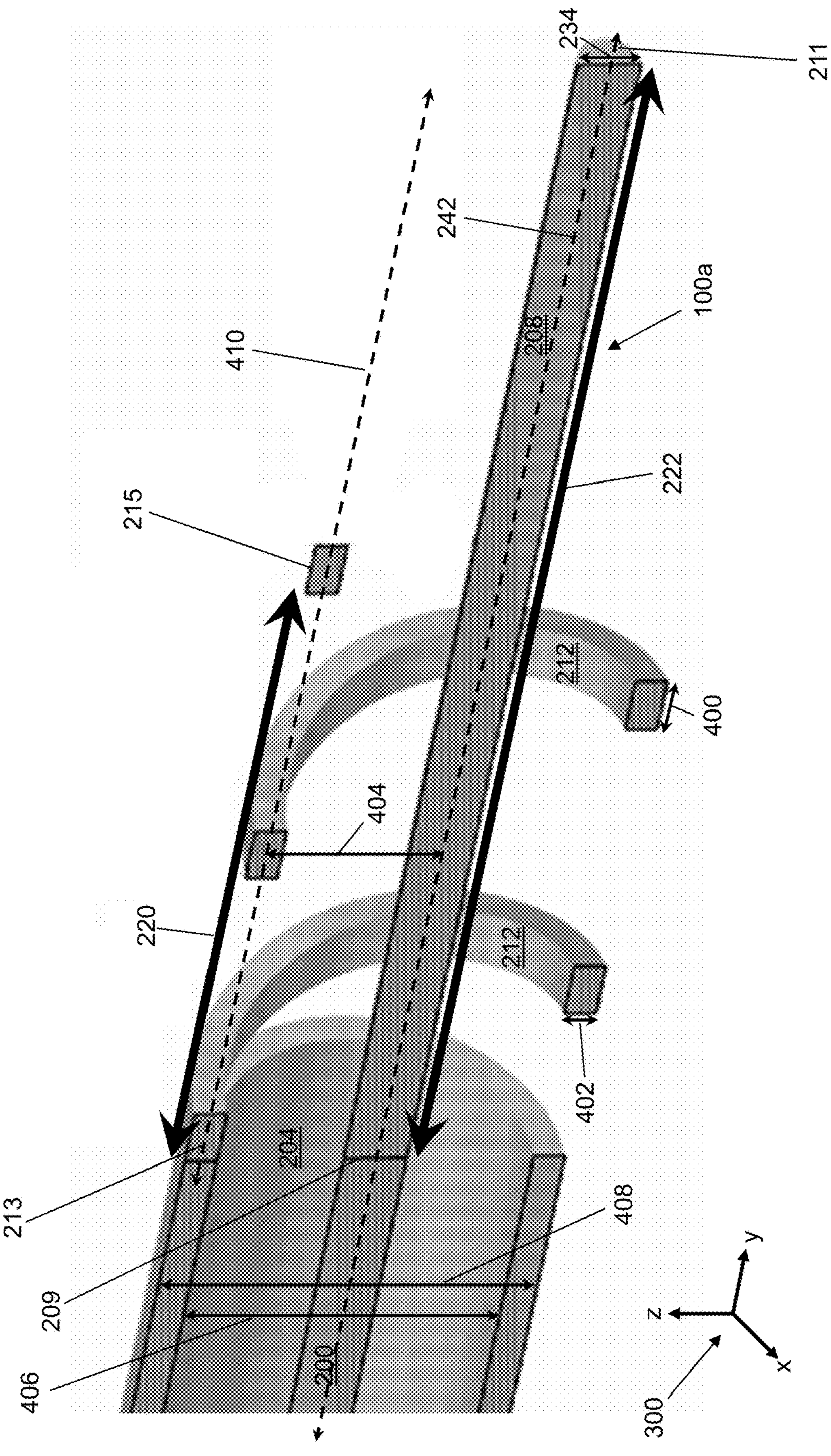
z
y
x

FIG. 3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402
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408
406
200
300
z
y
x

FIG. 4

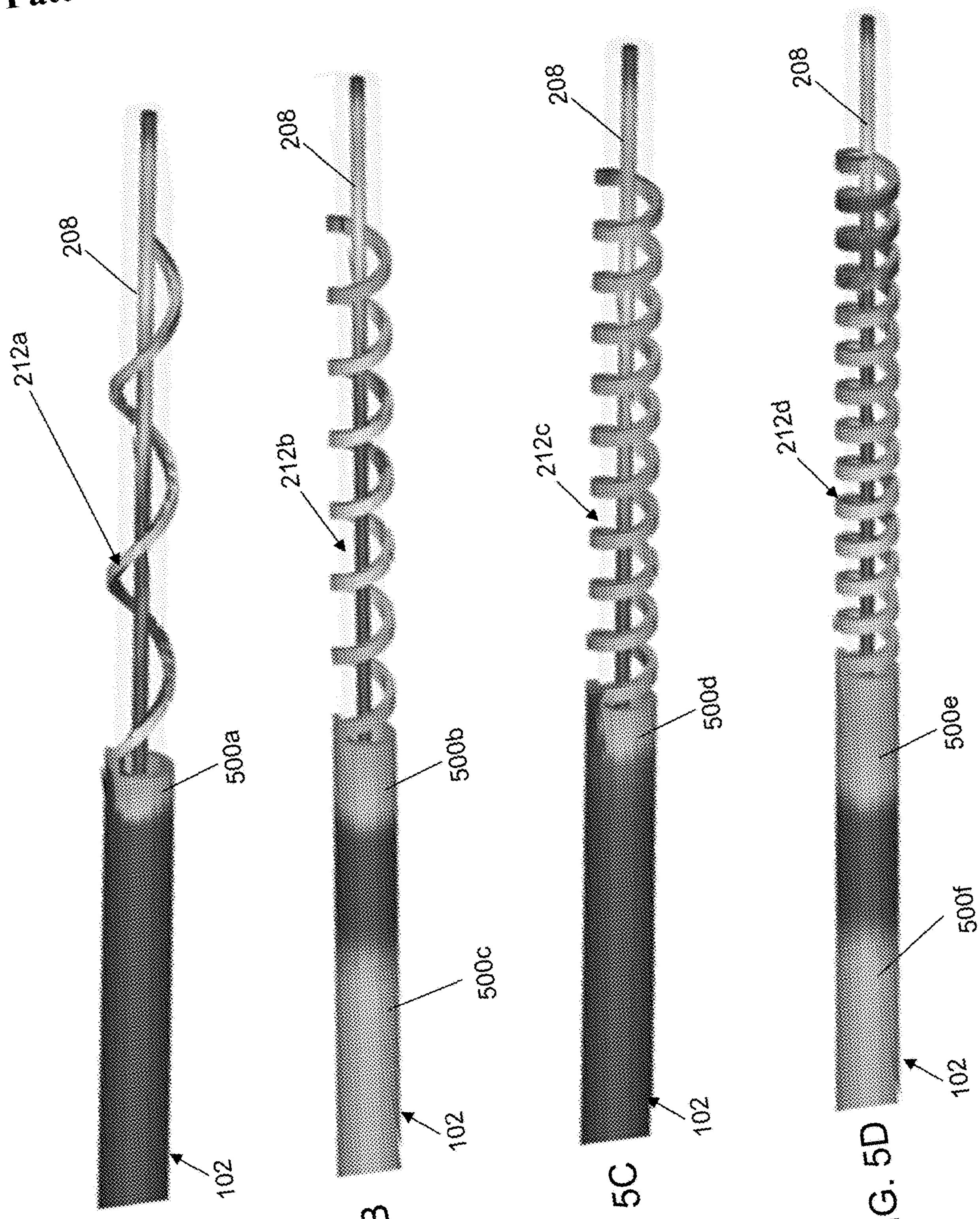


FIG. 5A

FIG. 5B

FIG. 5C

FIG. 5D

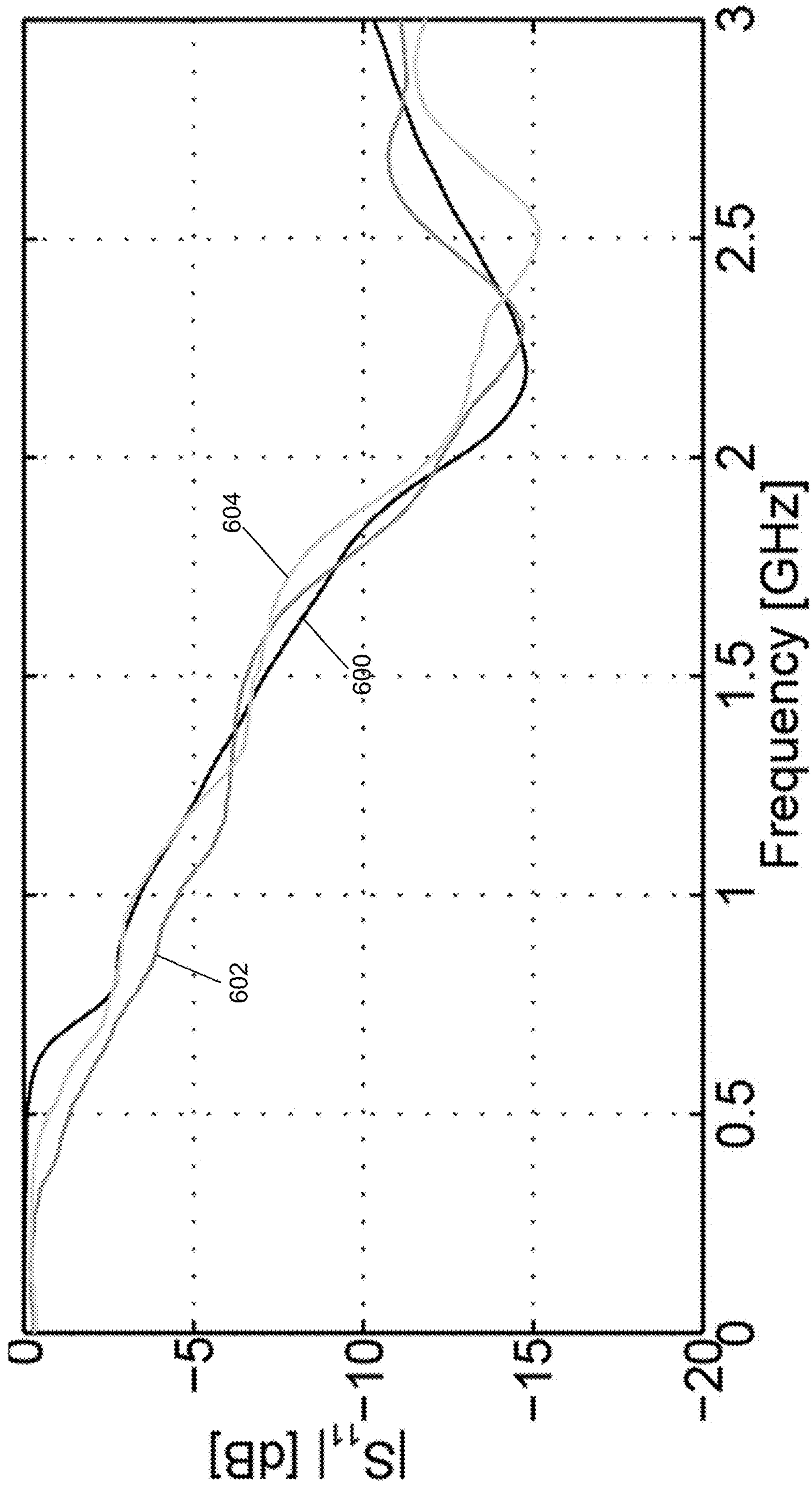
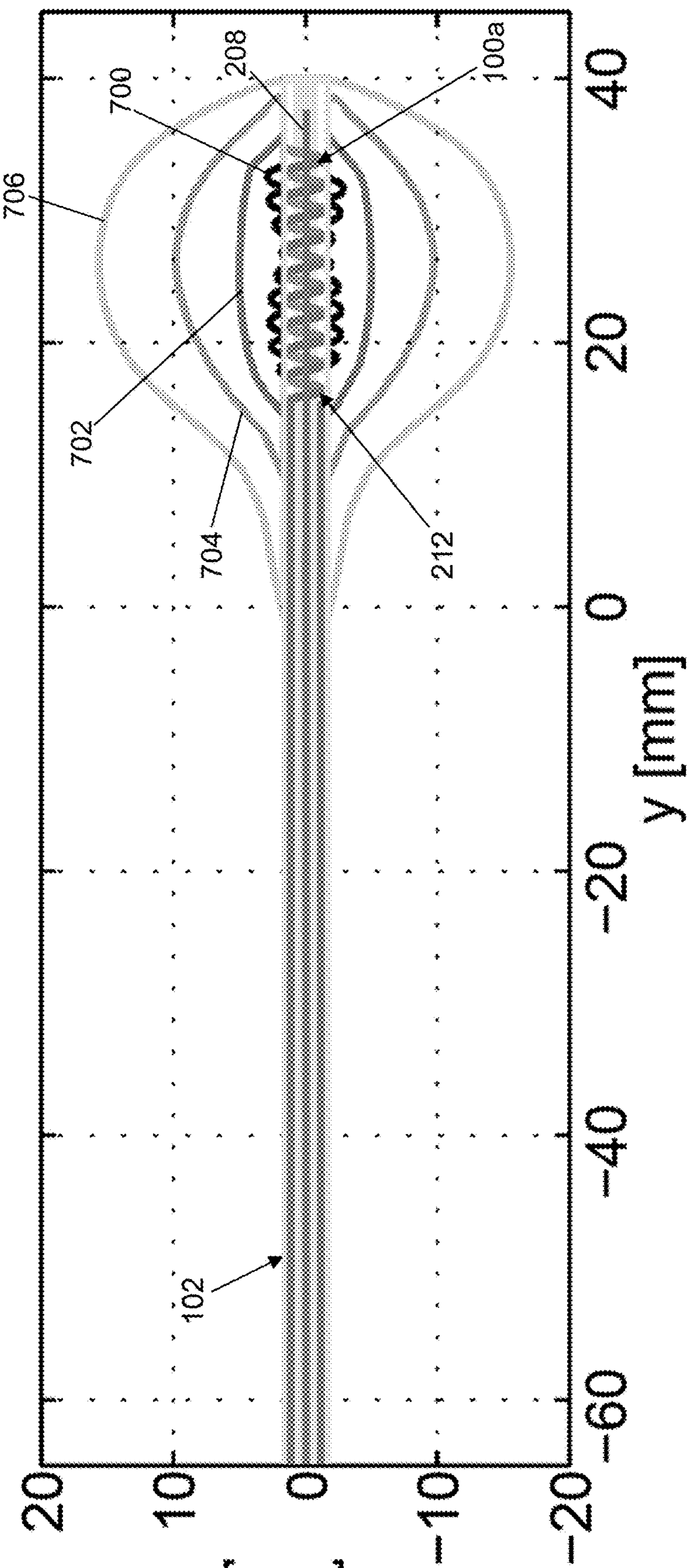


