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Behdad et al.

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(54) **MICROWAVE ABLATION ANTENNA SYSTEM**

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H01Q 9/42	(2006.01)
A61B 18/00	(2006.01)

(52) **U.S. Cl.**

CPC ***A61B 18/1815*** (2013.01); ***H01Q 9/42*** (2013.01); *A61B 2018/00529* (2013.01); *A61B 2018/00577* (2013.01); *A61B 2018/1846* (2013.01); *A61B 2018/1853* (2013.01); *A61B 2018/1892* (2013.01)

(58) **Field of Classification Search**

CPC A61B 18/1815; A61B 2018/183; A61B 2018/1823; A61B 2018/1853; A61B 2018/1876

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,246,438 A *	9/1993	Langberg	....	A61B 18/08 600/374
5,300,099 A	4/1994	Rudie		

(Continued)

FOREIGN PATENT DOCUMENTS

JP	2004-311334	11/2004
JP	2008-142467	6/2008

OTHER PUBLICATIONS

J Reinholm, The Characteristic Impedance of Coaxial Cables. Jun. 14, 2012. Electronics-lab.com, accessed Sep. 18, 2015. http://www.electronics-lab.com/the-characteristic-impedance-of-coaxial-cables/.*

(Continued)

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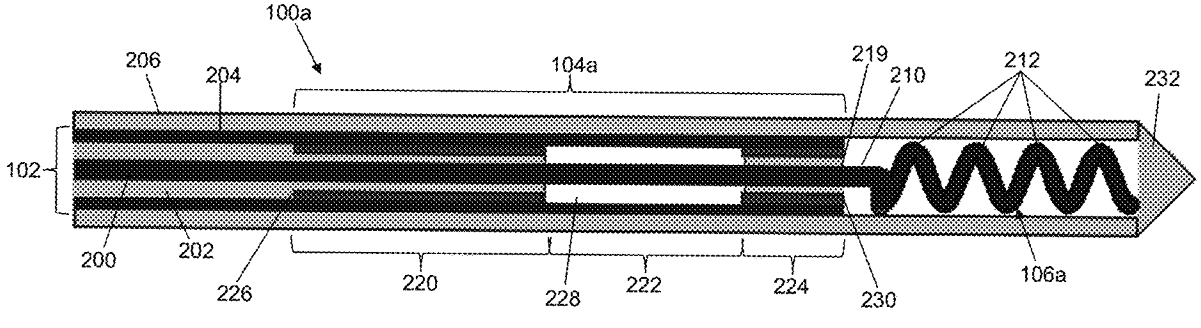
(57) **ABSTRACT**

An antenna system is provided. The antenna system includes a coaxial cable, an antenna, and an impedance matching structure. The coaxial cable includes 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 conductor having an electrical length of half a wavelength at a selected operating frequency. The impedance matching structure includes a second center conductor mounted between an end of the center conductor of the coaxial cable and a feed end of the antenna. The impedance matching structure is configured to match an impedance of the coaxial cable to an impedance of the antenna.

20 Claims, 16 Drawing Sheets



(56) References Cited

U.S. PATENT DOCUMENTS

5,683,382	A	11/1997	Lenihan	
6,051,018	A	4/2000	Larsen	
7,118,590	B1 *	10/2006	Cronin	A61B 18/14 606/33
7,194,297	B2	3/2007	Talpade et al.	
7,226,446	B1	6/2007	Mody et al.	
7,826,904	B2 *	11/2010	Appling	A61B 18/18 606/33
8,059,059	B2 *	11/2011	Bonn	A61B 18/18 343/793
8,280,525	B2 *	10/2012	Rusin	A61B 18/18 607/101
8,414,570	B2	4/2013	Turner et al.	
2006/0189973	A1	8/2006	van der Weide	
2009/0076492	A1 *	3/2009	Behnke	A61B 18/18 606/33
2010/0057070	A1 *	3/2010	Behnke	A61B 18/18 606/33
2010/0097284	A1	4/2010	Brannan et al.	
2010/0125269	A1	5/2010	Emmons et al.	
2010/0168727	A1 *	7/2010	Hancock	A61B 18/18 606/33
2010/0185192	A1 *	7/2010	Muller	A61B 18/18 606/33
2010/0217252	A1	8/2010	Rossetto et al.	
2010/0228244	A1 *	9/2010	Hancock	A61B 18/1815 606/33
2010/0305561	A1	12/2010	Prakash et al.	
2011/0034917	A1 *	2/2011	Brannan	A61B 18/00 606/41
2011/0208177	A1 *	8/2011	Brannan	A61B 18/1815 606/33
2011/0238060	A1	9/2011	Lee, Jr. et al.	
2014/0358140	A1	1/2014	Emmons	

OTHER PUBLICATIONS

International Search Report and Written Opinion for Intl. Patent Appl. No. PCT/US2015/012615, dated May 1, 2015, 10 pp.

International Search Report and Written Opinion for PCT/US2018/067469, dated Apr. 18, 2019.

* cited by examiner

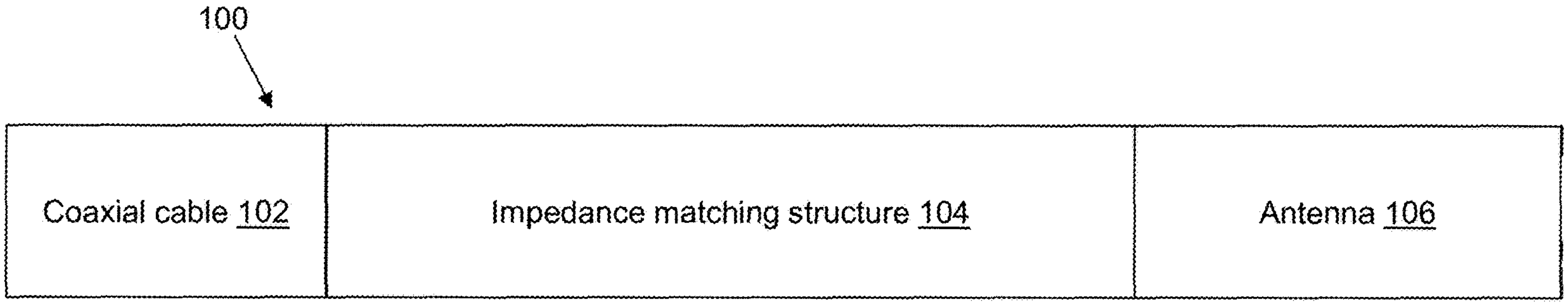

100
Coaxial cable 102
Impedance matching structure 104
Antenna 106

Fig. 1

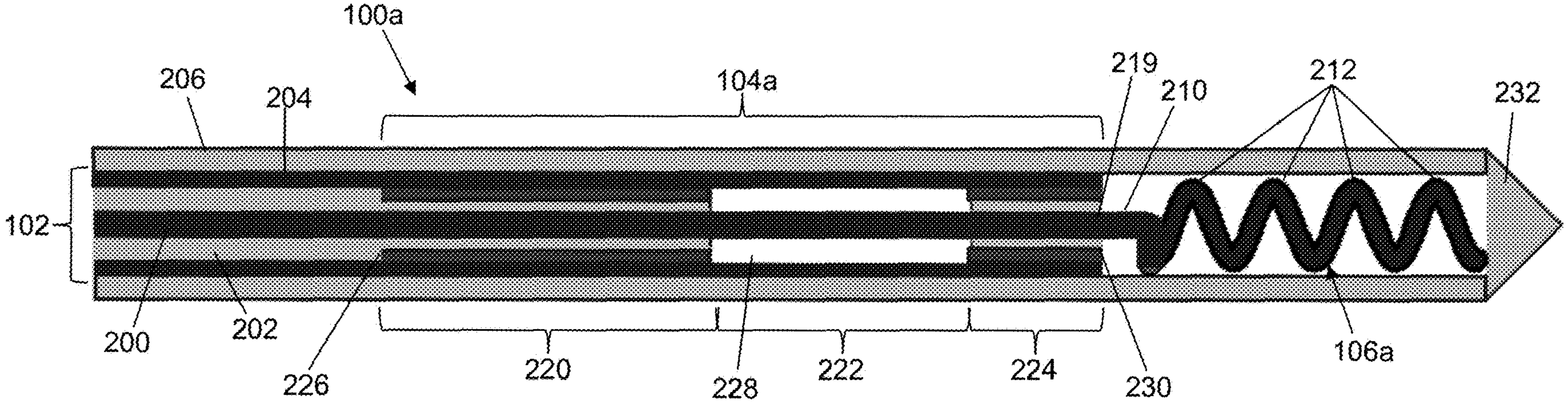

100a
206
204
104a
219
210
212
232
102
200
202
226
220
228
222
224
230
106a

Fig. 2

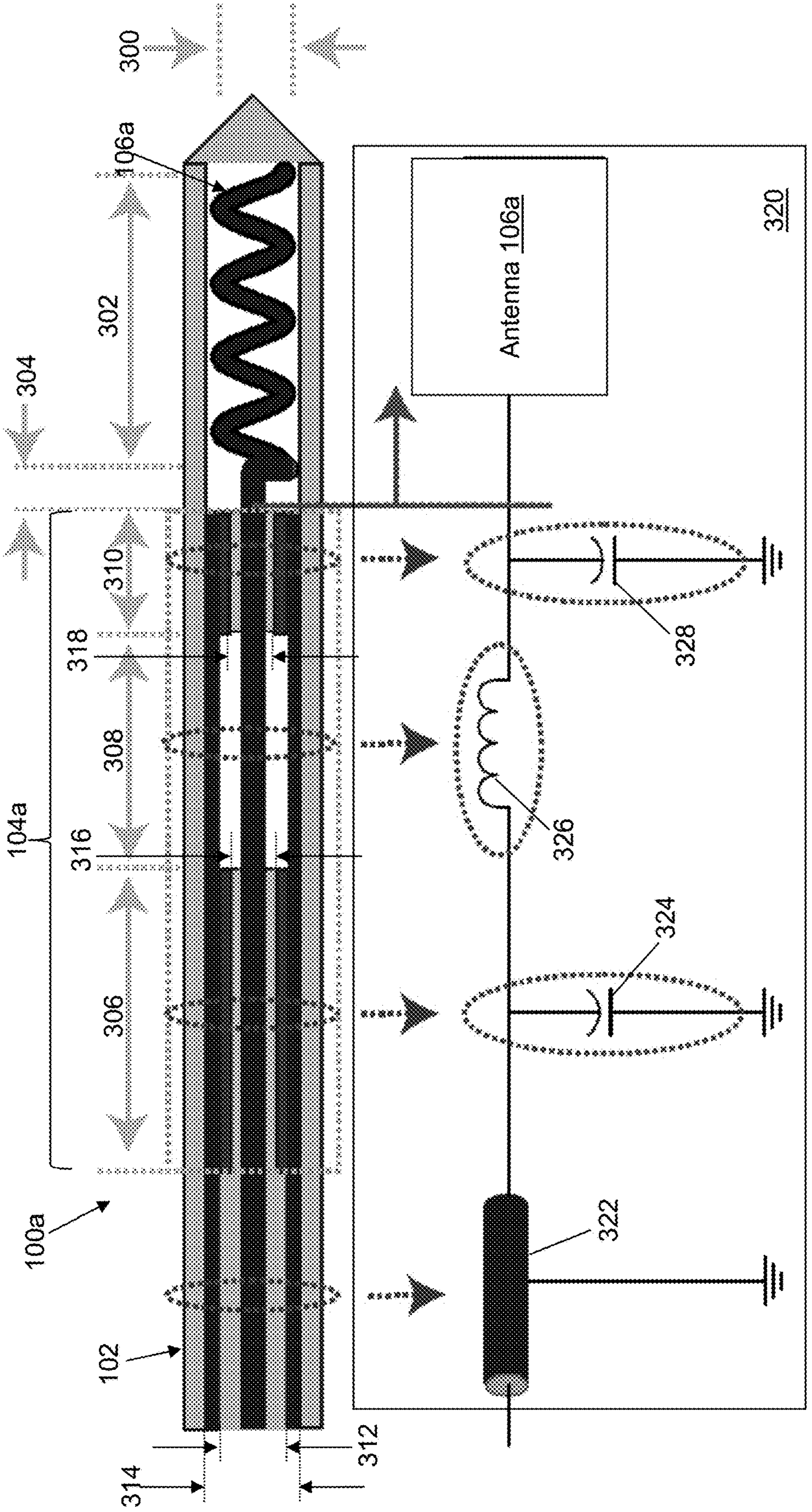

300
106a
302
304
Antenna 106a
320
310
318
308
316
306
104a
328
326
324
322
100a
102
314
312