FIG. 6


706
700
208
100a
702
704
212
102
y [mm]
z [mm]
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0
−20
−40
−60
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0
−10
−20

FIG. 7

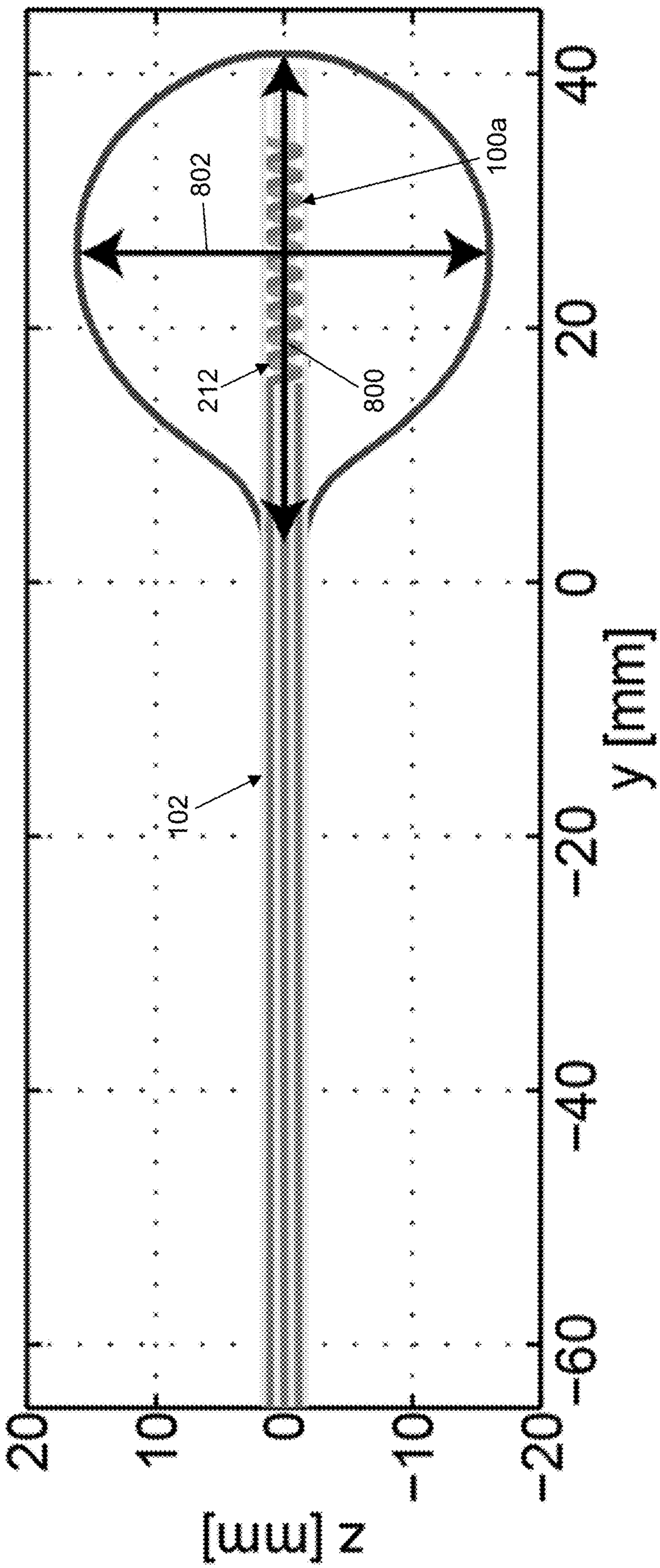


FIG. 8

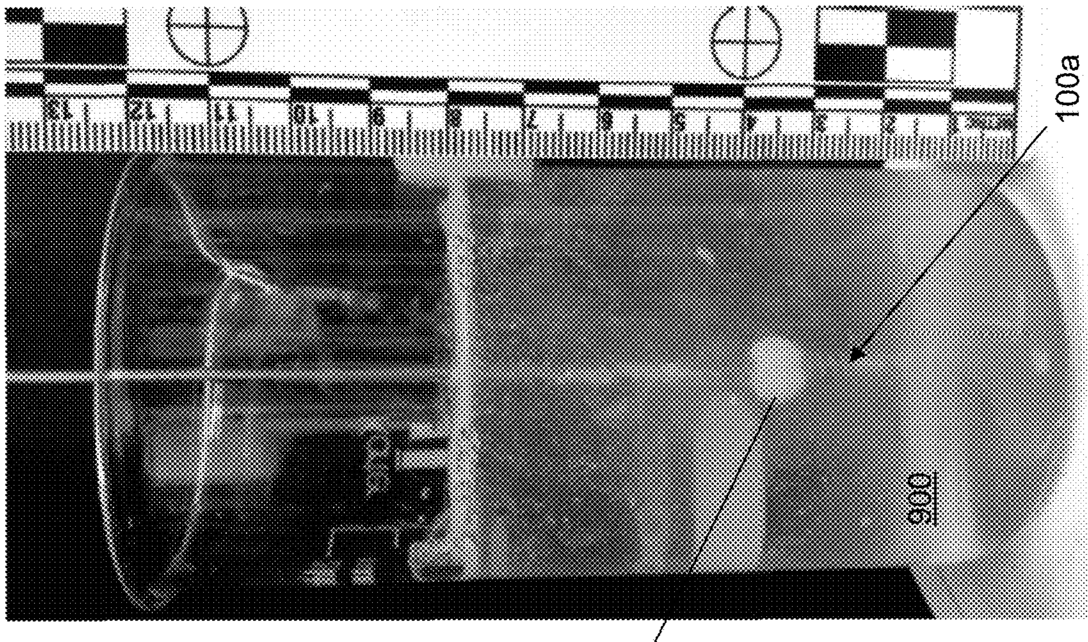


FIG. 9B

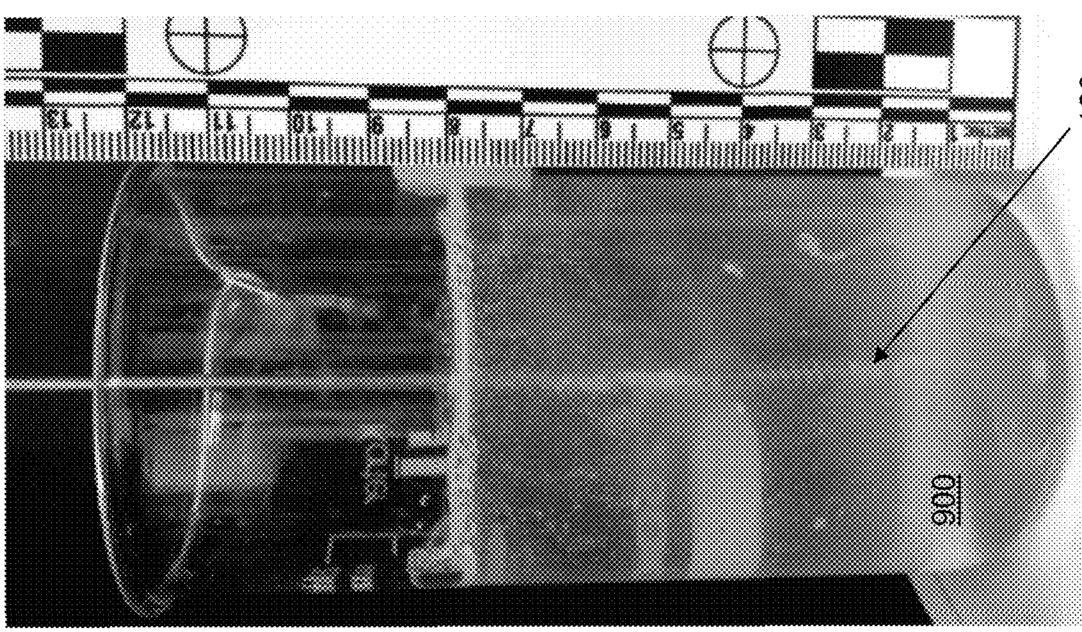


FIG. 9A

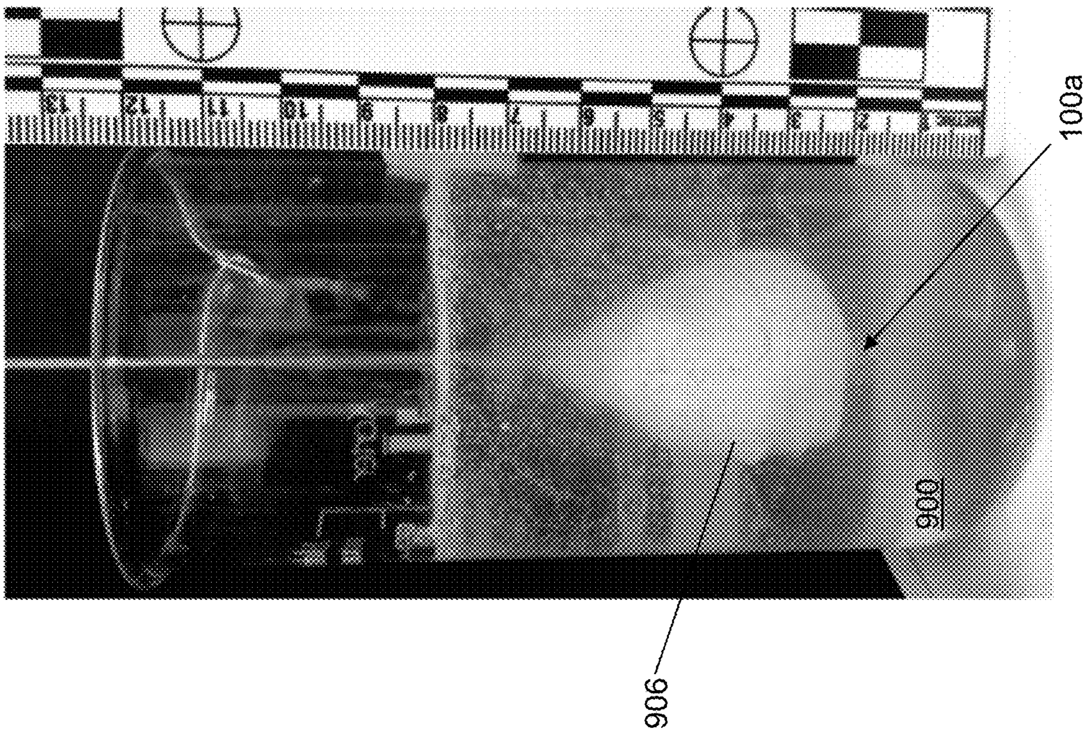


FIG. 9D

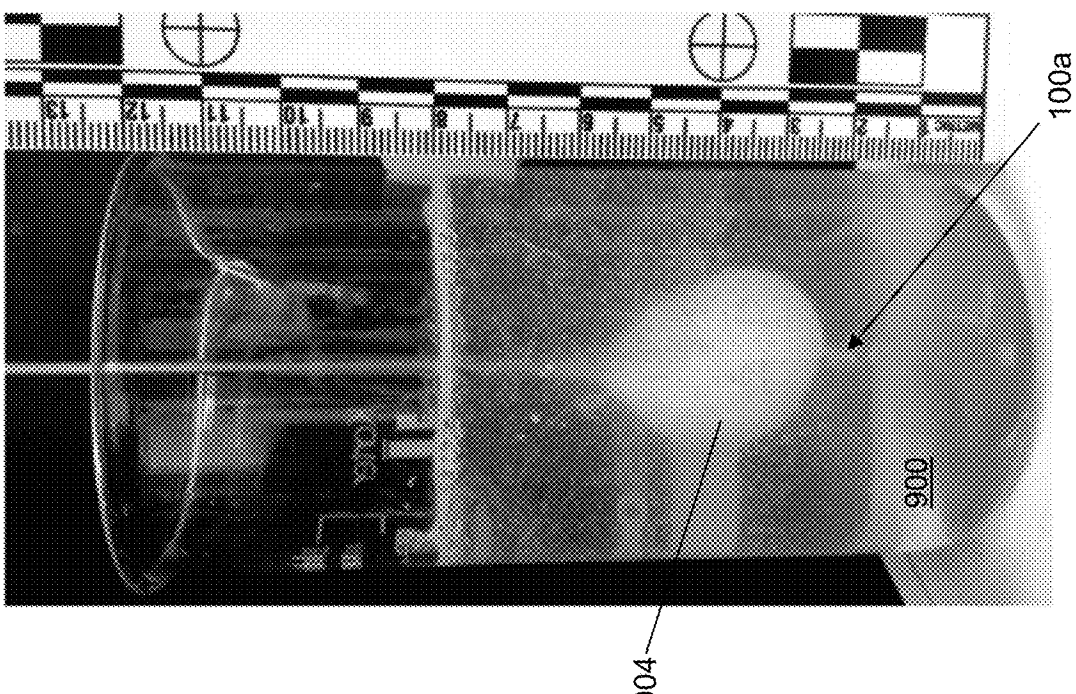


FIG. 9C

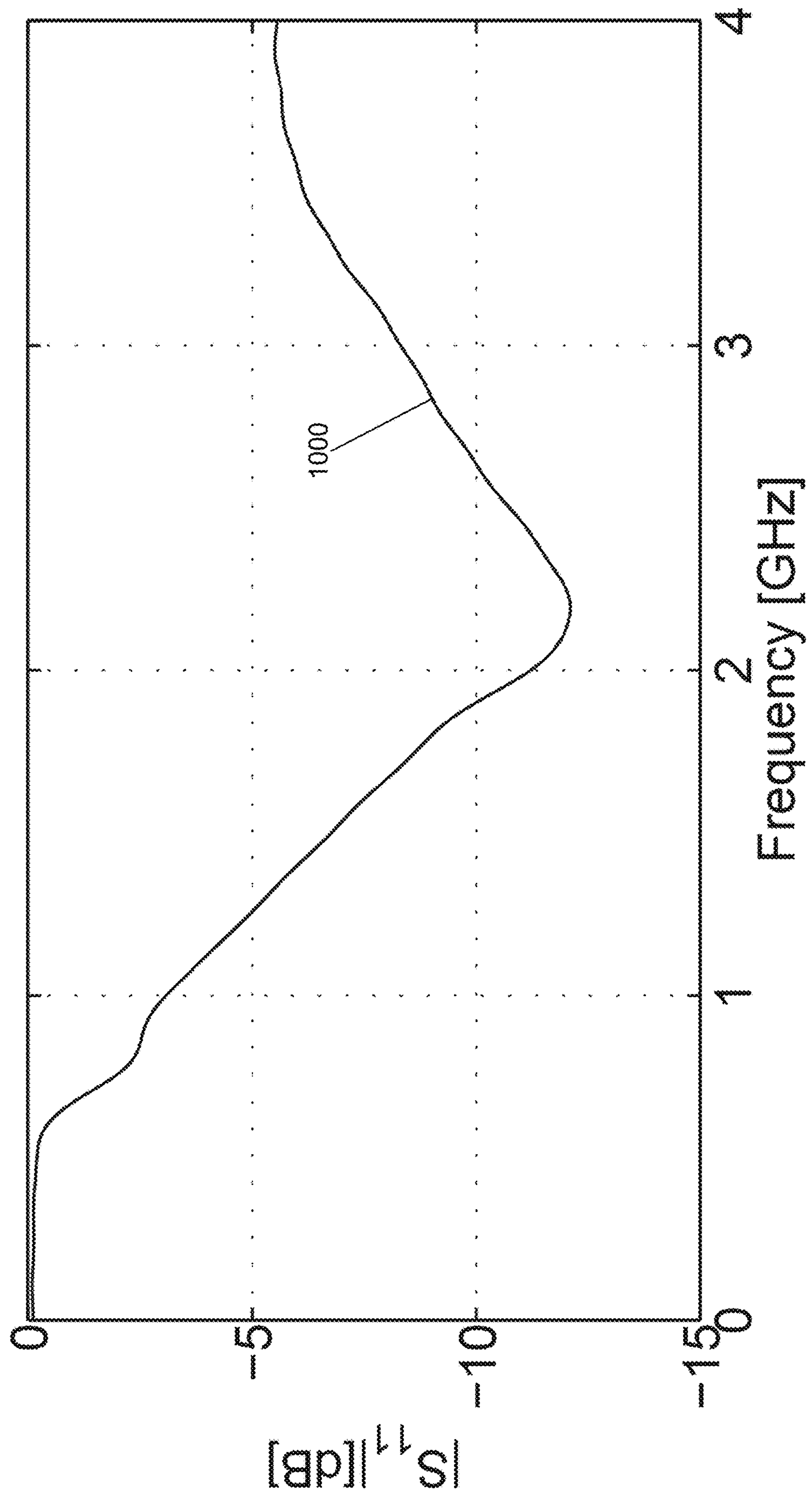


FIG. 10

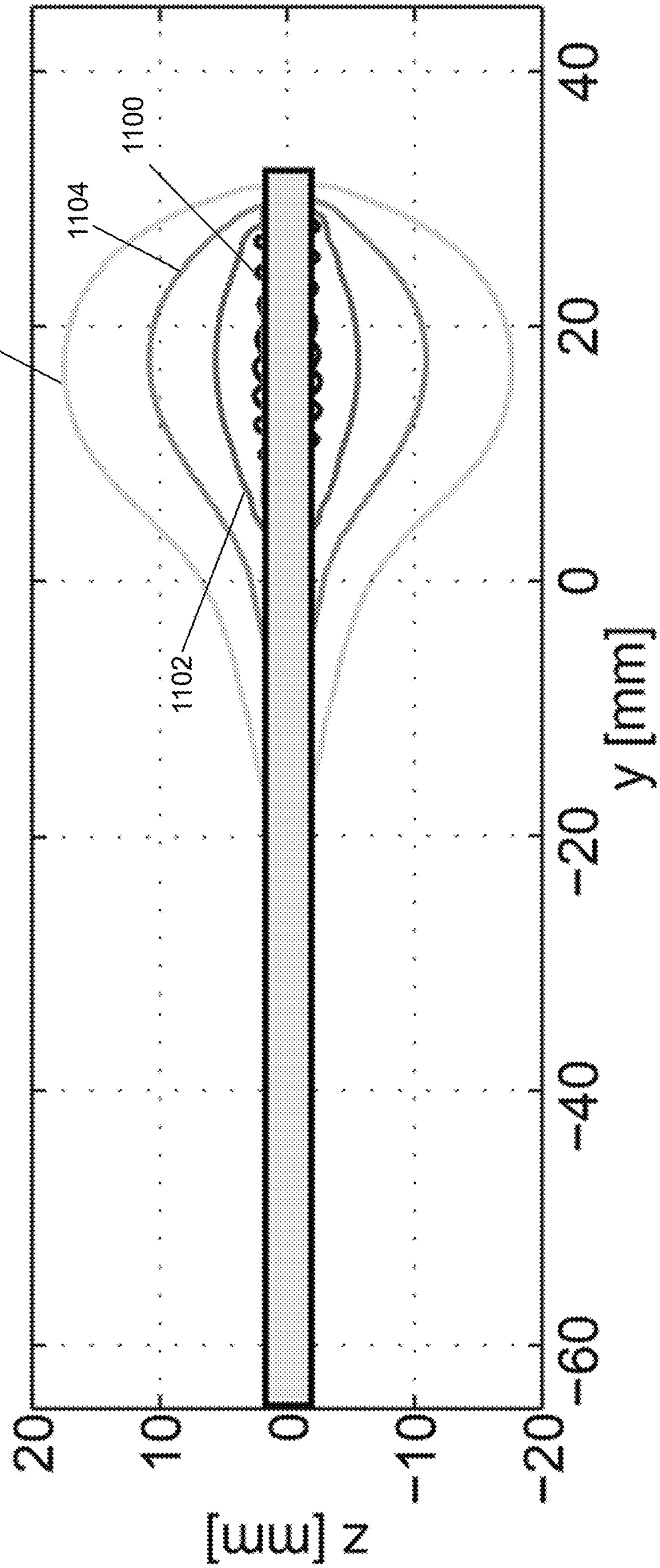
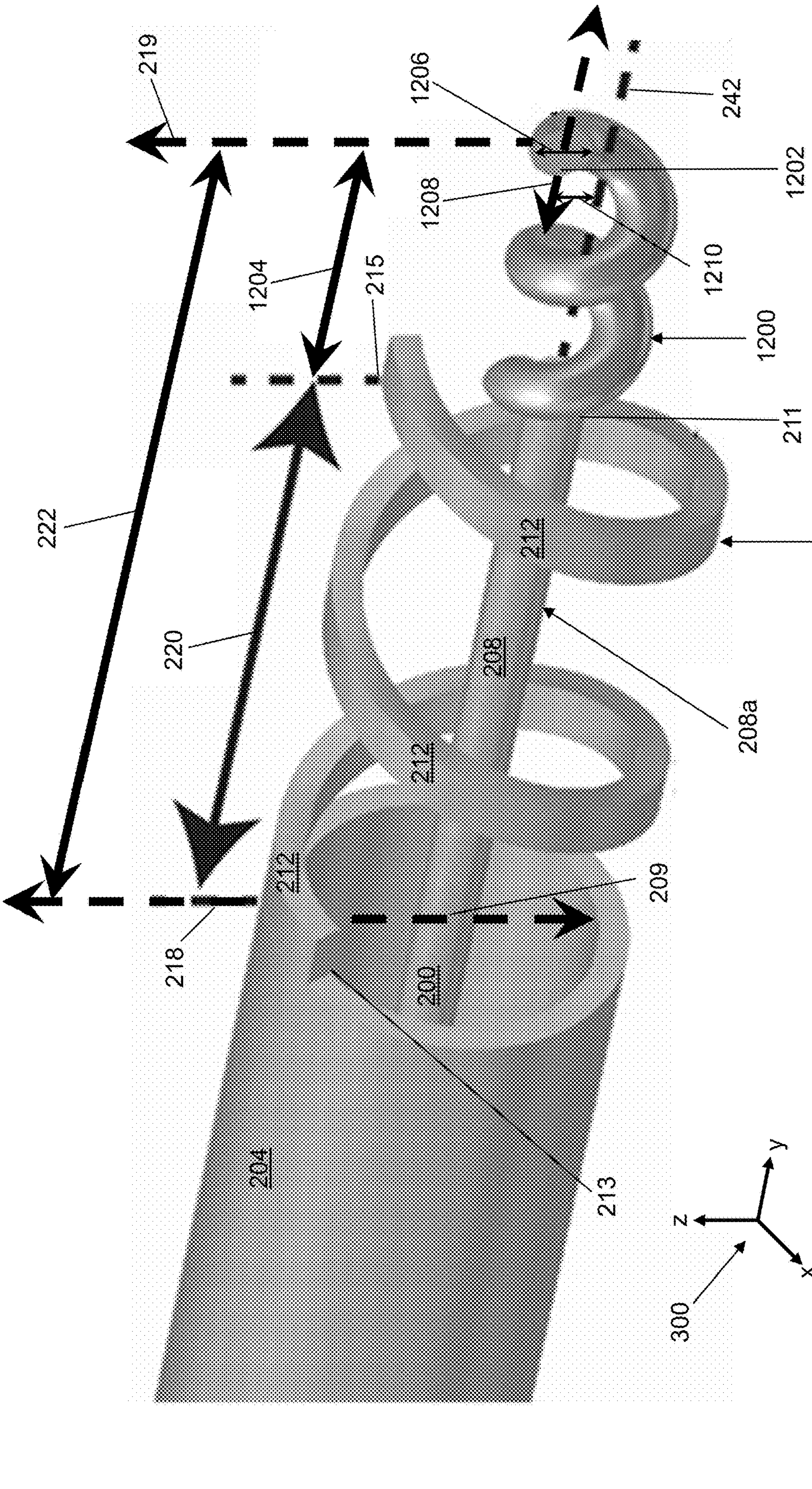


FIG. 11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1204