Fig. 3a

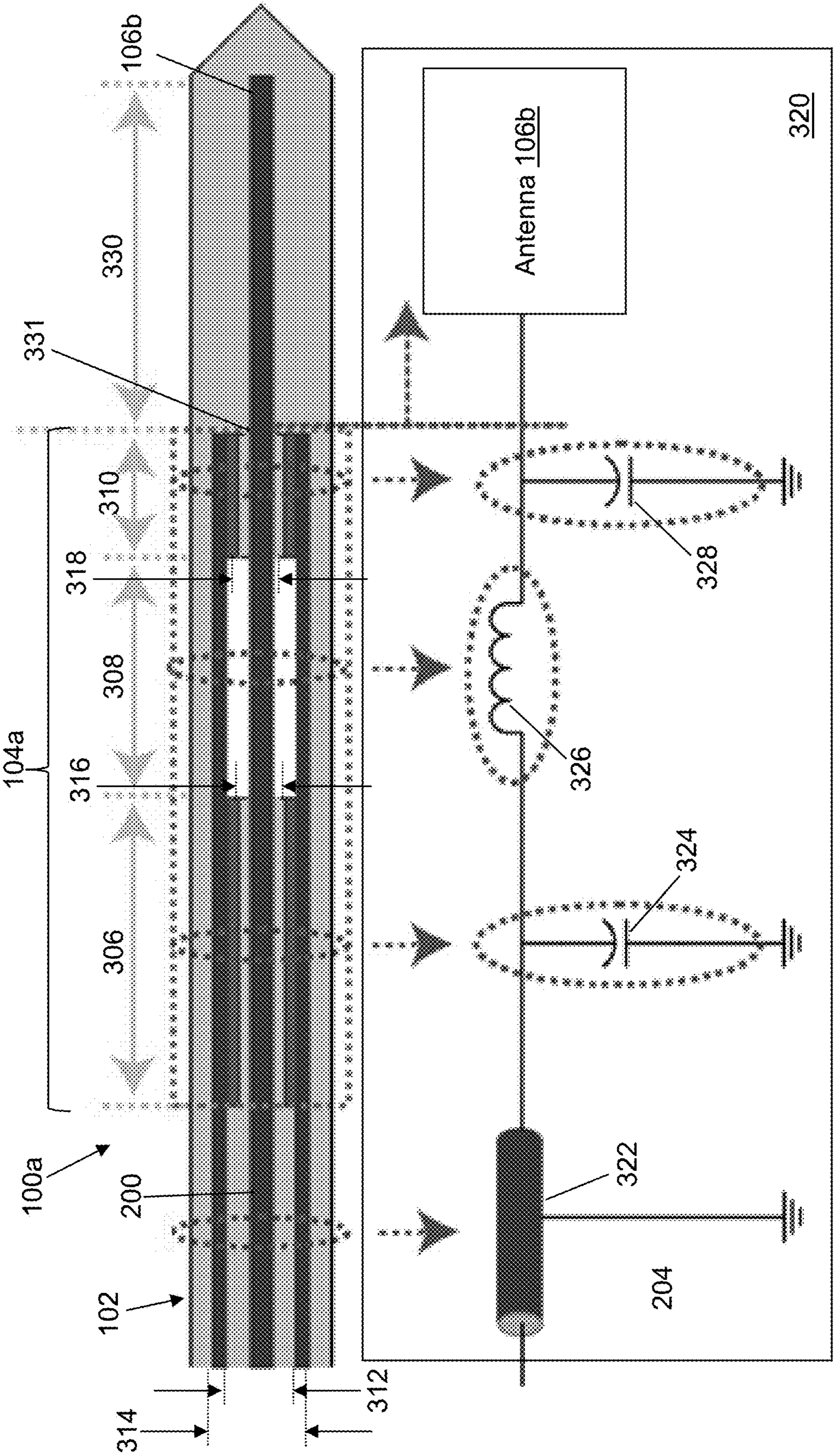

106b
330
331
310
318
308
316
306
104a
100a
200
102
314
312
Antenna 106b
320
328
326
324
322
204

Fig. 3b

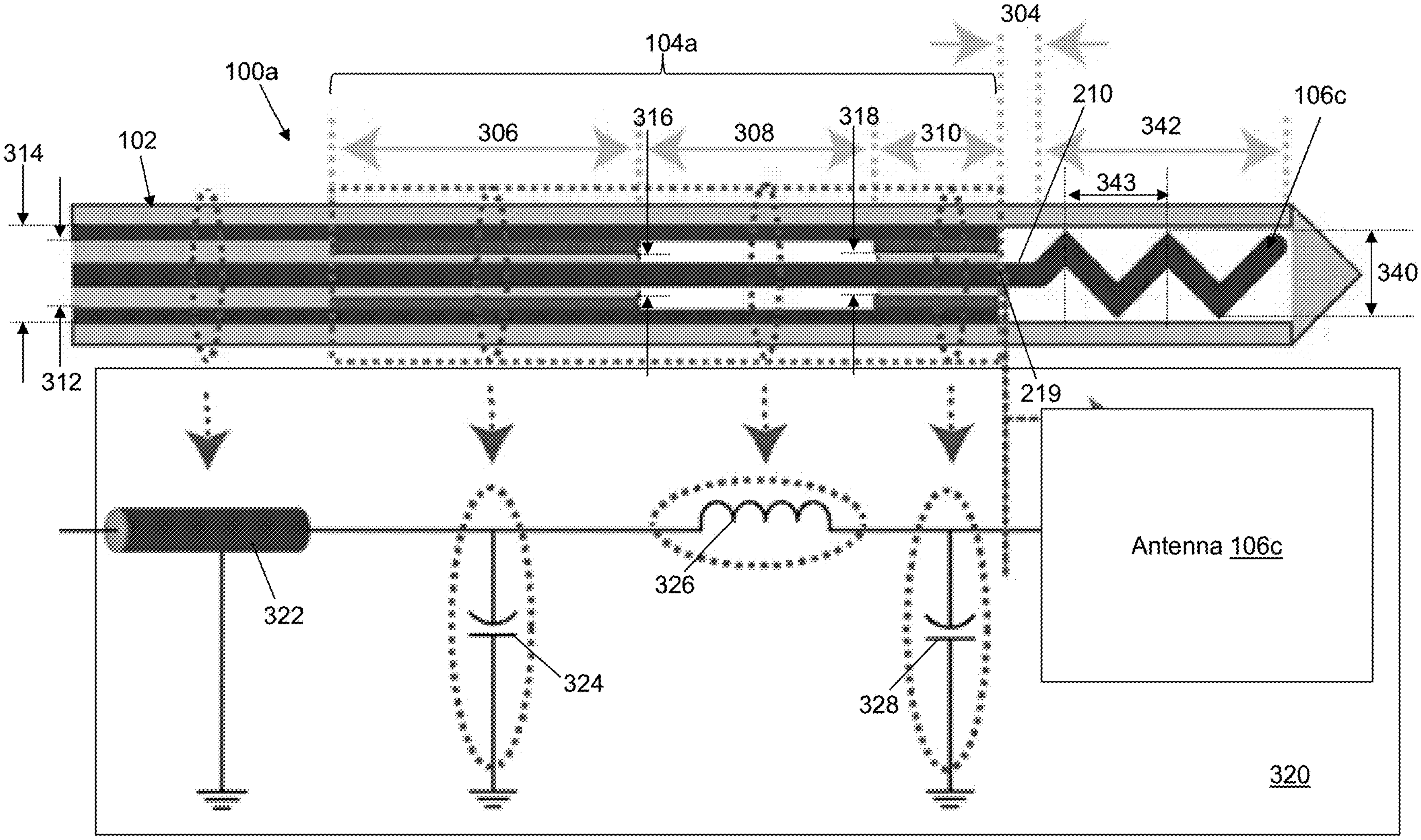

104a
304
100a
210
106c
314
102
306
316
308
318
310
342
343
340
312
219
322
324
326
328
Antenna 106c
320

Fig. 3c

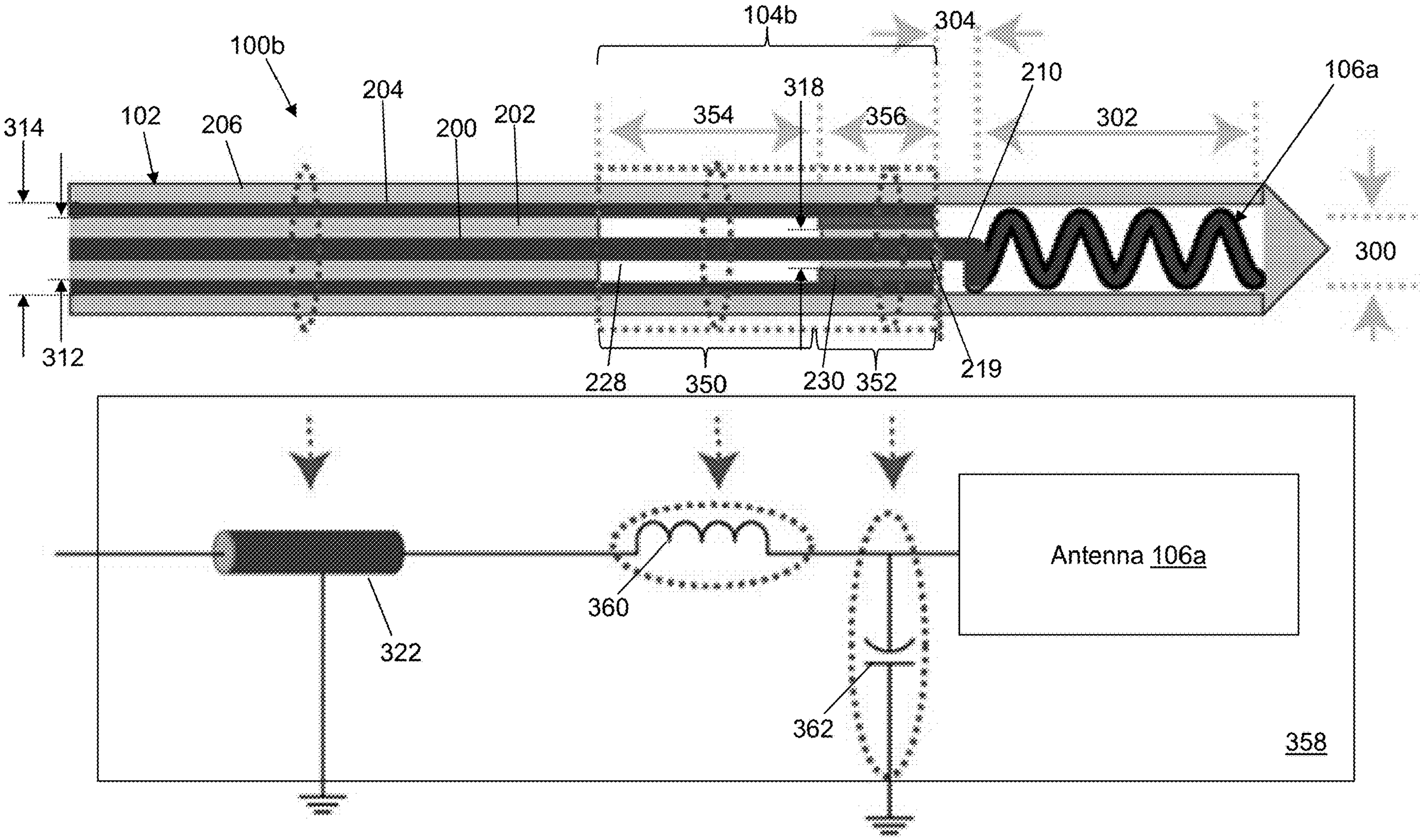

104b
304
100b
204
318
210
106a
314
102
206
200
202
354
356
302
300
312
228
350
230
352
219
Antenna 106a
360
322
362
358

Fig. 3d

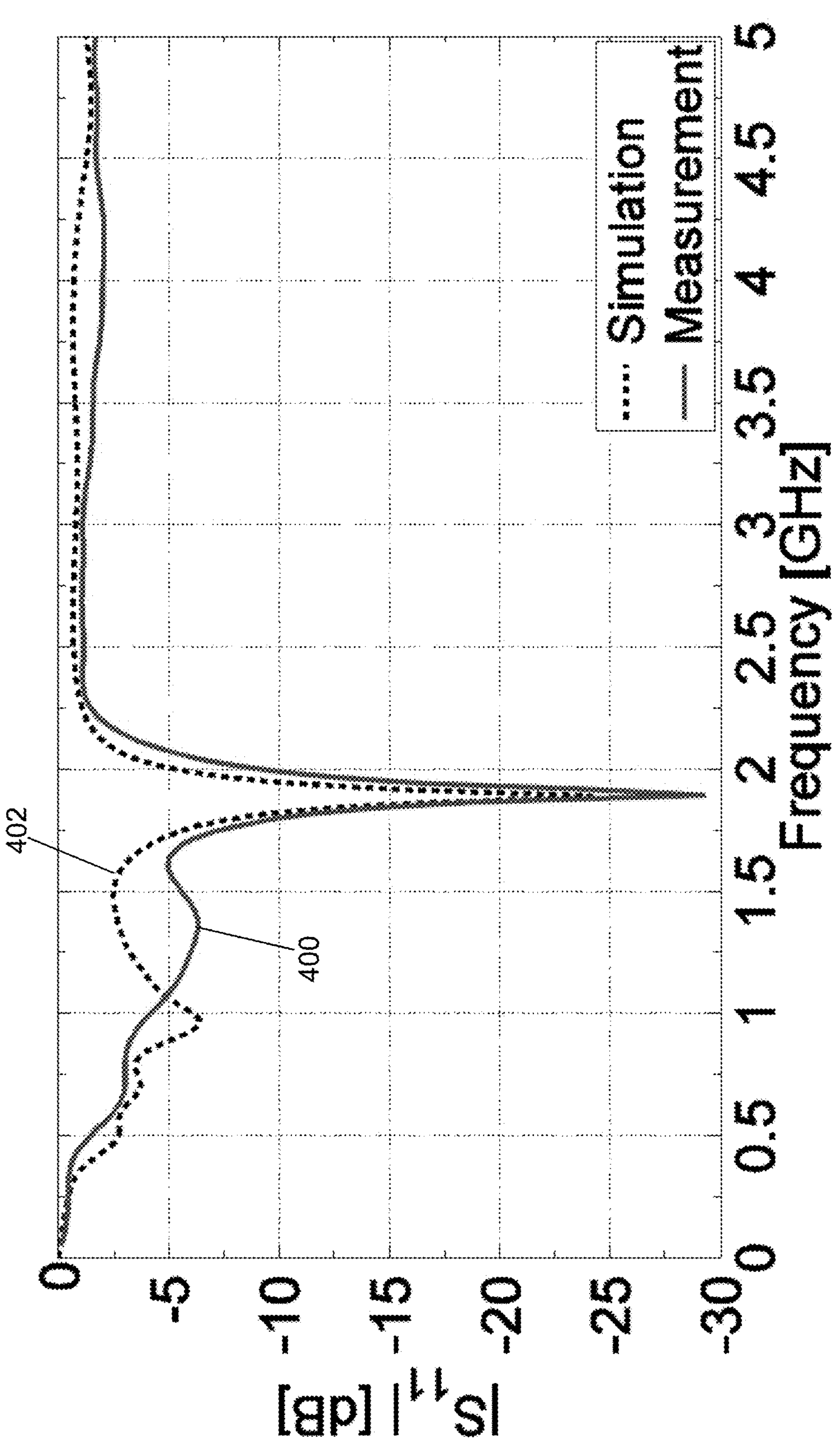

402
400
Simulation
Measurement
0
-5
-10
-15
-20
-25
-30
|S11| [dB]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Frequency [GHz]

Fig. 4

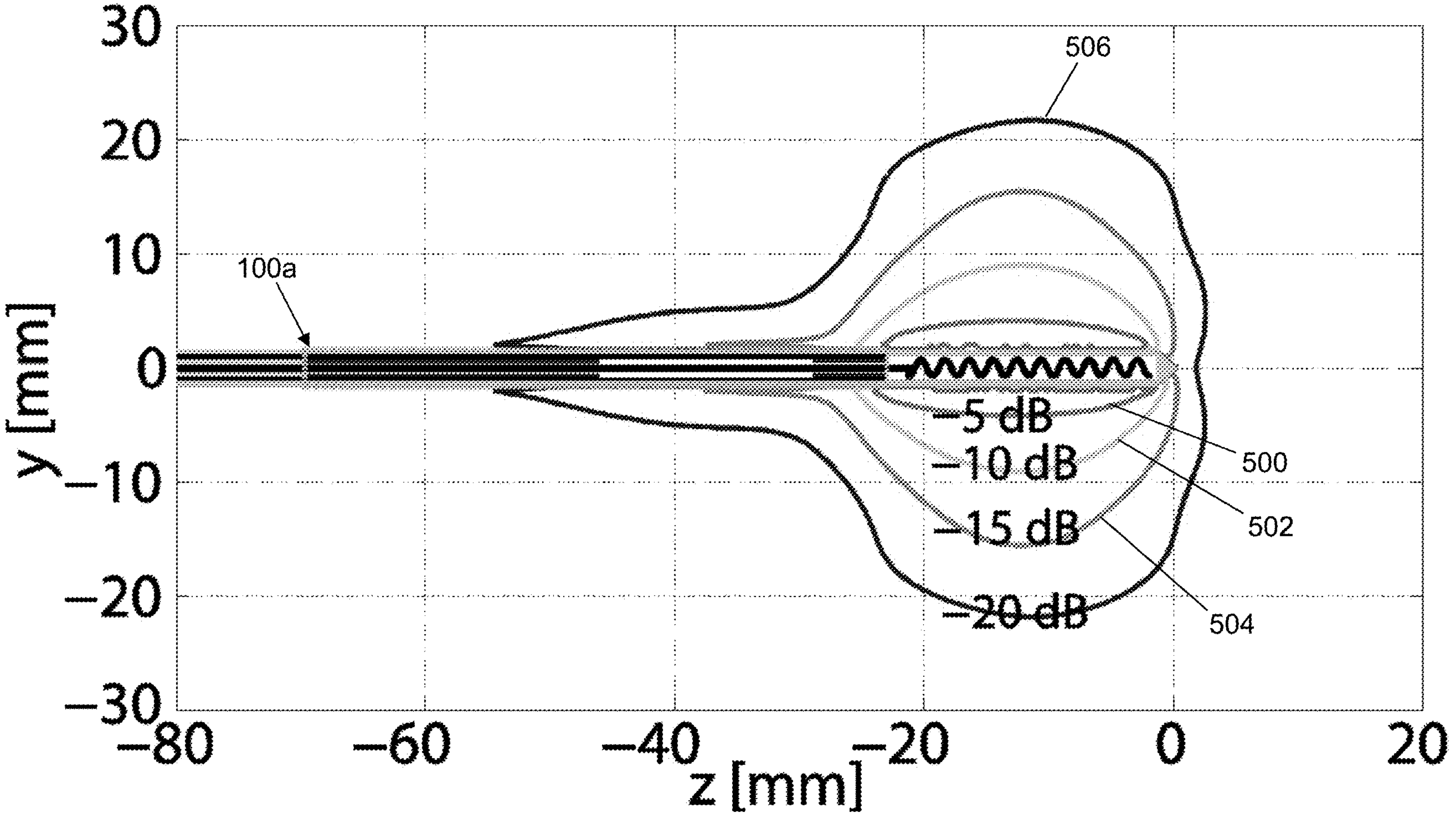

506
100a
−5 dB
−10 dB
−15 dB
−20 dB
500
502
504
30
20
10
0
−10
−20
−30
y [mm]
−80
−60
−40
−20
0
20
z [mm]