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204
213
300
z
y
x

FIG. 12

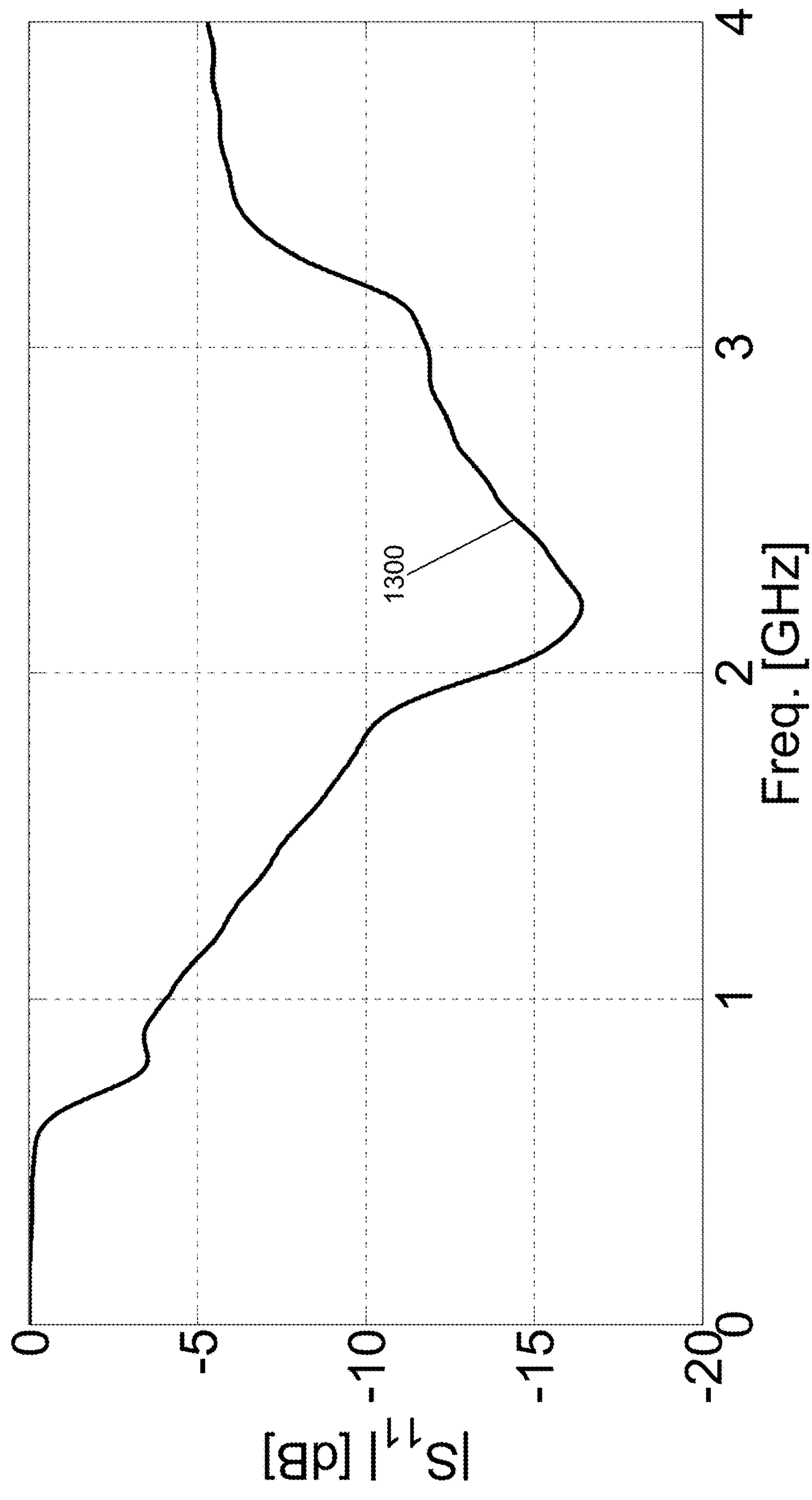

FIG. 13

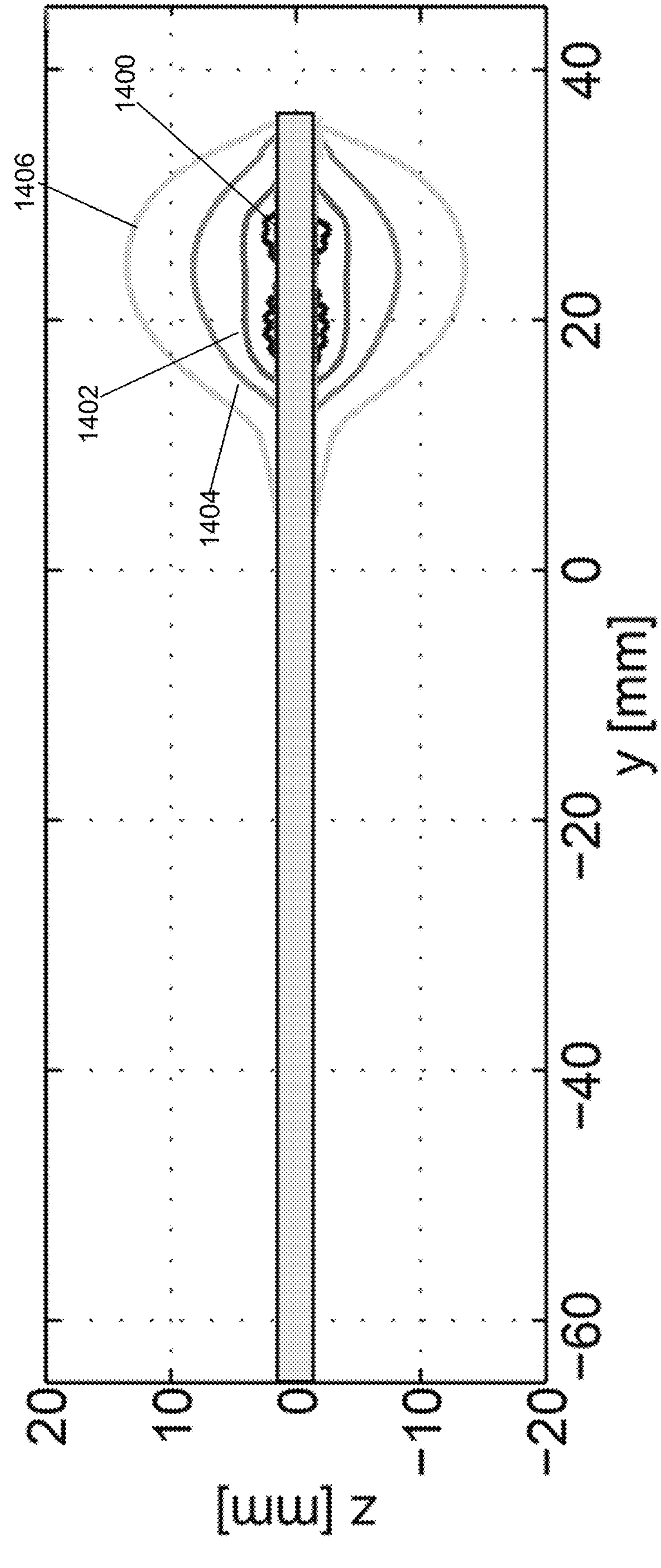

FIG. 14

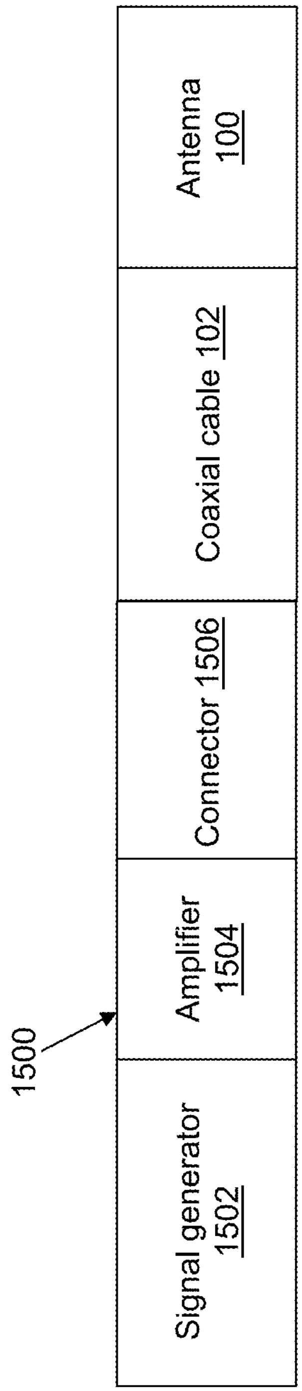
Antenna 100
Coaxial cable 102
Connector 1506
Amplifier 1504
Signal generator 1502
1500