Fig. 5

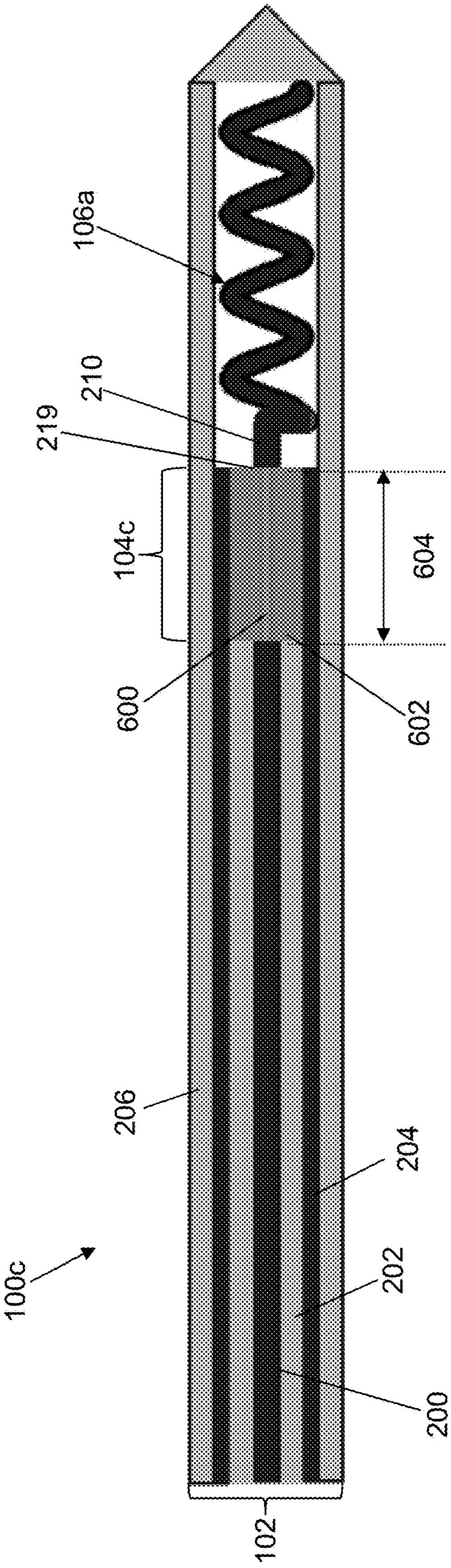


Fig. 6

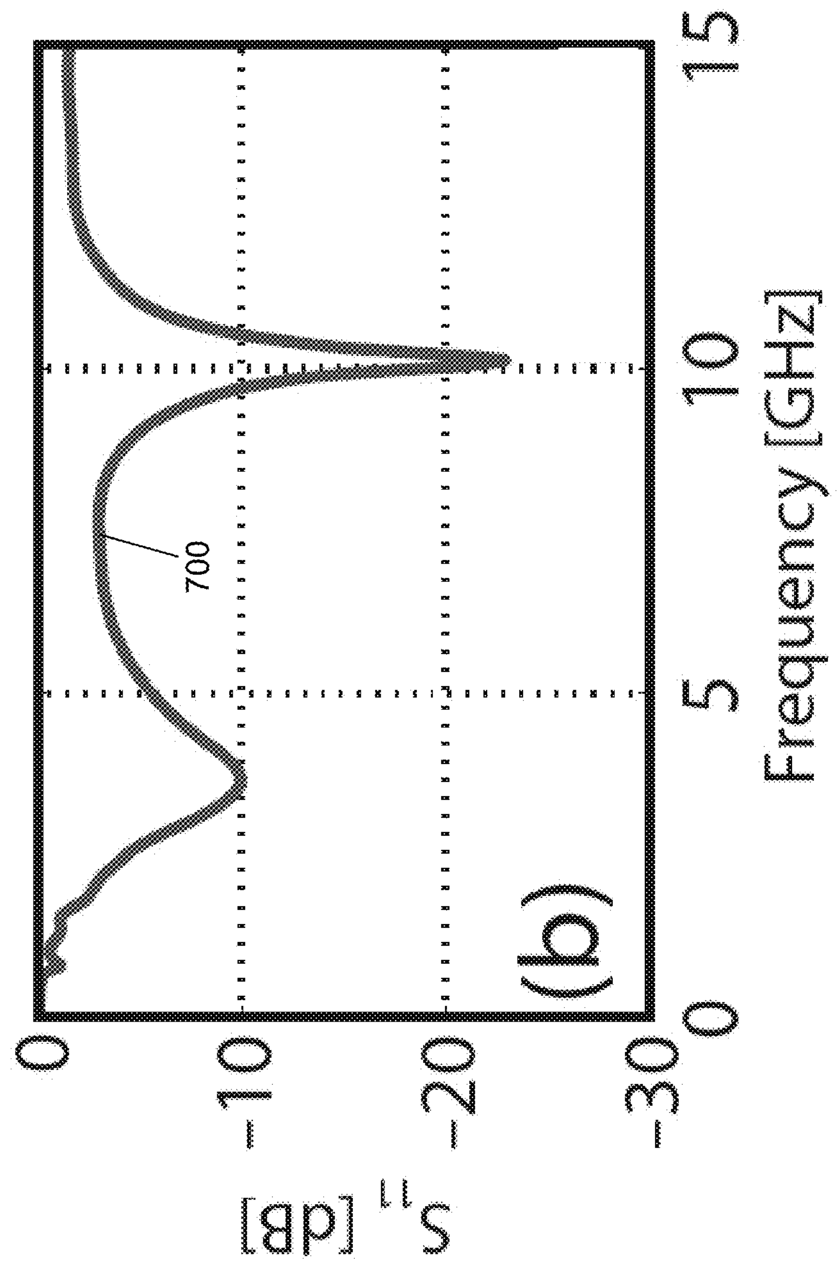


Fig. 7

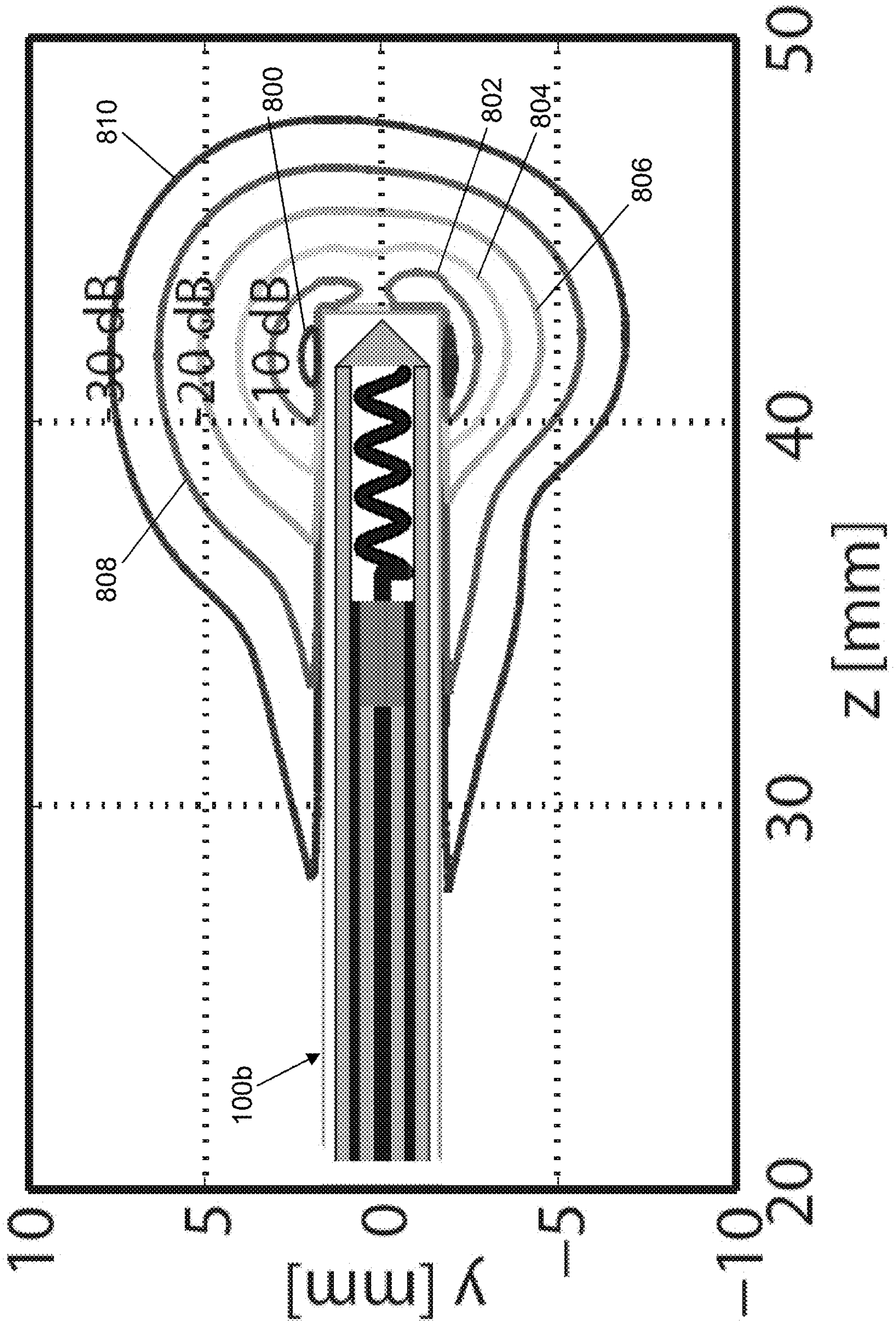

810
800
802
804
806
808
100b
−30 dB
−20 dB
−10 dB
10
5
0
−5
−10
y [mm]
20
30
40
50
z [mm]

Fig. 8

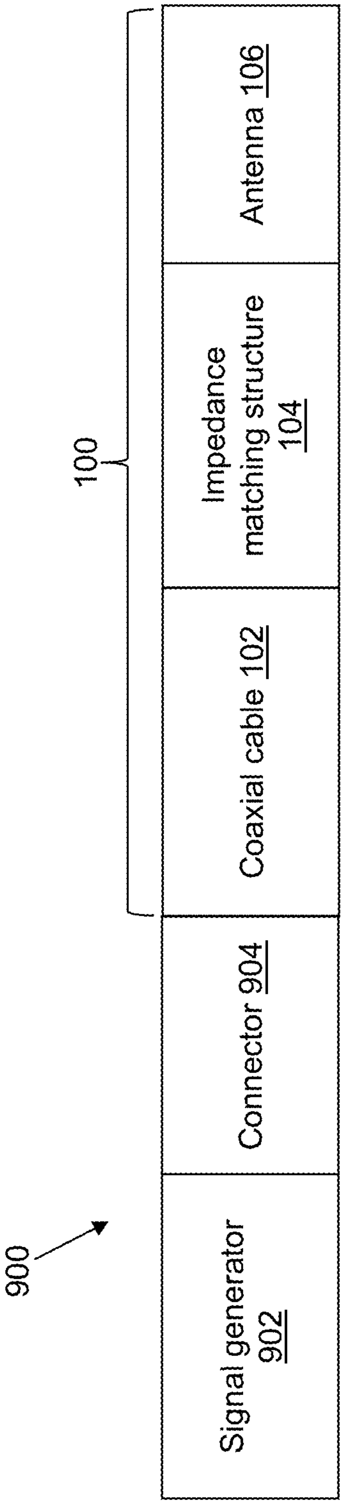

900
Signal generator 902
Connector 904
Coaxial cable 102
Impedance matching structure 104
Antenna 106
100

Fig. 9

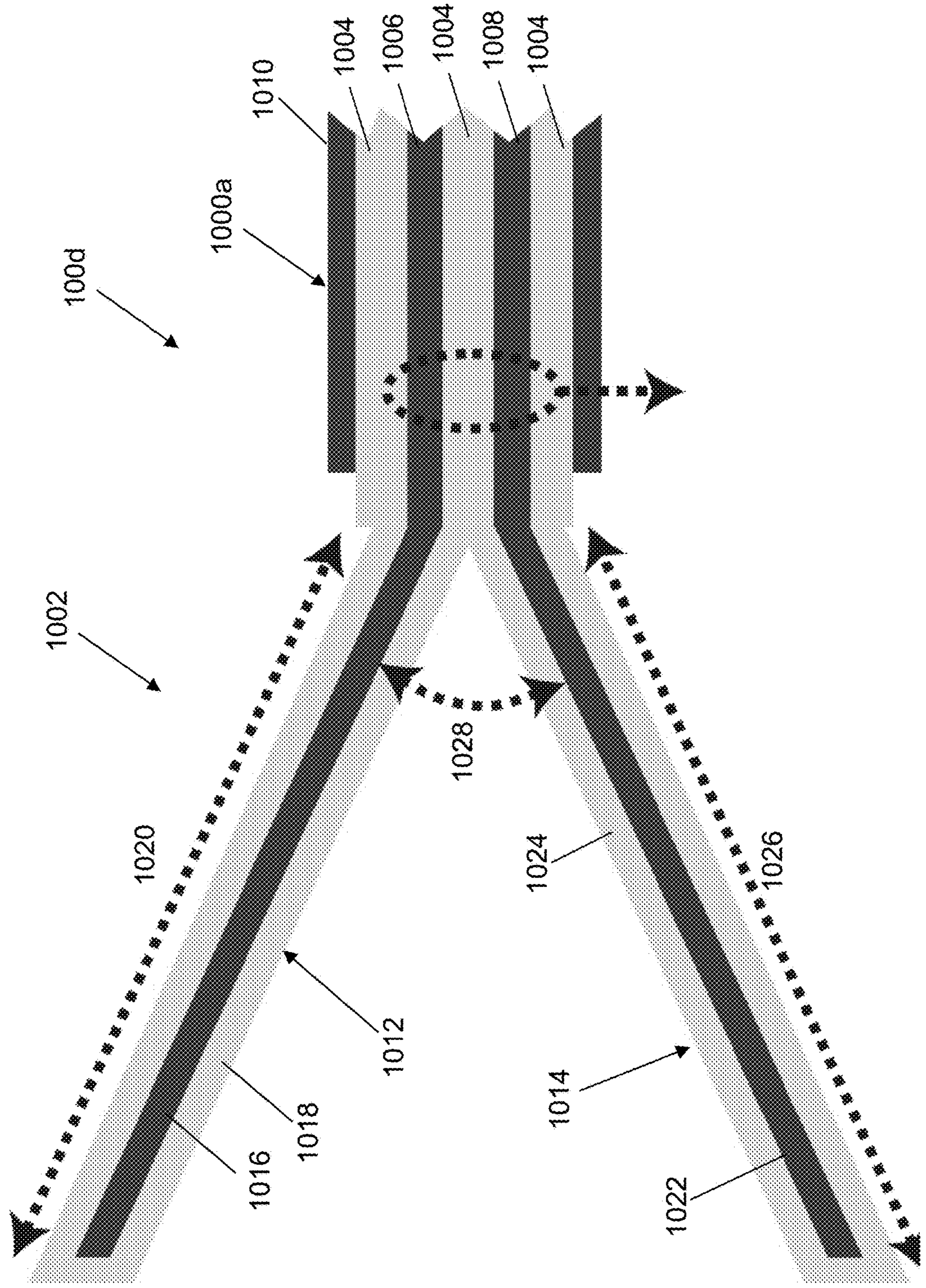

100d
1000a
1010
1004
1006
1004
1008
1004
1002
1028
1020
1012
1018
1016
1024
1026
1014
1022

Fig. 10

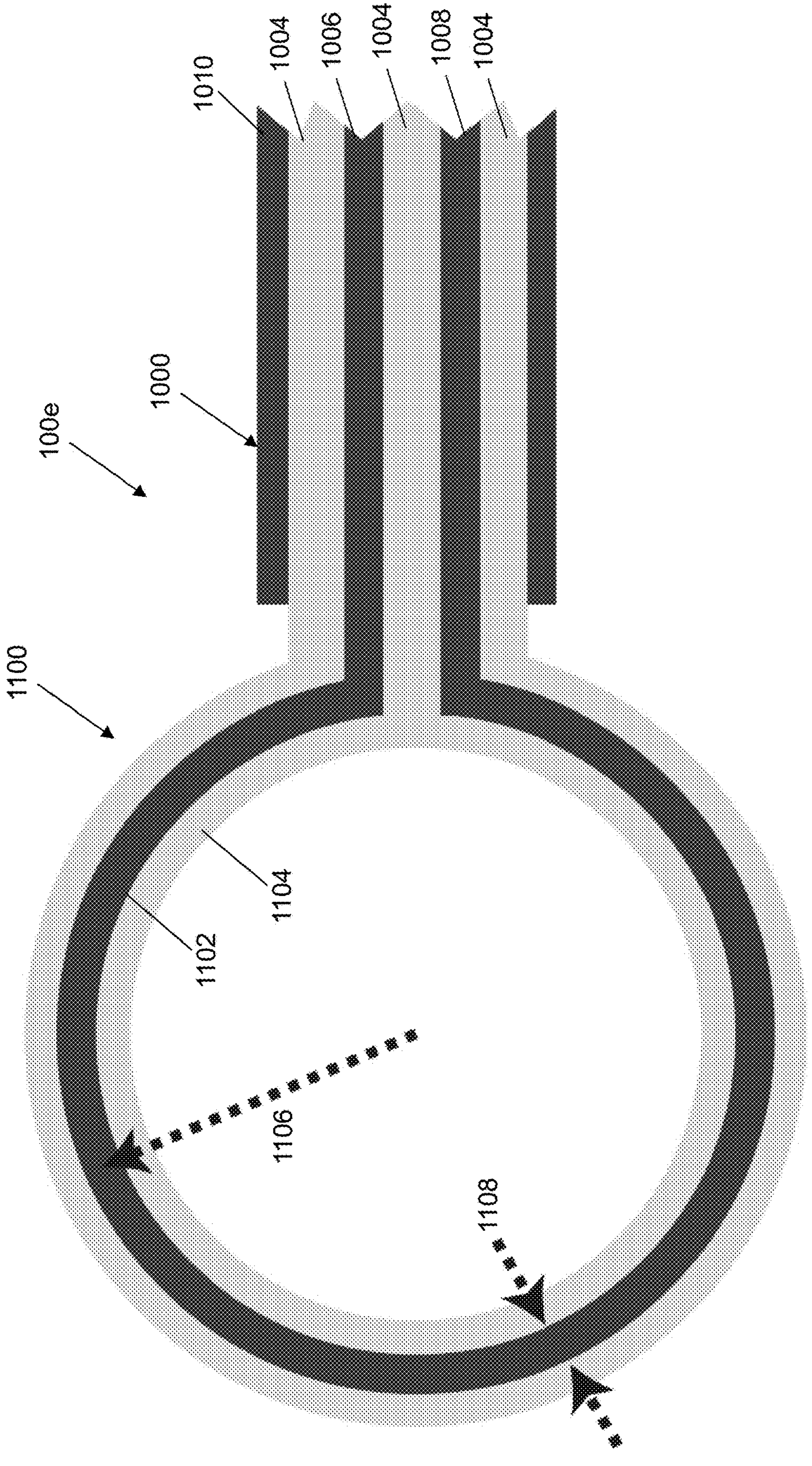

1010
1004
1006
1004
1008
1004
1000
100e
1100
1104
1102
1106
1108

Fig. 11

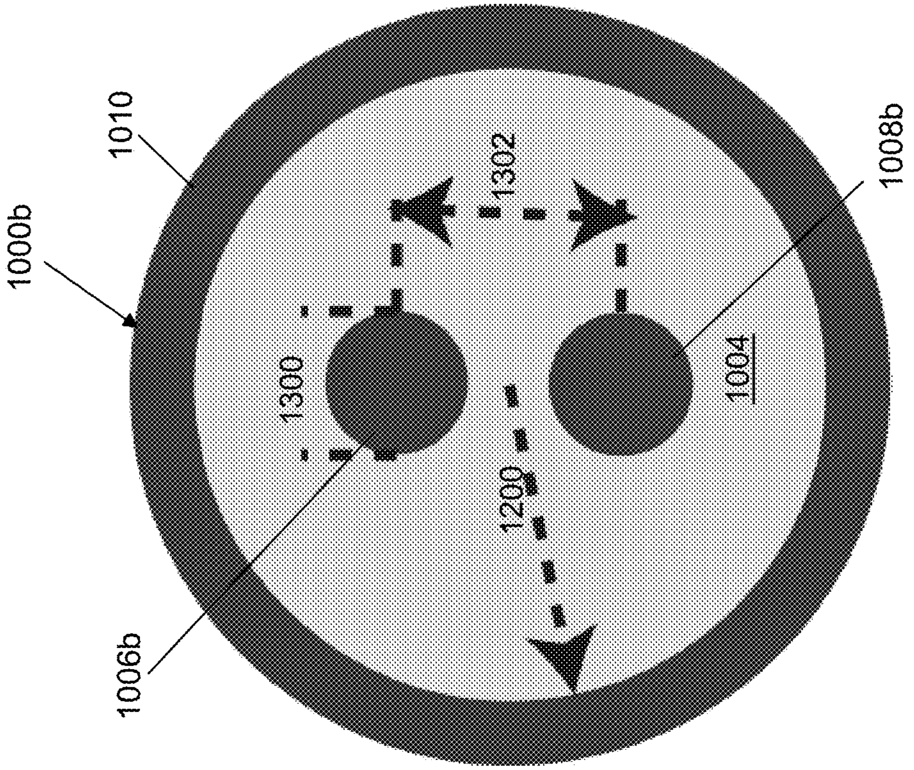

1000b
1010
1302
1008b
1300
1004
1200
1006b

Fig. 13

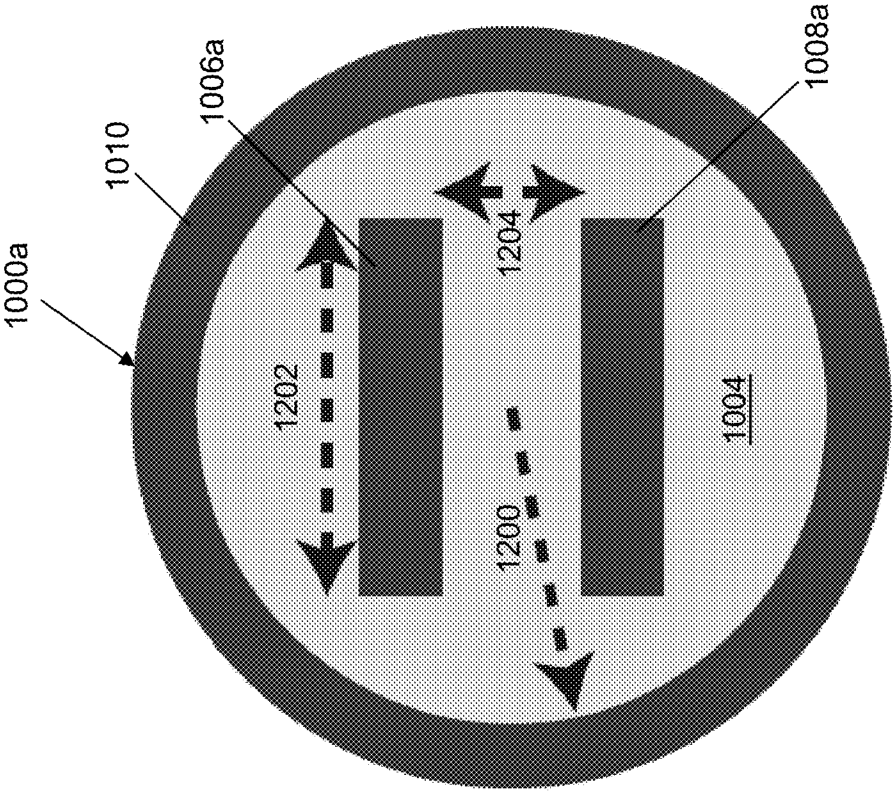

1000a
1010
1006a
1008a
1204
1202
1004
1200

Fig. 12

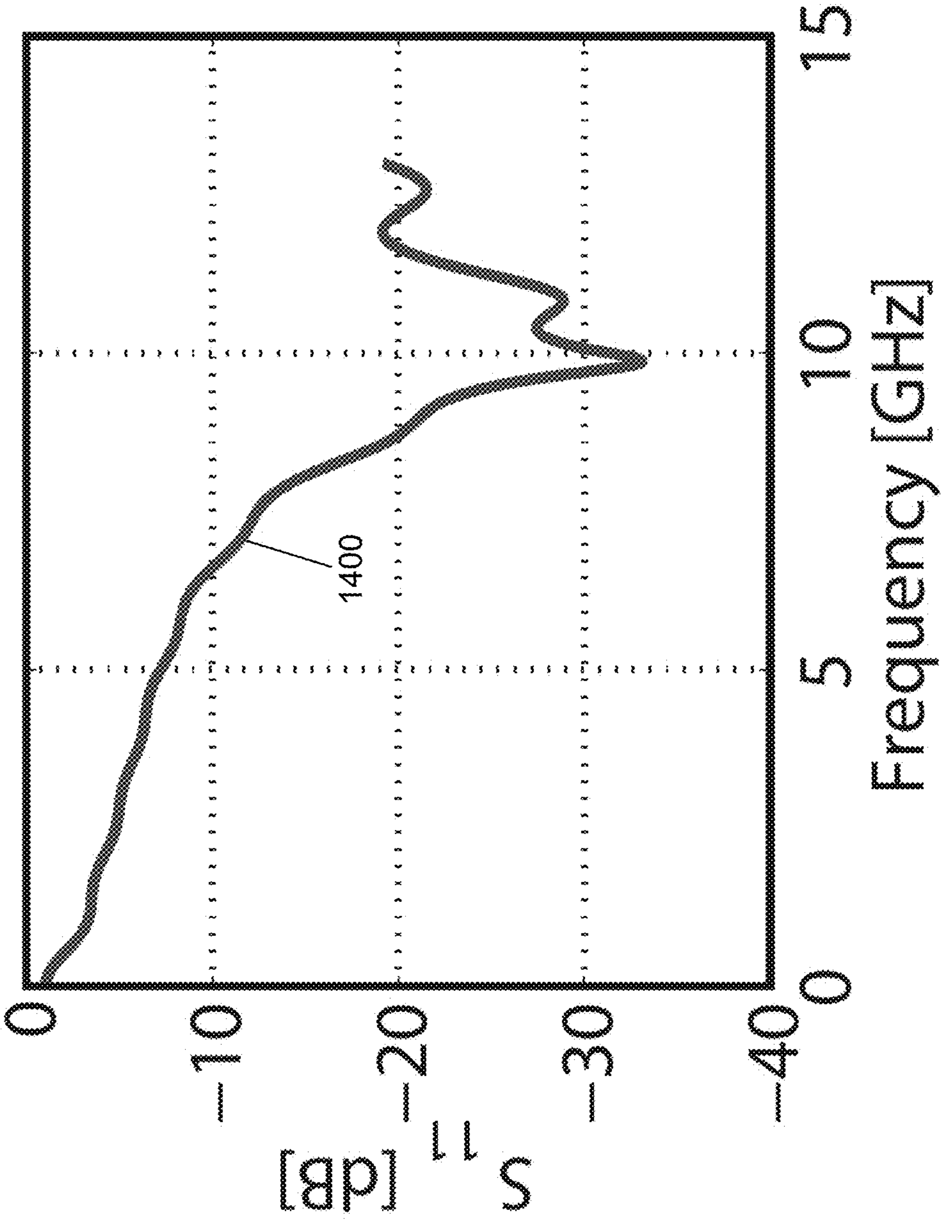


Fig. 14

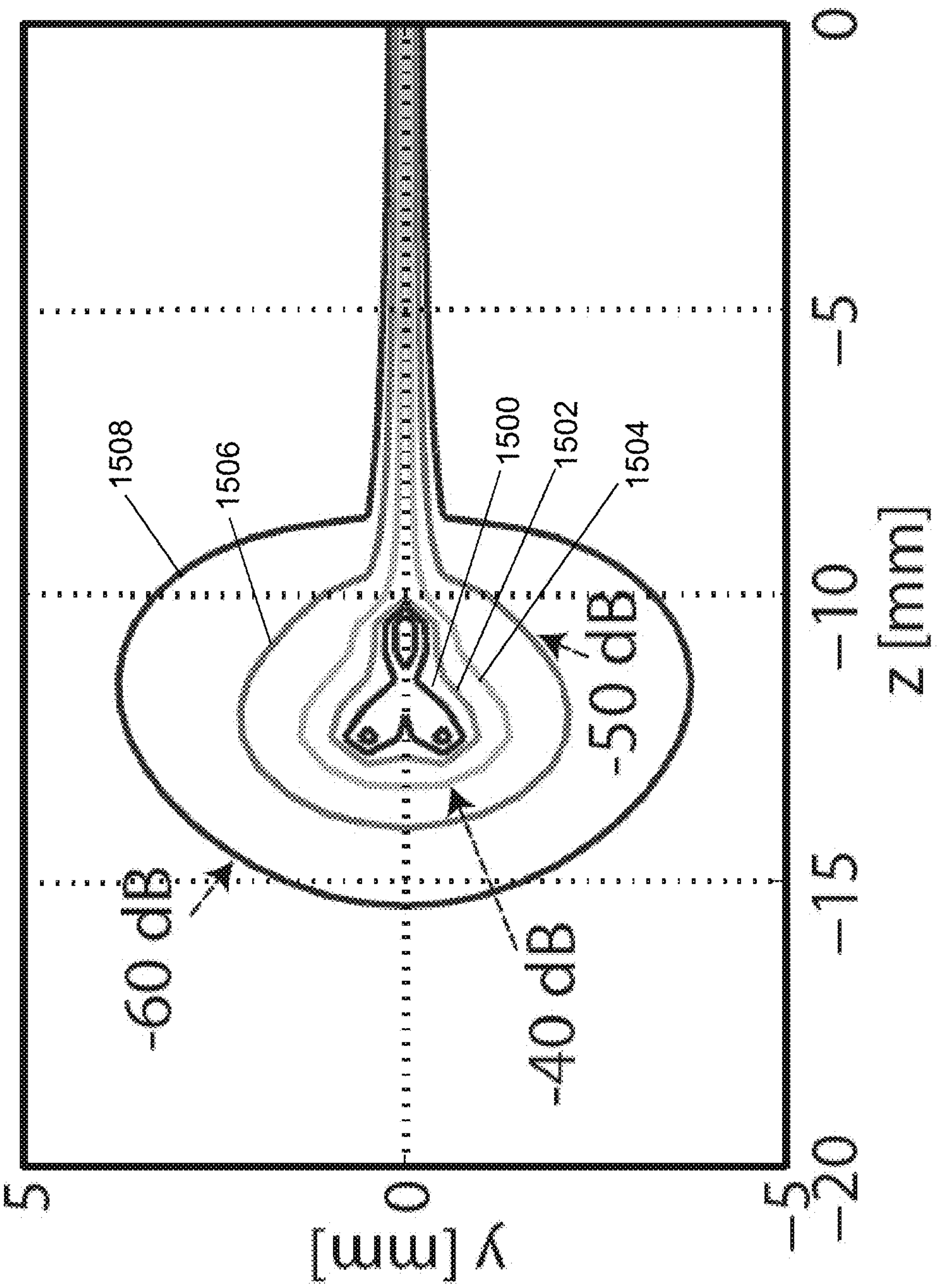


Fig. 15

MICROWAVE ABLATION ANTENNA SYSTEM

REFERENCE TO GOVERNMENT RIGHTS

This invention was made with government support under N00014-11-1-0618 awarded by the NAVY/ONR. 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. 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.

Typically, interstitial antennas used for MWA are implemented using coaxial cables. When a balanced antenna is fed by an unbalanced transmission line unwanted electric currents are excited on the outer conductors of the feeding coaxial cables. If not properly suppressed, these currents can result in undesired heating and potentially ablation of healthy tissue along the insertion path of the antenna. Balanced to unbalanced transformers (Baluns) are generally implemented to solve this problem. A balun uses a hollow circular conductor to encompass the feeding coaxial cable and, depending on the design, may or may not be electrically connected to it.

SUMMARY

An antenna system is provided. The antenna system includes, but is not limited to, a coaxial cable, an antenna, and an impedance matching structure. 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 conductor having an electrical length of half a wavelength at a selected operating frequency. The impedance matching structure includes, but is not limited to, a second center conductor mounted between an end of the center conductor of the coaxial cable and a feed end of the antenna. The impedance matching structure is configured to match an impedance of the coaxial cable to an impedance of the antenna.

A transmitter is provided that includes the antenna system, a signal generator, and a connector. The signal generator is configured to generate a signal at the selected operating frequency. The connector is configured to connect a second end of the coaxial cable opposite the end of the center conductor 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 block diagram of a microwave ablation (MWA) antenna system in accordance with an illustrative embodiment.

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

FIG. **3***a* depicts the view of the MWA antenna system of FIG. **2** and an equivalent circuit model of the MWA antenna system of FIG. **2** in accordance with an illustrative embodiment.

FIG. **3***b* depicts a view of a second MWA antenna system and an equivalent circuit model of the second MWA antenna system in accordance with an illustrative embodiment.

FIG. **3***c* depicts a view of a third MWA antenna system and an equivalent circuit model of the third MWA antenna system in accordance with an illustrative embodiment.

FIG. **3***d* depicts a view of a fourth MWA antenna system and an equivalent circuit model of the fourth MWA antenna system in accordance with an illustrative embodiment.

FIG. **4** shows a comparison between a simulated and a measured input impedance, S_{11}, of the MWA antenna system of FIG. **2** in accordance with an illustrative embodiment.

FIG. **5** shows a simulated specific absorption rate (SAR) pattern of the MWA antenna system of FIG. **2** in liver tissue in accordance with an illustrative embodiment.

FIG. **6** depicts a side cross sectional view of a second MWA antenna system of FIG. **1** in accordance with an illustrative embodiment.

FIG. **7** shows a simulated input impedance, S_{11}, of the MWA antenna system of FIG. **6** in liver tissue in accordance with an illustrative embodiment.

FIG. **8** shows a simulated SAR pattern of the MWA antenna system of FIG. **6** in the liver tissue in accordance with an illustrative embodiment.

FIG. **9** depicts a block diagram of a transmitter incorporating the MWA antenna system of FIG. **1** in accordance with an illustrative embodiment.

FIG. **10** depicts a side cross sectional view of a third MWA antenna system in accordance with an illustrative embodiment.

FIG. **11** depicts a side cross sectional view of a fourth MWA antenna system in accordance with an illustrative embodiment.

FIG. **12** depicts a front cross-sectional view of a two-wire transmission line of the third and/or fourth MWA antenna system of FIGS. **10** and **11** in accordance with an illustrative embodiment.

FIG. **13** depicts a front cross-sectional view of a second two-wire transmission line of the third and/or fourth MWA antenna system of FIGS. **10** and **11** in accordance with an illustrative embodiment.

FIG. **14** shows a simulated input impedance, S_{11}, of the MWA antenna system of FIG. **10** in the liver tissue in accordance with an illustrative embodiment.

FIG. **15** shows a simulated SAR pattern of the MWA antenna system of FIG. **10** in the liver tissue in accordance with an illustrative embodiment.

DETAILED DESCRIPTION

With reference to FIG. **1**, a block diagram of an antenna system **100** is shown in accordance with an illustrative embodiment. Antenna system **100** may include a coaxial cable **102**, an impedance matching structure **104**, and an antenna **106**. Impedance matching structure **104** is configured to match an impedance of coaxial cable **102** to an impedance of antenna **106**. Antenna system **100** may be used to perform microwave ablation (MWA), for example, of tissue. Antenna **106** may be any base fed monopole type antenna such as a monopole antenna, a helical antenna, a whip antenna, a rubber ducky antenna, a random wire antenna, an umbrella antenna, an inverted-L antenna, a T-antenna, a mast radiator, a ground plane antenna, a bent wire antenna, etc. Coaxial cable **102** may include any length of coaxial cable having any characteristic impedance.

With reference to FIG. **2**, a side cross-sectional view of a first antenna system **100***a* is shown in accordance with an illustrative embodiment. First antenna system **100***a* may include coaxial cable **102**, a first impedance matching structure **104***a*, and a first antenna **106***a*. First impedance matching structure **104***a* is configured to match the impedance of coaxial cable **102** to an impedance of first antenna **106***a*.