FIG. 15

DIPOLE ANTENNA FOR MICROWAVE ABLATION

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 is known for its quicker patient recovery and fewer complications and can serve as an alternative when surgical resection cannot be applied. 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. In general, a MWA antenna is expected to have a small overall diameter, a low reflection coefficient, and localized specific absorption rate (SAR) and heating patterns.

Most MWA antennas employ coaxial cables as their feed lines. Coaxial cable, however, is an unbalanced structure and current can flow on the outer surface of its outer conductor if the cable is not properly terminated. If not properly suppressed, this current can lead to unwanted heating of the healthy tissue along the insertion path of the antenna along the coaxial cable. This current can also cause the reflection coefficient of the antenna to be dependent on the insertion depth into the tissue.

Coaxial baluns have been the most ubiquitous solution for overcoming problems associated with the unbalanced currents flowing on the outer surface of the outer conductor of the coaxial cables. A coaxial balun is generally implemented by encompassing the outer conductor of the coaxial cable with another conducting cylinder. The inner surface of this extra cylinder and the outer surface of the outer conductor of the coaxial cable form a transmission line. The length of the balun and its termination are chosen such that a very large impedance is seen at the tip of the balun by the unbalanced currents. This high impedance prevents flow of unbalanced currents beyond the tip of the balun and greatly reduces the level of unwanted heating along the shaft of the antenna. While coaxial baluns help the antenna in providing a fairly localized SAR pattern, they increase the overall diameter and, as a result, the invasiveness of the MWA antenna.

A sector of the outer conductor of the coaxial cable along with its inner conductor may be extended beyond the feed point. These two extended conductors act as two arms of a dipole antenna, where each arm of the dipole may be a quarter of a wavelength long. Since currents flowing on the arms of this dipole antenna oppose each other, a very low

feed point impedance is achieved. This very low feed point impedance almost shorts the current at the feed point and prevents its flow on the outer surface of the outer conductor. However, while unwanted current is effectively suppressed, the impedance match is poor requiring an impedance matching structure.

SUMMARY

In an example embodiment, an antenna is provided that includes, but is not limited to, a first dipole arm and a second dipole arm. The first dipole arm is connected to a first conductor and is formed of a first conducting material. The first dipole arm extends in an axial direction from the first conductor. The second dipole arm is connected to a second conductor that is distinct from the first conductor and is formed of a second conducting material. The second dipole arm extends in the axial direction from the second conductor and is wound around the first dipole arm to form a number of loops. The second dipole arm does not contact the first dipole arm. An axial length of the second dipole arm in the axial direction is less than 90% of an axial length of the first dipole arm in the axial direction

In another example embodiment, an antenna system is provided that includes, but is not limited to, a coaxial cable and an antenna. 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 a first dipole arm and a second dipole arm. The first dipole arm is connected to the center conductor and is formed of a first conducting material. The first dipole arm extends in an axial direction from the center conductor. The second dipole arm is connected to the conductive shield that is distinct from the center conductor and is formed of a second conducting material. The second dipole arm extends in the axial direction from the conductive shield and is wound around the first dipole arm to form a number of loops. The second dipole arm does not contact the first dipole arm. An axial length of the second dipole arm in the axial direction is less than 90% of an axial length of the first dipole arm in the axial direction.

In yet another example embodiment, a microwave ablation system is provided that includes, but is not limited to, a coaxial cable, an antenna, a signal generator, and a connector. 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 a first dipole arm and a second dipole arm. The first dipole arm is connected to the center conductor and is formed of a first conducting material. The first dipole arm extends in an axial direction from the center conductor. The second dipole arm is connected to the conductive shield that is distinct from the center conductor and is formed of a second conducting material. The second dipole arm extends in the axial direction from the conductive shield and is wound around the first dipole arm to form a number of loops. The second dipole arm does not contact the first dipole arm. An axial length of the second dipole arm in the axial direction is less than 90% of an axial length of the first dipole arm in the axial direction.

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 view of a first antenna for use in the MWA antenna system of FIG. **1** in accordance with an illustrative embodiment.

FIG. **3** depicts a perspective view of the first antenna of FIG. **2** in accordance with an illustrative embodiment.

FIG. **4** depicts a lengthwise cross-sectional view of the first antenna of FIG. **2** in accordance with an illustrative embodiment.

FIGS. **5**A-**5**D depict perspective views of the first antenna of FIG. **2** with different numbers of turns of a helix portion in accordance with an illustrative embodiment.

FIG. **6** shows a simulated reflection coefficient, $|S_{11}|$, of the first antenna of FIG. **5**C in accordance with an illustrative embodiment.

FIG. **7** shows a simulated, normalized specific absorption rate (SAR) pattern of the first antenna of FIG. **5**C in the y-z plane in accordance with an illustrative embodiment.

FIG. **8** shows a simulated ablation zone of the first antenna of FIG. **5**C in the y-z plane in accordance with an illustrative embodiment.

FIGS. **9**A-**9**D show snapshots of the ablation zone of the first antenna of FIG. **5**C in egg white in accordance with an illustrative embodiment.

FIG. **10** shows a simulated reflection coefficient, $|S_{11}|$, of a modified MWA antenna for comparison.

FIG. **11** shows a simulated, normalized SAR pattern of a modified MWA antenna for comparison.

FIG. **12** depicts a perspective view of second antenna for use in the MWA antenna system of FIG. **1** in accordance with an illustrative embodiment.

FIG. **13** shows a simulated reflection coefficient, $|S_{11}|$, of the second antenna of FIG. **12** in accordance with an illustrative embodiment.

FIG. **14** shows a simulated, normalized SAR pattern of the second antenna of FIG. **12** in the y-z plane in accordance with an illustrative embodiment.

FIG. **15** 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_o. MWA can be used to provide thermal therapy for treatment of various types of cancer **106** in various tissue/organs **104**. Tissue/organs **104** may include liver, kidney, lung, bone, etc. MWA uses microwave frequency in the range 300 megahertz (MHz) to 300 gigahertz (GHz), though 915 MHz and 2.45 GHz are 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 view of a first antenna **100**_a_ is shown in accordance with an illustrative embodiment. With reference to FIG. **3**, a perspective view of first antenna **100**_a_ is shown in accordance with an illustrative embodiment. With reference to FIG. **4**, a lengthwise cross-sectional view of first antenna **100**_a_ is shown in accordance with an illustrative embodiment. First antenna **100**_a_ connects to and extends from coaxial cable **102**.

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**. Insulating jacket **206** may be a catheter in which first antenna **100**_a_ and all or a portion of coaxial cable **102** are inserted. 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 **202** 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. One or more of the materials may be biocompatible and suitable for insertion into living tissue.

Coaxial cable **102** may be formed of one or more rigid, semi-rigid, or flexible sections. The characteristic impedance may be off the shelf and range between approximately 20 and approximately 300 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.

A center conductor width **224** defines a cross-section width of center conductor **200**. When center conductor **200** has a circular cross-section, center conductor width **224** is a diameter of center conductor **200**. For illustration, center conductor width **224** is approximately 0.51 millimeters (mm). A dielectric material width **226** defines a cross-section width of dielectric material **202** that surrounds center conductor **200**. For illustration, dielectric material width **226** is approximately 0.58 mm. A conductive shield width **228** defines a cross-section width of conductive shield **204** that surrounds dielectric material **202**. For illustration, conductive shield width **228** is approximately 0.36 mm. An insulating jacket width **230** defines a cross-section width of insulating jacket **206** that surrounds conductive shield **204**. For illustration, insulating jacket width **230** is approximately 0.21 mm such that coaxial cable **102** has an outer diameter of approximately 2.8 mm. These dimensions yield the same impedance as that of commercially available semi-rigid coaxial cables (e.g. UT-085C) though other types of coaxial cable may be used in alternative embodiments.

First antenna **100**_a_ may form a dipole antenna that includes a first dipole arm **208** and a second dipole arm **212**. In the illustrative embodiment of FIGS. **2** to **4**, first dipole arm **208** 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**. First dipole arm **208** may be formed of conducting wire having one or more of a straight section, a helical section, etc. A cross-section of first dipole arm **208** 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** as more clearly shown referring to FIGS. **3** and **4**.

In the illustrative embodiment of FIGS. **2** to **4**, first dipole arm **208** is formed of a single straight section of circular cross-section that extends between a first end **209** and a second end **211**. First end **209** of first dipole arm **208** connects to center conductor **200** and extends in an axial direction illustrated by a center line **242** that extends lengthwise from center conductor **200** towards second end **211**.

A first antenna dielectric material **210** may surround first dipole arm **208** along a length of first dipole arm **208** and around second end **211** of first dipole arm **208**. First antenna dielectric material **210** may be the same material as and/or may be an extension of dielectric material **202**.

A second antenna dielectric material **214** may surround first antenna dielectric material **210**. A third antenna dielectric material **216** may surround second antenna dielectric material **214**. Third antenna dielectric material **216** may be the same material as and/or may be an extension of insulating jacket **206**. Third antenna dielectric material **216** may form a catheter body. For example, insulating jacket **206** and third antenna dielectric material **216** may be a catheter in which first antenna **100***a* and all or a portion of coaxial cable **102** are inserted. First antenna dielectric material **210**, second antenna dielectric material **214**, and third antenna dielectric material **216** may be selected from 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 to 30. For illustration, first antenna dielectric material **210** and third antenna dielectric material **216** are polytetrafluoroethylene, and second antenna dielectric material **214** is air. One or more of first antenna dielectric material **210**, second antenna dielectric material **214**, and third antenna dielectric material **216** may be formed of the same dielectric material to form a continuous layer of material that surrounds first dipole arm **208** and/or second dipole arm **212**.

In the illustrative embodiment of FIGS. **2** to **4**, second dipole arm **212** 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**. Second dipole arm **212** may be formed of conducting wire having one or more of a helical section, etc. A cross-section of second dipole arm **212** may be circular, square, elliptical, rectangular, etc. though it is typically rectangular when formed as an extension of conductive shield **204** of coaxial cable **102** as more clearly shown referring to FIGS. **3** and **4**.