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 **106***a* is a helical antenna formed of a conducting wire wound in the form of a helix. The dimensions of the helix (diameter and pitch) are small compared with the wavelength so that first antenna **106***a* acts similar to a monopole antenna. First antenna **106***a* may include a feed connector **210** and a plurality of helical turns **212**. First antenna **106***a* is formed of a conductive material. The plurality of helical turns **212** have an electrical length of half a wavelength at a selected operating frequenc, which is also known as a second resonance mode. As known to a person of skill in the art, the wavelength of operation, λ_o, of antenna system **100** is defined as $\lambda_o=c/f_o$, where c is the speed of light in an environment in which antenna system **100** is used, such as a body tissue, and f_o is the selected operating frequency.

At a frequency where the electrical length of the plurality of helical turns **212** is approximately half a wavelength, an electric current at feed connector **210** achieves a minimum while the voltage is maximized. The resulting high input impedance creates a natural choke point for the currents that tend to flow on the outer surface of conductive shield **204** of coaxial cable **102** eliminating the need to use a balun. Despite the high feed-point impedance, matching between first antenna **106***a* and coaxial cable **102** can be achieved using first impedance matching structure **104***a*.

First impedance matching structure **104***a* is mounted between coaxial cable **102** and a feed end **219** of feed connector **210** of first antenna **106***a*. First impedance matching structure **104***a* may include a first capacitive section **220**, an inductive section **222**, and a second capacitive section **224**. First impedance matching structure **104***a* may be formed from an extension of coaxial cable **102**. First capacitive section **220**, inductive section **222**, and second capacitive section **224** may include center conductor **200** extending a length of first capacitive section **220**, inductive section **222**, and second capacitive section **224**. Feed connector **210** is electrically connected to center conductor **200** extending from second capacitive section **224**.

First capacitive section **220** further may include dielectric material **202** surrounding center conductor **200** along the length of first capacitive section **220**, conductive shield **204** surrounding dielectric material **202** along the length of first capacitive section **220**, and insulating jacket **206** surrounding conductive shield **204** along the length of first capacitive section **220**. A portion of dielectric material **202** is removed along the length of first capacitive section **220** adjacent conductive shield **204**. A second conductive material **226** is inserted to replace the removed portion of dielectric material **202**. In an alternative embodiment, all of dielectric material **202** is removed along the length of first capacitive section **220** adjacent conductive shield **204**, and conductive material **226** is inserted to replace a portion of the removed dielectric material **202** and a different, or the same, dielectric material is inserted to replace the remaining portion of the removed dielectric material **202**. In an illustrative embodiment, second conductive material **226** is copper.

Dielectric material **202** surrounding center conductor **200** may be removed along the length of inductive section **222** and replaced with a second dielectric material **228** having a lower dielectric constant than dielectric material **202**. In an illustrative embodiment, second dielectric material **228** is a gas such as air, oxygen, nitrogen, that has a dielectric constant close to that of vacuum, i.e., approximately one. Conductive shield **204** surrounds second dielectric material **228** along the length of inductive section **222** and insulating jacket **206** surrounds conductive shield **204** along the length of inductive section **222**.

Second capacitive section **224** further may include dielectric material **202** surrounding center conductor **200** along the length of second capacitive section **224**, conductive shield **204** surrounding dielectric material **202** along the length of second capacitive section **224**, and insulating jacket **206** surrounding conductive shield **204** along the length of second capacitive section **224**. A portion of dielectric material **202** is removed along the length of second capacitive section **224** adjacent conductive shield **204**. A third conductive material **230** is inserted to replace the removed portion of dielectric material **202**. In an alternative embodiment, all of dielectric material **202** is removed along the length of second capacitive section **224** adjacent conductive shield **204**, and third conductive material **230** is inserted to replace a portion of the removed dielectric material **202** and a different, or the same, dielectric material is inserted to replace the remaining portion of the removed dielectric material **202**. In an illustrative embodiment, third conductive material **230** is copper.

In an illustrative embodiment, insulating jacket **206** surrounds first antenna **106***a*. A cover **232** may extend across an end of insulating jacket **206** to enclose first antenna **106***a*. Insulating jacket **206** and cover **232** may be mounted to allow movement relative to first antenna **106***a* so that first antenna **106***a* is protected while antenna system **100***a* is inserted into a tissue and is exposed once inserted into the tissue.

Referring to FIG. **3***a*, the plurality of helical turns **212** of first antenna **106***a* have a diameter **300**, a total height **302**, and a number of turns, n. Diameter **300**, total height **302**, and n can be determined, for example, using CST Microwave Studio®, a three dimensional electromagnetic simulation tool developed by CST Computer Simulation Technology AG, to yield a desired, localized specific absorption rate (SAR) pattern. Feed connector **210** is generally circular and has a height **304**. To simplify fabrication, a diameter of feed connector **210** may be the same as a diameter of center conductor **200** and/or as a diameter of the wire that is used to create the plurality of helical turns **212**. The input impedance at feed end **219** of feed connector **210** is used to design first impedance matching structure **104***a*. For example, the input impedance can be computed using CST Microwave Studio®, another electromagnetic simulation tool, or measured experimentally. Height **304** may be determined by the electromagnetic simulation tool based on its effect on the desired high input impedance.

First capacitive section **220** has a first length **306**. Inductive section **222** has a second length **308**. Second capacitive section **224** has a third length **310**. Conductive shield **204** has an inner diameter **312** and an outer diameter **314**. Second conductive material **226** has an inner diameter **316**. Third conductive material **230** has an inner diameter **318**.

In the illustrative embodiment, first impedance matching structure **104***a* is a transmission line implementation of a π network of reactive elements as shown with reference to an equivalent circuit model **320**. Coaxial cable **102** is modeled as a coaxial transmission line having characteristic impedance **322**. First capacitive section **220** is modeled as a capacitor having a first capacitance **324**. Inductive section **222** is modeled as an inductor having an inductance **326**. Second capacitive section **224** is modeled as a capacitor having a second capacitance **328**.

As discussed previously, first capacitive section **220** and second capacitive section **224** may be formed using low-impedance coaxial-cable sections by inserting a hollow copper tube in the region between center conductor **200** and conductive shield **204** of coaxial cable **102**. The hollow copper tube is electrically connected to an inner surface of conductive shield **204** to form a new outer conductor with reduced inner diameters **316** and **318**. This increases the capacitance per unit length of coaxial cable **102**. Inductive section **222** may be formed using a section of coaxial cable **102** in which dielectric material **202** is removed to decrease the capacitance per unit length of the line.

The inductance per unit length of inductive section **222** can be increased by reducing a diameter of center conductor **200** along the length of inductive section **222** to achieve inductance **326** with a shorter length of transmission line. First capacitive section **220** and second capacitive section **224** further may be formed using the same or a different dielectric material that has a higher dielectric constant than the removed dielectric material **202** between center conductor **200** and conductive material **226** and between center conductor **200** and third conductive material **230**, respectively. This further increases the capacitance per unit length of first capacitive section **220** and second capacitive section **224** to achieve first capacitance **324** and second capacitance **328** with a shorter length of transmission line.

The values of first capacitance **324**, inductance **326**, and second capacitance **328** are chosen to provide an impedance match between first antenna **106***a* and coaxial cable **102**.

First length **306** of first capacitive section **220** may be estimated assuming a short transmission line approximation and using

$$C_1 \ln\left(\frac{b_1}{a}\right) \Big/ 2\pi\epsilon_1,$$

where C_1 is first capacitance **324**, b_1 is inner diameter **316** of second conductive material **226**, a is the diameter of center conductor **200**, and $\in_1$ is a permittivity of the dielectric material between center conductor **200** and second conductive material **226**.

Second length **308** of inductive section **222** may be estimated assuming a short transmission line approximation and using

$$2\pi L / \mu \ln\left(\frac{b}{a}\right),$$

where L is inductance **326**, b is inner diameter **312** of conductive shield **204**, and μ is a permeability of second dielectric material **228**.

Third length **310** of second capacitive section **224** may be estimated assuming a short transmission line approximation and using

$$C_2 \ln\left(\frac{b_2}{a}\right) \Big/ 2\pi\epsilon_2,$$

where C_2 is second capacitance **328**, b_2 is inner diameter **318** of third conductive material **230**, and $\in_2$ is a permittivity of the dielectric material between center conductor **200** and third conductive material **230**. In an illustrative embodiment, first length **306**, second length **308**, and third length **310** may be calculated using the parameters above and finely tuned using full wave electromagnetic (EM) simulations in CST Microwave Studio® or another EM simulation tool.

Referring to FIG. **3***b*, a second antenna **106***b* is a monopole antenna formed of conducting wire having a length **330**. Length **330** can be determined, for example, using CST Microwave Studio®, a three dimensional electromagnetic simulation tool developed by CST Computer Simulation Technology AG, to yield a desired, localized specific absorption rate (SAR) pattern. A cross section of second antenna **106***b* may be circular, square, elliptical, rectangular, etc. A base **331** of second antenna **106***b* is mounted to and extends from center conductor **200**. To simplify fabrication, a cross section of second antenna **106***b* may be the same as that of center conductor **200**. The input impedance at base **331** of second antenna **106***b* is used to design first impedance matching structure **104***a*.

Second antenna **106***b* has an electrical length of half a wavelength at the selected operating frequency. At the selected operating frequency where the electrical length of second antenna **106***b* is approximately half a wavelength, an electric current at base **331** of second antenna **106***b* achieves a minimum while the voltage is maximized resulting in a high input impedance that creates a natural choke point for the currents that tend to flow on the outer surface of conductive shield **204** of coaxial cable **102** eliminating the need to use a balun. Despite the high feed-point impedance, matching between second antenna **106***b* and coaxial cable **102** can be achieved using first impedance matching structure **104***a*.

Referring to FIG. **3***c*, a third antenna **106***c* is a bent wire antenna formed of a conducting wire bent to form a number of bends, n. Third antenna **106***c* has a width **340** and a total height **342**. The dimensions of the bent wire (diameter and pitch **343**) are small compared with the wavelength so that third antenna **106***c* acts similar to a monopole antenna. Third antenna **106***c* may include feed connector **210**. The number of bends, n, are mounted to and extend from feed connector **210**.

Width **340**, total height **342**, and the number of bends, n, can be determined, for example, using CST Microwave Studio®, a three dimensional electromagnetic simulation tool developed by CST Computer Simulation Technology AG, to yield a desired, localized specific absorption rate (SAR) pattern. To simplify fabrication, a cross section of feed connector **210** may be the same as a diameter of center conductor **200** and/or as a diameter of the wire that is used to create the number of bends, n. The input impedance at feed end **219** of feed connector **210** is used to design first impedance matching structure **104***a*. For example, the input impedance can be computed using CST Microwave Studio®, another electromagnetic simulation tool, or measured experimentally.

The number of bends, n, have an electrical length of half a wavelength at a selected operating frequency. At the selected operating frequency where the electrical length of the number of bends is approximately half a wavelength, an electric current at feed end **219** of feed connector **210** achieves a minimum while the voltage is maximized. The resulting high input impedance creates a natural choke point for the currents that tend to flow on the outer surface of conductive shield **204** of coaxial cable **102** eliminating the need to use a balun. Despite the high feed-point impedance, matching between third antenna **106***c* and coaxial cable **102** can be achieved using first impedance matching structure **104***a*.

First impedance matching structure **104***a* may include additional or fewer capacitive sections and additional inductive sections in alternative embodiments. For example, a second inductive section may be mounted to the left of first capacitive section **220**. As another example, referring to FIG. **3***d*, a second antenna system **100***b* is shown in accordance with an illustrative embodiment. Second antenna system **100***b* may include coaxial cable **102**, a second impedance matching structure **104***b*, and first antenna **106***a*.

Second impedance matching structure **104***b* is mounted between coaxial cable **102** and feed end **219** of feed connector **210** of first antenna **106***a*. Second impedance matching structure **104***b* may include a second inductive section **350** and a third capacitive section **352**. Second impedance matching structure **104***b* may be formed from an extension of coaxial cable **102**. Second inductive section **350** and third capacitive section **352** may include center conductor **200** extending a length of second inductive section **350** and third capacitive section **352**. Feed connector **210** is electrically connected to center conductor **200** extending from third capacitive section **352**.

Dielectric material **202** surrounding center conductor **200** may be removed along a fourth length **354** of second inductive section **350** and replaced with second dielectric material **228** having a lower dielectric constant than dielectric material **202**. Conductive shield **204** surrounds second dielectric material **228** along fourth length **354** of second inductive section **350** and insulating jacket **206** surrounds conductive shield **204** along fourth length **354** of second inductive section **350**.

Third capacitive section **352** further may include dielectric material **202** surrounding center conductor **200** along a fifth length **356** of third capacitive section **352**, conductive shield **204** surrounding dielectric material **202** along fifth length **356** of third capacitive section **352**, and insulating jacket **206** surrounding conductive shield **204** along fifth length **356** of third capacitive section **352**. A portion of dielectric material **202** may be removed along fifth length **356** of third capacitive section **352** adjacent conductive shield **204**. Third conductive material **230** is inserted to replace the removed portion of dielectric material **202**. In an alternative embodiment, all of dielectric material **202** is removed along fifth length **356** of third capacitive section **352** adjacent conductive shield **204**, and third conductive material **230** is inserted to replace a portion of the removed dielectric material **202** and a different, or the same, dielectric material is inserted to replace the remaining portion of the removed dielectric material **202**.

Second impedance matching structure **104***b* is a transmission line implementation of reactive elements as shown with reference to an equivalent circuit model **358**. Coaxial cable **102** is modeled as a coaxial transmission line having characteristic impedance **322**. Second inductive section **350** is modeled as an inductor having a second inductance **360**. Third capacitive section **352** is modeled as a capacitor having a third capacitance **362**. Second inductance **360** and third capacitance **362** are chosen to provide an impedance match between first antenna **106***a* and coaxial cable **102**.

Fourth length **354** of second inductive section **350** may be estimated assuming a short transmission line approximation and using

$$2\pi L/\mu\ln\left(\frac{b}{a}\right),$$

where L is second inductance **360**. Fifth length **356** of third capacitive section **352** may be estimated assuming a short transmission line approximation and using

$$C_2\ln\left(\frac{b_2}{a}\right)/2\pi\epsilon_2,$$

where C_2 is third capacitance **362**. In an illustrative embodiment, fourth length **354** and fifth length **356** may be calculated using the parameters above and finely tuned using full wave electromagnetic (EM) simulations in CST Microwave Studio® or another EM simulation tool.

Referring to FIG. **4**, a comparison between simulated and measured input impedance, S_{11}, of first antenna system **100***a* is shown in accordance with an illustrative embodiment. The simulated results assumed liver tissue; whereas, the measured results were obtained using a reference material that mimics liver tissue. A first curve **400** shows the measured input impedance S_{11}. A second curve **402** shows the simulated input impedance S_{11}.

An operating frequency f_o of first antenna **106***a* was selected as 1.9 GHz. Design parameters for first antenna **106***a* were diameter **300** equal 1.6 millimeters (mm), total height **302** equal 20 mm, height **304** equal 2 mm, and n equal 10 turns. Characteristic impedance **322** of coaxial cable **102** was 50 ohms. Design parameters for first capacitive section **220** were first length **306** equal 22 mm, a equal 0.574 mm, b_1 equal 0.876 mm of copper tubing, and $\in_1$ is the permittivity of polytetrafluoroethylene. Design parameters for second capacitive section **224** were third length **310** equal 6 mm, a equal 0.574 mm, b_2 equal 0.876 mm of copper tubing, and $\in_1$ is the permittivity of Teflon® (polytetrafluoroethylene). Design parameters for inductive section **222** were second length **308** equal 18 mm, a equal 0.574 mm, b equal 1.676 mm of copper tubing, and μ is the permeability of air.

Coaxial cable **102** consisted of 50Ω UT-085C-LL semi-rigid coaxial cable with a maximum outer diameter of 2.197 mm. First antenna **106***a* was placed in a Teflon® catheter with an outer diameter of 3.2 mm. The relatively large dimensions were chosen to simplify the fabrication process during the proof-of-concept demonstration phase. The outer diameter of first antenna **106***a* can be significantly reduced with a proper choice of a smaller coaxial cable **102** and a correspondingly thinner catheter. The dimensions of the helical antenna and matching section indicated in the preceding paragraph were optimized to provide good impedance matching and a localized SAR pattern at 1.9 GHz.

First curve **400** of the fabricated antenna was measured using a vector network analyzer when first antenna **106***a* was inserted in a 45:55 mixture of methanol and deionized water, whose relative permittivity at 1.9 GHz matches the liver tissue assumed in the simulation. The prototype was initially fabricated with the same dimensions as those determined in the simulations. However, a slight shift in the operating frequency was observed. Specifically, first antenna **106***a* was matched at 2.05 GHz instead of 1.90 GHz. This was attributed to the non-idealities that exist in the fabricated prototype (e.g. slight deviation of the fabricated dimensions, air gaps in the Teflon® insulation layer of first capacitive section **220** and second capacitive section **224**, etc.). This frequency shift, however, was eliminated in a second prototype, wherein first length **306** was increased from 22 mm to 24 mm and third length **310** was increased from 6 mm to 7 mm. The measured S**11** of this prototype is shown in second curve **402** and shows excellent impedance matching at 1.9 GHz. In both prototypes, the S**11** measurements were stable as the insertion depth of first antenna **106***a* was changed indicating that no currents are excited on conductive shield **204**.