In the illustrative embodiment of FIGS. **2** to **4**, second dipole arm **212** is formed of a single helix of rectangular cross-section that extends between a first end **213** and a second end **215**. First end **213** of second dipole arm **212** connects to conductive shield **204** and forms a transition point between conductive shield **204** and second dipole arm **212**. Second dipole arm **212** extends in an axial direction lengthwise from conductive shield **204** towards second end **215** of second dipole arm **212** forming a plurality of loops with first dipole arm **208** forming a center of each loop of the plurality of loops. In an illustrative embodiment, each loop has a circular shape when projected into a feed plane defined parallel to an x-z plane indicated by x-y-z reference frame **300** shown referring to FIG. **3**. For example, referring to FIG. **2**, second dipole arm **212** includes five complete circular loops; whereas, referring to FIGS. **3** and **4**, second dipole arm **212** includes two complete circular loops. A number of loops or turns formed by second dipole arm **212** may be determined as discussed further below. A number of loops or turns need not be an integer value.

As understood by a person of skill in the art, the wavelength of operation, λ_o, of first antenna **100***a* is defined as $\lambda_o=c/f_o$, where c is the effective speed of light in the effective medium formed between first antenna dielectric material **210**, second antenna dielectric material **214**, insulating jacket **206**, and an environment in which antenna **100** is used, such as a body tissue, and f_o is a selected operating frequency of a signal carried by center conductor **200** of coaxial cable **102**. For illustration, f_o, may be between 300 MHz and 300 GHz though 500 MHz and 30 GHz may be preferred. The wavelength of operation, λ_o, is a wavelength at the selected operating frequency in a medium in which first antenna **100***a* is selected to operate. For example, the medium also includes first antenna dielectric material **210**, second antenna dielectric material **214**, and third antenna dielectric material **216** as well as the body tissue into which antenna **100** is inserted to perform MWA.

First dipole arm **208** has a first dipole arm length **222** measured between the feed plane defined parallel to the x-z plane indicated by x-y-z reference frame **300** and an end plane also defined parallel to the x-z plane. For illustration, first dipole arm length **222** may be a multiple of $0.25\lambda_o$, such as $0.25\lambda_o$, $0.5\lambda_o$, $0.75\lambda_o$, etc. The feed plane and the end plane are perpendicular to an axial direction that is parallel to the y-axis of x-y-z reference frame **300**. Center line **242** is also parallel to the y-axis.

Second dipole arm **212** has a second dipole arm length **220** measured between the feed plane and second end **215** of second dipole arm **212** in direction that is parallel to the y-axis. First dipole arm length **222** is also measured from the feed plane in a direction that is parallel to the y-axis. Selection of second dipole arm length **220** is discussed further below. FIG. **2** shows first antenna **100***a* in the y-z reference frame **232**. The feed plane includes a feed vector **218** that extends radially from a center of first dipole arm **208** at a transition point or connection point between center conductor **200** of coaxial cable **102** and first end **209** of first dipole arm **208**. The end plane includes second end **211** of first dipole arm **208**. An end vector **219** extends radially from a center of first dipole arm **208** through second end **211** of first dipole arm **208**. As a result, first dipole arm length **222** is measured between feed vector **218** and end vector **219** that is defined by a distal end of first dipole arm **208**.

Feed vector **218** also extends through an edge of first end **213** of second dipole arm **212** that connects to conductive shield **204**. First end **209** of first dipole arm **208** is a feed end of first dipole arm **208**. First end **213** of second dipole arm **212** is a feed end of second dipole arm **212**. First dipole arm **208** and second dipole arm **212** are not connected to and do not contact or touch each other at any point.

A first dipole arm width **234** defines a cross-section width of first dipole arm. When first dipole arm **208** has a circular cross-section, first dipole arm width **234** is a diameter of first dipole arm **208**. For illustration, first dipole arm width **234** is equal to center conductor width **224** and is approximately 0.51 millimeters (mm). A first antenna dielectric material width **236** defines a cross-section width of first antenna dielectric material **210** that surrounds first dipole arm **208**. For illustration, first antenna dielectric material width **236** is equal to dielectric material width **226** and is approximately 0.58 mm. A second antenna dielectric material width **238** defines a cross-section width of second antenna dielectric material **214** that surrounds first antenna dielectric material **210**. For illustration, second antenna dielectric material width **238** is equal to conductive shield width **228** and is approximately 0.36 mm. A third antenna dielectric material width **240** defines a cross-section width of third antenna dielectric material **216** that surrounds second antenna dielectric material **214**. For illustration, third antenna dielectric material width **240** is equal to insulating jacket width **230** and is approximately 0.21 mm such that first antenna **100***a* also has an outer diameter of approximately 2.8 mm. No balun is used with first antenna **100***a* so that first antenna **100***a* is minimally invasive based on the wavelength of operation, λ_o, selected for use to perform MWA.

Referring to FIG. **4**, a second dipole arm cross-section length **400** defines a cross-section length of a conductor that forms second dipole arm **212**, and a second dipole arm cross-section width **402** defines a cross-section width of the conductor that forms second dipole arm **212**. For illustration, second dipole arm cross-section length **400** is selected to be equal to first dipole arm width **234**; and second dipole arm cross-section width **402** is selected to be equal to second antenna dielectric material width **238**. Of course, if the conductor that forms second dipole arm **212** has a circular cross-section, second dipole arm cross-section length **400** is equal to second dipole arm cross-section width **402** and both are a diameter of the circular cross-section. In the illustrative embodiment, second dipole arm cross-section length **400** is approximately equal to 0.51 mm, and second dipole arm cross-section width **402** is approximately equal to 0.36 mm.

A separation width **404** defines a radial separation distance between a center of first dipole arm **208** defined by center line **242** and a center of second dipole arm **212** defined by a second center line **410**. Separation width **404** may vary as it is measured radially around first dipole arm **208** depending on a shape of the conductor of first dipole arm **208** and the conductor of second dipole arm **212** and on a shape formed by first dipole arm **208** and second dipole arm **212**. Separation width **404** is measured in a plane that is parallel to the x-z plane and can be used for a complete loop or turn of second dipole arm **212** to compute a mean value.

An overall length of the conductor of second dipole arm **212** can be computed using $l_t=\sqrt{l_h^2+(\pi ND)^2}$, where l_t is the overall length, l_h is second dipole arm length **220**, N is the number of loops or turns of second dipole arm **212**, and D is a mean value of an inner diameter **406** of conductive shield **204** and an outer diameter **408** of conductive shield **204**. D is also twice separation distance **404**. Second dipole arm length **220** l_h is selected to simultaneously have a simulated reflection coefficient, $|S_{11}|$, that is less than −10 dB, and a compact specific absorption rate (SAR) pattern at the selected operating frequency f_o. To achieve this, second dipole arm length **220** l_h is less than first dipole arm length **222** by at least 10% of first dipole arm length **222** such that $l_h \leq 0.9*l_m$, where l_m is first dipole arm length **222**.

Second dipole arm length **220** is selected such that a good impedance match and a localized SAR pattern is achieved at the frequency of operation. Second dipole arm length **220** l_h can be chosen between $0.1\lambda_o$ to $0.2\lambda_o$, inclusive. The overall length l_t is selected to be $0.25\lambda_o+m*0.5\lambda_o$, where m=0, 1, 2, . . . subject to fine-tuning as understood by a person of skill of art. For illustration, the overall length L_t may be selected as $0.25\lambda_o$, $0.75\lambda_o$, $1.25\lambda_o$, $1.75\lambda_o$, etc. N can be determined using $N=\sqrt{l_t^2-l_h^2}/(\pi D)$.

Referring to FIGS. **5**A to **5**D, perspective views of first antenna **100***a* with different numbers of turns N of second dipole arm **212** are shown for integer multiples N_m of $l_t=N_m\lambda_o/4$ in accordance with an illustrative embodiment. Referring to FIG. **5**A, $l_t=\lambda_o/4$ was used, and the equation $N=\sqrt{l_t^2-l_h^2}/(\pi D)$ was solved to compute N=2.7 for second dipole arm **212***a*. Referring to FIG. **5**B, $l_t=\lambda_o/2$ was used, and the equation $N=\sqrt{l_t^2-l_h^2}/(\pi D)$ was solved to compute N=7.1 for second dipole arm **212***b*. Referring to FIG. **5**C, $l_t=3\lambda_o/4$ was used, and the equation $N=\sqrt{l_t^2-l_h^2}/(\pi D)$ was solved to compute N=9.9 for second dipole arm **212***c*. Referring to FIG. **5**D, $l_t=\lambda_o$ was used, and the equation $N=\sqrt{l_t^2-l_h^2}/(\pi D)$ was solved to compute N=13.2 for second dipole arm **212***d*.

A current flowing on an outer surface of conductive shield **204** was substantially reduced for l_t having odd values for integer multiples N_m. For example, a first region **500***a*, shown referring to FIG. **5**A, had a normalized current density between ~−22 decibels (dB) and ~−28 dB for $l_t=\lambda_o/4$ for second dipole arm **212***a* in an illustrative embodiment. Remaining regions of coaxial cable **102** connected to second dipole arm **212***a* had a normalized current density less than ~−28 dB.

A second region **500***b* and a third region **500***c* had a normalized current density between ~−22 decibels (dB) and ~−24 dB for $l_t=\lambda_o/2$ for second dipole arm **212***b* in the illustrative embodiment shown referring to FIG. **5**B. Remaining regions of coaxial cable **102** connected to second dipole arm **212***b* had a normalized current density less than ~−24 dB.

A fourth region **500***d* had a normalized current density between ~−22 decibels (dB) and ~−28 dB for $l_t=3\lambda_o/4$ for second dipole arm **212***c* in the illustrative embodiment shown referring to FIG. **5**C. Remaining regions of coaxial cable **102** connected to second dipole arm **212***c* had a normalized current density less than ~−28 dB.

A fifth region **500***e* and a sixth region **500***f* had a normalized current density between ~−22 decibels (dB) and ~−24 dB for $l_t=\lambda_o$ for second dipole arm **212***d* in the illustrative embodiment shown referring to FIG. **5**D. Remaining regions of coaxial cable **102** connected to second dipole arm **212***d* had a normalized current density less than ~−24 dB.

To maintain a localized SAR pattern while obtaining a decent impedance (less than −10 dB) match, $l_t=3\lambda_o/4$ is selected as an optimal value. Using $l_t=3\lambda_o/4$, a current direction along second dipole arm **212** reverses a distance equal to $\lambda_o/4$ away from the feed end of second dipole arm **212** becoming aligned with the current direction along first dipole arm **208**. As a result, an input impedance of first antenna **100***a* increases and the impedance match with coaxial cable **102** improves. Wrapping second dipole arm **212** around first dipole arm **208** also helps first antenna **100***a* produce symmetric SAR patterns.

Using the provided illustrative dimensions for coaxial cable **102** and first antenna **100***a*, and selecting the operating frequency as 1.9 gigahertz (GHz), l_m=23 mm was chosen for first dipole arm length **222**, and an optimized value of l_h=18 mm was chosen for second dipole arm **212** or $l_h \leq 0.783*l_m$ making second dipole arm length **220** l_h 21.7% less than first dipole arm length **222**. The frequency of 1.9 GHz was chosen because the power amplifier used in experiments worked in the 1.8 GHz to 2 GHz range. This frequency is close to the 2.45 GHz ISM band that is commonly used in commercial MWA systems. The results presented herein relative to first antenna **100***a* are expected to be applicable to other operating frequencies including 2.45 GHz. Full-wave electromagnetic (EM) simulations were performed using CST Microwave Studio to design first antenna **100***a* for operation in egg white. Egg white was chosen because it simplifies real-time monitoring of an ablation zone as it forms. The frequency-dependent dielectric properties of egg white were measured using an Agilent vector network analyzer (E8364A) and an Agilent dielectric probe kit (85070E). These properties were imported into CST Microwave Studio for running the full-wave EM simulations.

Second dipole arm cross-section length **400** l_c=0.51 mm was selected as mentioned previously because a longer length degrades the simulated reflection coefficient, $|S_{11}|$, and a shorter length decreases a power handling capability of second dipole arm **212**. Therefore, l_c=0.51 mm—the same value as first dipole arm width **234**—provided a good compromise between the power handling capability, low simulated reflection coefficient ($|S_{11}|$) and a localized SAR pattern. $l_t=3\lambda_o/4$ was used as discussed previously resulting in N=9.9 for second dipole arm **212***c* computed by solving

$$N=\sqrt{l_t^2-l_h^2}\Big/(\pi D)\text{ with }D=\frac{1.67+2.38}{2}=2.025\text{ m},$$

which is also twice separation distance **404**.

Referring to FIG. **6**, simulated and measured reflection coefficient, $|S_{11}|$, of first antenna **100***a* with N=9.9 for second dipole arm **212** are shown. A first $|S_{11}|$ curve **600** shows the simulated $|S_{11}|$ as a function of operating frequency. A second $|S_{11}|$ curve **602** shows a pre-ablation measured $|S_{11}|$ as a function of operating frequency. A third $|S_{11}|$ curve **604** shows a post-ablation measured $|S_{11}|$ as a function of operating frequency. The $|S_{11}|$ curves **600**, **602**, and **604** show that first antenna **100***a* is well matched at 1.9 GHz with an $|S_{11}|$ value of −11 dB without using an internal impedance matching network.

Referring to FIG. **7**, a normalized SAR pattern of first antenna **100***a* with N=9.9 for second dipole arm **212** is shown in the y-z plane. The SAR pattern was normalized to its associated maximum value. The simulated results assumed egg white. A −5 decibel (dB) curve **700** shows a SAR level reduced by 5 dB. A −10 dB curve **702** shows a SAR level reduced by 10 dB. A −15 dB curve **704** shows a SAR level reduced by 15 dB. A −20 dB curve **706** shows a SAR level reduced by 20 dB. First antenna **100***a* and coaxial cable **102** are shown for reference. The results of FIG. **7** show that first antenna **100***a* generates a symmetric SAR pattern. The SAR pattern is compact and almost confined to a longitudinal extent of first dipole arm **208** and second dipole arm **212**. This efficient confinement eliminates the need for a balun thus reducing an overall form factor and invasiveness of first antenna **100***a*.

Referring to FIG. **8**, a simulated ablation zone of first antenna **100***a* is shown in the y-z plane. The simulated ablation zone has an ablation length **800** and an ablation width **802**. First antenna **100***a* and coaxial cable **102** are shown for reference. The SAR pattern generated for egg white for first antenna **100***a* operating at 1.9 GHz was imported into CST Multiphysics Suite to serve as a thermal source for transient thermal simulations with a scaled power of 40 watts (W). In the simulations, the initial temperature of the egg white was set to 25 degrees Celsius (C). The thermal properties of egg white were defined as a thermal conductivity of 0.55 watts/kelvin/meter (W/K/m), a heat capacity of 3.8 kilojoules/K/kilogram (kJ/K/kg), and a density of 1041 kg/m^3. The simulated ablation zone shown in FIG. **8** was determined after simulating 5 minutes of ablation. Ablation length **800** and ablation width **802** represent a 60 degrees C. contour, which is a median temperature of a congestion zone and was selected to define the boundary of the ablation zone. As FIG. **8** shows, first antenna **100***a* operating at 1.9 GHz produces an approximately spherical ablation zone with no tail observed along an insertion path of first antenna **100***a*. To quantify a degree of sphericity of the ablation zone, an axial ratio (AR) was defined as a ratio of ablation length **800** to ablation width **802**. A value of one indicates a completely spherical ablation zone. For first antenna **100***a* operating at 1.9 GHz, an AR equal to 1.15 was computed indicating a nearly spherical ablation zone.

A prototype of first antenna **100***a* operating at 1.9 GHz was fabricated. Laser fabrication technology was used to fabricate second dipole arm **212** out of C122 seamless round copper tube with inner and outer diameters of 1.67 mm and 2.38 mm, respectively. The fabricated second dipole arm **212** was soldered to a UT-085C semi-rigid coaxial cable that was used to feed first antenna **100***a*. The inner diameter of conductive shield **204** was 1.67 mm (the same value as the C122 copper tube) and as a result, the soldered joint did not adversely affect the performance of first antenna **100***a*. Insulating jacket **206** and third antenna dielectric material **216** were formed using a fluorinated ethylene propylene heat shrink the far end of which was sealed by epoxy to completely envelop first antenna **100***a*. After the epoxy cured for 48 hours, a heat gun was used to shrink a diameter of the heat shrink to 2.8 mm. Before conducting an ablation experiment, first antenna **100***a* was placed inside egg white and its pre-ablation $|S_{11}|$ was measured using a vector network analyzer (Agilent E5071C). Second $|S_{11}|$ curve **602** of FIG. **6** shows the measured results. First $|S_{11}|$ curve **600** that was simulated and second $|S_{11}|$ curve **602** that was measured agree reasonably well with the fabricated first antenna **100***a* having $|S_{11}|$ of −12 dB at 1.9 GHz. The differences between first $|S_{11}|$ curve **600** that was simulated and second $|S_{11}|$ curve **602** that was measured can be attributed to fabrication tolerances and uncertainties in the dielectric properties of the egg white.

The fabricated first antenna **100***a* was used to perform an ablation experiment in egg white. An output of a signal generator (HP 8350B sweep oscillator) was fed as an input to a solid-state power amplifier (DMS 7066). An output of the amplifier was fed to coaxial cable **102** that fed the fabricated first antenna **100***a*. The ablation experiment was performed at 1.9 GHz for 5 minutes at a power level of 40 W. The $|S_{11}|$ of the fabricated first antenna **100***a* was monitored during the ablation experiment using a circulator and a power meter. The level of $|S_{11}|$ was observed to be less than −10 dB during the entire ablation process, which indicates that fabricated first antenna **100***a* remained matched to coaxial cable **102** as the dielectric properties of the egg white changed. This observation is in agreement with the measured post-ablation $|S_{11}|$ shown in third $|S_{11}|$ curve **604** of FIG. **6**. The $|S_{11}|$ value changed from a pre-ablation value of −12 dB to a post-ablation value of −10.5 dB at 1.9 GHz.

Referring to FIGS. **9**A to **9**D, snapshots of the ablation zone generated by fabricated first antenna **100***a* in egg white **900** are shown at four different time points. FIG. **9**A shows egg white **900** at ablation time t_a=0. FIG. **9**B shows egg white **900** with a first ablation zone **902** at t_a=60 seconds.

FIG. **9**C shows egg white **900** with a second ablation zone **904** at t_a=180 seconds. FIG. **9**D shows egg white **900** with a third ablation zone **906** at t_a=300 seconds. The evolution of the ablation zone can be seen clearly. The produced ablation zone is localized and no tail is observed along the insertion path of fabricated first antenna **100***a*. The longitudinal and lateral expansions of the ablation zone after five minutes of ablation were 4.0 cm and 3.2 cm, respectively. The axial ratio of the produced ablation zone was calculated to be 1.25, indicating a fairly spherical ablation zone. In fact, as FIGS. **9**A to **9**D show, the ablation zone of first antenna **100***a* maintained a fairly spherical shape during the entire ablation process and the dimensions of the ablation zone closely follow those of the simulation (3.8×3.3 cm^2) confirming the capability of first antenna **100***a* to produce localized ablation zones. Several phenomena occur during MWA that were not modeled in the simulations due to a lack of proper models and due to software limitations (i.e. charring, water vapor generation, vapor condensation). Together these result in the small discrepancies that can be seen between the dimensions of the ablation zones in the simulation and the experiment.

Referring to FIG. **10**, a simulated reflection coefficient, $|S_{11}|$, of a modified MWA antenna is shown by a fourth $|S_{11}|$ curve **1000**. The modified MWA antenna was identical to first antenna **100***a* except $l_m=l_h$=23 mm was used with N=9.9, which still corresponds to $l_t=3\lambda_o/4$. The simulated reflection coefficient, $|S_{11}|$, at 1.9 GHz was −9 dB, which is unacceptable because it should be below −10 dB. For comparison, the simulated reflection coefficient, $|S_{11}|$, at 1.9 GHz was −11.5 dB for first antenna **100***a*.

Referring to FIG. **11**, a simulated SAR pattern generated by the modified MWA antenna is shown. A −5 decibel (dB) curve **1100** shows a SAR level reduced by 5 dB. A −10 dB curve **1102** shows a SAR level reduced by 10 dB. A −15 dB curve **1104** shows a SAR level reduced by 15 dB. A −20 dB curve **1106** shows a SAR level reduced by 20 dB. The modified antenna generated a symmetric SAR pattern. The SAR pattern is not as localized as that show in FIG. **7** for first antenna **100***a* though.

Referring to FIG. **12**, a perspective view of a second antenna **100***b* is shown in accordance with an illustrative embodiment. Second antenna **100***b* includes a third dipole arm **208***a* and second dipole arm **212**. Third dipole arm **208***a* includes first dipole arm **208** and a first dipole arm extension **1200** that connects to and extends from first dipole arm **208**. First dipole arm **208** of second antenna **100***b* has a length approximately equal to that of second dipole arm **212** though this is not required.

First dipole arm extension **1200** is formed of a conductive material that may be the same material as and/or may be an extension of first dipole arm **208**. First dipole arm extension **1200** may be formed of conducting wire having one or more of a helical section, etc. A cross-section of first dipole arm extension **1200** may be circular, square, elliptical, rectangular, etc. though it is typically circular when formed as an extension of first dipole arm **208** as shown in FIG. **12**. In the illustrative embodiment of FIG. **12**, first dipole arm extension **1200** is formed of a single helix of circular cross-section that extends between a second end **211** of first dipole arm **208** and a second end **1202** of first dipole arm extension **1200**. First dipole arm extension **1200** extends in lengthwise from second end **211** of first dipole arm **208** towards second end **1202** of first dipole arm extension **1200** parallel to center line **242** of first dipole arm **208**. Like second dipole arm **212**, first dipole arm extension **1200** forms a plurality of loops with center line **242** forming a center of each circular loop of the plurality of circular loops. For example, referring to FIG. **12**, first dipole arm extension **1200** includes two complete circular loops. First dipole arm extension **1200** is located a second separation width **1210** from center line **242**. Like separation width **404**, second separation width **1210** is measured between center line **242** and a third center line **1208** of first dipole arm extension **1200**.

When combined, first dipole arm **208** and first dipole arm extension **1200** have first dipole arm length **222** measured between feed vector **218** and end vector **219**. First dipole arm extension **1200** has first dipole arm extension length **1204** measured between second end **211** of first dipole arm **208** and end vector **219**. A first dipole arm extension width **1206** defines a cross-section width of first dipole arm extension **1200**. When first dipole arm extension **1200** has a circular cross-section, first dipole arm extension width **1206** is a diameter of first dipole arm extension **1200**. For illustration, first dipole arm extension width **1206** is equal to center conductor width **224** and to first dipole arm width **234** and is approximately 0.51 millimeters (mm). For further illustration, a length of first dipole arm **208** may be equal to second dipole arm length **220** between first end **209** and second end **211** of first dipole arm **208**. For still further illustration, second separation distance **1210** may be 0.5 mm though first dipole arm extension **1200** may be located at other heights up to that defined by separation width **404**.

A number of turns of second dipole arm **212** may be selected as 10 using $N=\sqrt{l_t^2-l_h^2}/(\pi D)$ with $l_t=3\lambda_o/4$ with l_h=14 mm. Again, second dipole arm length **220** l_h can be chosen between $0.1\lambda_o$ and $0.2\lambda_o$, inclusive. A number of turns of first dipole arm extension **1200**N_{h2} may be selected as 3 using $N_{h2}=\sqrt{l_{t2}^2-l_{h2}^2}/(\pi D_{h2})$, where the overall length of first dipole arm extension **1200** is l_{t2}=10 mm, first dipole arm extension length **1204** is l_{h2}=4, and D_{h2}=1.0 mm, where D_{h2} is twice second separation distance **1210**. Based on these dimensions, first dipole arm length **222** l_m=18 mm based on (14+4) mm.

In the illustrative embodiment of first antenna **100***a*, first dipole arm length **222** of first dipole arm **208** was 23 mm. In the illustrative embodiment of second antenna **100***b*, first dipole arm **208** was reduced in length by 9 mm to 14 mm. To compensate, first dipole arm extension **1200** was formed as a helix with N_{h2}=3 turns. A helix with D_{h2}=1 mm and N_{h2}=3 turns has an overall length of l_{t2}=10 mm, resulting in an overall first arm length of first dipole arm **208** and of first dipole arm extension **1200** of 24 mm, which is approximately equal to 23 mm. l_h=14 mm was chosen for second dipole arm **212** or $l_h\leq0.778*l_m$ making second dipole arm length **220** l_h 22.2% less than first dipole arm length **222**.

Referring to FIG. **13**, a simulated reflection coefficient, $|S_{11}|$, of second antenna **100***b* is shown by a fifth $|S_{11}|$ curve **1300**. The simulated reflection coefficient, $|S_{11}|$, at 1.9 GHz was −10.3 dB.

Referring to FIG. **14**, a simulated SAR pattern generated by second antenna **100***b* is shown. A −5 decibel (dB) curve **1400** shows a SAR level reduced by 5 dB. A −10 dB curve **1402** shows a SAR level reduced by 10 dB. A −15 dB curve **1404** shows a SAR level reduced by 15 dB. A −20 dB curve **1406** shows a SAR level reduced by 20 dB.

Referring to FIG. **15**, a block diagram of a MWA system **1500** is shown in accordance with an illustrative embodiment. MWA system **1500** may include a signal generator **1502**, an amplifier **1504**, a connector **1506**, coaxial cable **102**, and antenna **100** that may be first antenna **100***a* or second antenna **100***b*. Signal generator **1502** generates an analog signal at the operating frequency selected for first antenna **100**_a_ or second antenna **100**_b_. A duty cycle of the analog signal may be controlled by signal generator **1502** based, for example, on an ablation zone size and heating rate. The analog signal may be amplified by amplifier **1504**. Connector **1506** connects a second end of coaxial cable **102** opposite first antenna **100**_a_ or second antenna **100**_b_ to amplifier **1504**. The loss through coaxial cable **102** may be considered when adjusting an output power level of amplifier **1504** for a desired input power level to first antenna **100**_a_ or second antenna **100**_b_. Connector **1506** may be a coaxial connector designed to maintain the coaxial form across the connection and having a same impedance as coaxial cable **102**.

First antenna **100**_a_ and second antenna **100**_b_ are balun-free dipole antennas that generate localized heating patterns in microwave ablation. The dipole antenna of first antenna **100**_a_ is created by extending the outer and inner conductors of coaxial cable **102**. One dipole arm is a helical outer conductor (second dipole arm **212**) encompassing the other arm that is the extended center conductor **200** that is the inner conductor of coaxial cable **102**. In the illustrative embodiment, the overall lengths of second dipole arm **212** and first dipole arm **208** are three quarters and one quarter of a wavelength, respectively. The current direction in the conductor of second dipole arm **212** reverses direction a quarter of a wavelength away from the feed point becoming aligned with the current direction in the conductor of first dipole arm **208**. This creates a low input impedance, choking the current on an outer surface of conductive shield **204** of coaxial cable **102**. The fields produced by the currents flowing on the dipole arms destructively interfere closer to the feed point, while constructively interfering further from it, which helps first antenna **100**_a_ and second antenna **100**_b_ produce nearly spherical ablation zones. First antenna **100**_a_ and second antenna **100**_b_ can be used to perform minimally invasive ablation therapy within flexible and maneuverable embodiments.

First antenna **100**_a_ and second antenna **100**_b_ have several advantages compared to previous MWA antennas: 1) first antenna **100**_a_ and second antenna **100**_b_ generate localized ablation zones without using a balun, 2) the length of the radiating section of first antenna **100**_a_ and second antenna **100**_b_ can be made compact; and 3) first antenna **100**_a_ and second antenna **100**_b_ do not need an impedance matching network. 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 and/or a size determined based on a type of procedure. Additionally, for simplicity of construction some of the width dimensions are illustrated as the same though this is not required.

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" in the detailed description 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 comprising:

a first dipole arm connected to a first conductor and formed of a first conducting material, wherein the first dipole arm extends in an axial direction from the first conductor; and

a second dipole arm connected to a second conductor that is distinct from the first conductor and formed of a second conducting material, wherein the second dipole arm extends in the axial direction from the second conductor and is wound around the first dipole arm to form a number of loops, wherein the second dipole arm does not contact the first dipole arm,

wherein an axial length of the second dipole arm in the axial direction is less than 90% of an axial length of the first dipole arm in the axial direction, wherein the axial length of the first dipole arm is approximately 0.25λ, where λ is a wavelength at an operating frequency of a signal carried by the first conductor and the second conductor in a medium in which the antenna is selected to operate, wherein the axial length of the second dipole arm is between 0.1Λ and 0.2λ, inclusive.

2. The antenna of claim **1**, wherein the axial length of the second dipole arm in the axial direction is less than 80% of the axial length of the first dipole arm in the axial direction.

3. The antenna of claim **1**, wherein a total length of the first dipole arm is an integer multiple of a quarter wavelength at the operating frequency of the signal carried by the first conductor and the second conductor in the medium in which the antenna is selected to operate.

4. The antenna of claim **1**, wherein a total length of the first dipole arm is approximately 0.25λ.

5. The antenna of claim **1**, wherein a total length of the second dipole arm is approximately 0.25λ+m*0.52λ, where m is an integer value.

6. The antenna of claim **1**, wherein a total length of the second dipole arm is approximately 0.75λ.

7. The antenna of claim **1**, wherein the number of loops is $N=\sqrt{l_t^2-l_h^2}/(\pi D)$, where N is the number of loops, l_t is a total length of the second dipole arm, l_h is the axial length of the second dipole arm, and D is twice a separation distance between a center of the first dipole arm in a radial plane perpendicular to the axial direction and a center of the second dipole arm in the radial plane perpendicular to the axial direction measured as a mean value for a complete loop of the second dipole arm in the axial direction.

8. The antenna of claim **1**, wherein the second conductor is an outer conductor of a coaxial cable.

9. The antenna of claim **8**, wherein the first conductor is an inner center conductor of the coaxial cable.

10. The antenna of claim **9**, wherein the first conductor is an extension of the inner center conductor of the coaxial cable.

11. The antenna of claim **1**, further comprising a dipole arm extension connected to an end of the first dipole arm that is opposite the connection between the first conductor and the first dipole arm, wherein the dipole arm extension is formed of a third conducting material, wherein the dipole arm extension extends in the axial direction from the first dipole arm and is wound around a center axis of the axial direction through a center of the first dipole arm to form a second number of loops, wherein the second dipole arm does not contact the dipole arm extension, wherein the axial length of the first dipole arm in the axial direction includes an axial length of the dipole arm extension.

12. The antenna of claim **11**, wherein the first conducting material and the third conducting material are the same material.

13. The antenna of claim **11**, wherein the second number of loops is $N=\sqrt{l_t^2-l_h^2}/(\pi D)$, where N is the second number of loops, l_t is a total length of the dipole arm extension, l_h is the axial length of the dipole arm extension, and D is twice a separation distance between a center of the dipole arm extension in a radial plane perpendicular to the axial direction measured as a mean value for a complete loop of the second dipole arm in the axial direction and a center of the first dipole arm in the radial plane perpendicular to the axial direction.

14. 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; and
- an antenna comprising
  - a first dipole arm connected to the center conductor and formed of a first conducting material, wherein the first dipole arm extends in an axial direction from the center conductor; and
  - a second dipole arm connected to the conductive shield that is distinct from the center conductor and formed of a second conducting material, wherein the second dipole arm extends in the axial direction from the conductive shield and is wound around the first dipole arm to form a number of loops, wherein the second dipole arm does not contact the first dipole arm,
- wherein an axial length of the second dipole arm in the axial direction is less than 90% of an axial length of the first dipole arm in the axial direction, wherein the axial length of the first dipole arm is approximately 0.25λ, where λ is a wavelength at an operating frequency of a signal carried by the first conductor and the second conductor in a medium in which the antenna is selected to operate, wherein the axial length of the second dipole arm is between 0.1λ and 0.2λ, inclusive.

15. The antenna system of claim **14**, wherein a total length of the second dipole arm is approximately 0.25λ+m*0.5λ, where m is an integer value.

16. A microwave ablation system comprising:
- 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 first dipole arm connected to the center conductor and formed of a first conducting material, wherein the first dipole arm extends in an axial direction from the center conductor; and
    - a second dipole arm connected to the conductive shield that is distinct from the center conductor and formed of a second conducting material, wherein the second dipole arm extends in the axial direction from the conductive shield and is wound around the first dipole arm to form a number of loops, wherein the second dipole arm does not contact the first dipole arm,
    - wherein an axial length of the second dipole arm in the axial direction is less than 90% of an axial length of the first dipole arm in the axial direction;
- 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 antenna to the signal generator to receive the generated signal.

17. The microwave ablation system of claim **16**, wherein the axial length of the first dipole arm is approximately 0.25λ, where λ is a wavelength at an operating frequency of a signal carried by the first conductor and the second conductor in a medium in which the antenna is selected to operate, wherein the axial length of the second dipole arm is between 0.1λ and 0.2λ, inclusive.

18. The antenna system of claim **14**, wherein the number of loops is $N=\sqrt{l_t^2-l_h^2}/(\pi D)$, where N is the number of loops, l_t is a total length of the second dipole arm, l_h is the axial length of the second dipole arm, and D is twice a separation distance between a center of the first dipole arm in a radial plane perpendicular to the axial direction and a center of the second dipole arm in the radial plane perpendicular to the axial direction measured as a mean value for a complete loop of the second dipole arm in the axial direction.

19. The antenna system of claim **14**, further comprising a dipole arm extension connected to an end of the first dipole arm that is opposite the connection between the first conductor and the first dipole arm, wherein the dipole arm extension is formed of a third conducting material, wherein the dipole arm extension extends in the axial direction from the first dipole arm and is wound around a center axis of the axial direction through a center of the first dipole arm to form a second number of loops, wherein the second dipole arm does not contact the dipole arm extension, wherein the axial length of the first dipole arm in the axial direction includes an axial length of the dipole arm extension.

20. The antenna system of claim **19**, wherein the second number of loops is $N=\sqrt{l_t^2-l_h^2}/(\pi D)$, where N is the second number of loops, l_t is a total length of the dipole arm extension, l_h is the axial length of the dipole arm extension, and D is twice a separation distance between a center of the dipole arm extension in a radial plane perpendicular to the axial direction measured as a mean value for a complete loop of the second dipole arm in the axial direction and a center of the first dipole arm in the radial plane perpendicular to the axial direction.

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