Referring to FIG. **5**, a simulated normalized SAR pattern of first antenna **106***a* inserted into liver tissue at the insertion depth of 85 mm is shown. The simulated normalized SAR pattern includes a −5 dB curve **500**, a −10 dB curve **502**, a −15 dB curve **504**, and a −20 dB curve **506**. The SAR levels are reduced by more than 20 dB compared to a maximum SAR value at a longitudinal distance of 60 mm from the tip of first antenna **106***a*. The localization of the SAR pattern indicates that the currents excited on conductive shield **204** of coaxial cable **102** are effectively suppressed by the high input impedance at feed connector **210** of first antenna **106***a*.

The balun is eliminated by using first antenna **106***a* at a frequency where its input impedance is very high, which effectively chokes the currents on an outer surface of coaxial cable **102** and acts as a natural balun. Despite the high feed-point impedance, first impedance matching structure **104***a* is used to achieve impedance matching between first antenna **106***a* and coaxial cable **102**. The simulated SAR pattern of first antenna **106***a* verifies localized heating potential at the desired frequency of operation. First antenna system **100***a* offers a practical solution to decrease an overall diameter of coax-fed interstitial antennas and to reduce the invasiveness of the MWA treatment.

With reference to FIG. **6**, a side cross-sectional view of a third antenna system **100***c* is shown in accordance with an illustrative embodiment. Third antenna system **100***c* may include coaxial cable **102**, a third impedance matching structure **104***c*, and first antenna **106***a*. Third impedance matching structure **104***c* is configured to match the impedance of coaxial cable **102** to the impedance of first antenna **106***a*. Third impedance matching structure **104***c* may be formed from an extension of coaxial cable **102**. Third impedance matching structure **104***c* may include a second center conductor **600**, a third dielectric material **602**, conductive shield **204**, and insulating jacket **206**. Feed connector **210** is electrically connected to second center conductor **600**. Third impedance matching structure **104***c* is mounted between coaxial cable **102** and feed end **219** of feed connector **210** of first antenna **106***a*.

Third dielectric material **602** surrounds second center conductor **600** along a length **604** of third impedance matching structure **104***c*, conductive shield **204** surrounds third dielectric material **602** along length **604** of third impedance matching structure **104***c*, and insulating jacket **206** surrounds conductive shield **204** along length **604** of third impedance matching structure **104***c*.

Second center conductor **600** may be formed by removing a portion of the diameter of center conductor **200**. Dielectric material **202** surrounding center conductor **200** is removed along length **604** of third impedance matching structure **104***c* and replaced with third dielectric material **602** having a lower dielectric constant than dielectric material **202**. In an illustrative embodiment, third dielectric material **602** is air. In an illustrative embodiment, length **604** is a quarter-wavelength.

Third impedance matching structure **104***c* may be modeled as a transformer. The characteristic impedance of third impedance matching structure **104***c* may be determined from

$$Z' = \frac{1}{2\pi}\sqrt{\mu/\varepsilon}\,\ln\frac{b}{a'},$$

where b is inner diameter **312** of conductive shield **204**, a' is the diameter of second center conductor **600**, μ is a permeability of third dielectric material **602**, and E is a permittivity of third dielectric material **602**. $Z'=\sqrt{Z_0 Z_{in}}$, where Z_0 is characteristic impedance **322** of coaxial cable **102**, and Z_{in} is the input impedance of first antenna **106***a* at feed end **219** of feed connector **210**. The diameter of second center conductor **600** may be determined as

$$a' = \frac{b}{e^{z' 2\pi\sqrt{\frac{\varepsilon}{\mu}}}}.$$

Referring to FIG. **7**, a simulated input impedance, S_{11}, of third antenna system **100***c* in liver tissue is shown in accordance with an illustrative embodiment. A curve **700** shows the simulated input impedance S_{11}. An operating frequency f_o of first antenna **106***a* was selected as 10 GHz. Design parameters for first antenna **106***a* were diameter **300** equal 2.2 mm, total height **302** equal 2 mm, height **304** equal 0.75 mm, and n equal

$$1\frac{1}{8}$$

turns. Characteristic impedance **322** of coaxial cable **102** was 50 ohms. Design parameters for third impedance matching structure **104***c* were length **604** equal 5 mm, a equal 0.512 mm, b equal 1.676 mm, the diameter of second center conductor **600** equal 0.18 mm, and μ is the permeability of air. The simulated S11 shown in curve **700** shows excellent impedance matching at 10 GHz.

Referring to FIG. **8**, a simulated normalized SAR pattern of first antenna **106***a* of third antenna system **100***c* inserted into liver tissue at an insertion depth of 53 mm is shown. The simulated normalized SAR pattern includes a −5 dB curve **800**, a −10 dB curve **802**, a −15 dB curve **804**, a −20 dB curve **806**, a −25 dB curve **808**, and a −30 dB curve **810**. The SAR levels are reduced by more than 30 dB compared to a maximum SAR value at a longitudinal distance of 15 mm from the tip of first antenna **106***a*. The localization of the SAR pattern indicates that the currents excited on conductive shield **204** of coaxial cable **102** are effectively suppressed by the high feed point impedance of the antenna.

Referring to FIG. **9**, a block diagram of a transmitter **900** is shown in accordance with an illustrative embodiment. Transmitter **900** may include a signal generator **902**, a connector **904**, and antenna system **100**. Signal generator **902** generates an analog signal at the operating frequency selected for antenna system **100**. A duty cycle of the analog signal may be controlled by signal generator **902** based, for example, on an ablation zone size and heating rate. Connector **904** connects a second end of coaxial cable **102** opposite the end of center conductor **200** that mounts to impedance matching structure **104** to signal generator **902**. Connector **904** may be a coaxial connector designed to maintain the coaxial form across the connection and having the same impedance as coaxial cable **102**. Antenna system **100** receives the analog signal with a matching impedance at a feed end and radiates an electromagnetic wave into the surrounding tissue.

With reference to FIG. **10**, a side cross-sectional view of a fourth antenna system **100***d* is shown in accordance with an illustrative embodiment. Fourth antenna system **100***d* may be used to perform MWA. Fourth antenna system **100***d* may include a two-wire balanced cable **1000** and a fourth antenna **1002**. Two-wire balanced cable **1000** is a balanced transmission line composed of a two-conductor, balanced line enclosed by a floating shield. Two-wire balanced cable **1000** may include a dielectric material **1004**, a first conductive line **1006**, a second conductive line **1008**, and a floating shield **1010**. Floating shield **1010** may have a floating potential instead of being grounded.

Two-wire balanced cable **1000** may include any length of cable having any characteristic impedance. First conductive line **1006** and second conductive line **1008** are parallel to each other and extend along a length of two-wire balanced cable **1000**. First conductive line **1006** and second conductive line **1008** may be formed of a solid conductive material such as copper plated steel, silver plated steel, silver plated copper, silver plated copper clad steel, copper, copper clad aluminum, steel, etc. Dielectric material **1004** may include foamed polyethylene, solid polyethylene, polyethylene foam, polytetrafluoroethylene, air, air space polyethylene, vacuum, etc. Dielectric material **1004** surrounds both first conductive line **1006** and second conductive line **1008** along the length of two-wire balanced cable **1000** to maintain a uniform spacing between first conductive line **1006** and second conductive line **1008**. Floating shield **1010** can be made from many different conductive materials such as copper, aluminum, etc. Floating shield **1010** surrounds dielectric material **1004** along the length of two-wire balanced cable **1000**.

A current flow in first conductive line **1006** is balanced by a current flow in second conductive line **1008**. Floating shield **1010** contains the fields of first conductive line **1006** and second conductive line **1008** and ensures that the fields do not penetrate into the tissue surrounding floating shield **1010**.

Fourth antenna **1002** may be any base fed balanced type antenna such as a dipole antenna, a loop antenna, etc. In the illustrative embodiment of FIG. **10**, fourth antenna **1002** is a dipole antenna. Fourth antenna **1002** may include a first arm **1012** and a second arm **1014**. First arm **1012** may include a third conductive line **1016** surrounded by a second dielectric material **1018** along a length **1020** of first arm **1012**. Third conductive line **1016** may be an extension of first conductive line **1006**, and second dielectric material **1018** may be an extension of dielectric material **1004**. Second arm **1014** may include a fourth conductive line **1022** surrounded by a third dielectric material **1024** along a length **1026** of second arm **1014**. Fourth conductive line **1022** may be an extension of second conductive line **1008**, and third dielectric material **1024** may be an extension of dielectric material **1004**. First arm **1012** and second arm **1014** extend from two-wire balanced cable **1000** at an angle **1028** formed between first arm **1012** and second arm **1014**.

With reference to FIG. **11**, a side cross-sectional view of a fifth antenna system **100***e* is shown in accordance with an illustrative embodiment. Fifth antenna system **100***e* may be used to perform MWA. Fifth antenna system **100***e* may include two-wire balanced cable **1000** and a fifth antenna **1100**. In the illustrative embodiment of FIG. **11**, fifth antenna **1100** is a loop antenna. Fifth antenna **1100** may include a fifth conductive line **1102** surrounded by a fourth dielectric material **1104**. Fifth conductive line **1102** may connect between first conductive line **1006** and second conductive line **1008** of two-wire balanced cable **1000**. Fourth dielectric material **1104** may be an extension of dielectric material **1004**. Fifth conductive line **1102** has a radius **1106** and a width **1108**.

With reference to FIG. **12**, a front cross-sectional view of a first two-wire balanced cable **1000***a* is shown in accordance with an illustrative embodiment. First two-wire balanced cable **1000***a* may include dielectric material **1004**, a first conductive line **1006***a*, a second conductive line **1008***a*, and floating shield **1010**. Dielectric material **1004** has a radius **1200**. First conductive line **1006***a* and second conductive line **1008***a* are formed of rectangular strips having a width **1202** and separated by a distance **1204**.

With reference to FIG. **13**, a front cross-sectional view of a second two-wire balanced cable **1000***b* is shown in accordance with an illustrative embodiment. Second two-wire balanced cable **1000***b* may include dielectric material **1004**, a first conductive line **1006***b*, a second conductive line **1008***b*, and floating shield **1010**. Dielectric material **1004** has radius **1200**. First conductive line **1006***b* and second conductive line **1008***b* are formed of circular wires having a diameter **1300** and separated by a distance **1302**.

Referring to FIG. **14**, a simulated input impedance, S_{11}, of fourth antenna system **100***d* in liver tissue is shown in accordance with an illustrative embodiment. A curve **1400** shows the simulated input impedance S_{11}. An operating frequency f_o of fourth antenna **1002** was selected as 10 GHz. Fourth antenna **1002** was fed by first two-wire balanced cable **1000***a*. Design parameters for first two-wire balanced cable **1000***a* are radius **1200** equal 0.2 mm, width **1202** equal

0.3 mm, and distance **1204** equal 0.05 mm. Length **1020** of first arm **1012** and length **1026** of second arm **1014** were equal to 2 mm and angle **1028** between first arm **1012** and second arm **1014** was 20°. A full-wave EM simulation was conducted to predict the response of third antenna system **100***c* in liver tissue. The simulated S**11** shown in curve **1400** shows excellent impedance matching at 10 GHz.

Referring to FIG. **15**, a simulated normalized SAR pattern of fourth antenna **1002** inserted into liver tissue at an insertion depth of 57 mm is shown. The simulated normalized SAR pattern includes a −20 dB curve **1500**, a −30 dB curve **1502**, a −40 dB curve **1504**, a −50 dB curve **1506**, and a −60 dB curve **1508**. The SAR levels are reduced by more than 60 dB compared to a maximum SAR value at a longitudinal distance of 5 mm from the tip of fourth antenna **1002**. The SAR pattern is localized to the region surrounding fourth antenna **1002** and is cut off along first two-wire balanced cable **1000***a*. The maximum SAR level in the area immediately outside of floating shield **1010** of first two-wire balanced cable **1000***a* is at least 60 dB below the peak SAR value. This indicates that no electric current flows on an outer surface of floating shield **1010**.

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

a base fed monopole type antenna comprising a conductor having an electrical length of half a wavelength at a selected operating frequency for the antenna system, wherein the conductor is configured to radiate an electromagnetic wave into surrounding tissue when the antenna system is used; and

an impedance matching structure comprising

- a second center conductor located between an end of the center conductor of the coaxial cable and a feed connector of the antenna as a continuous extension of the first conductive material of the center conductor of the coaxial cable;
- a second conductive shield that is a continuous extension of the second conductive material of the conductive shield of the coaxial cable;
- a capacitive section located adjacent a feed end of the feed connector of the antenna, the capacitive section comprising
  - a second dielectric material surrounding a portion of the second center conductor that extends the length of the capacitive section; and
  - a third conductive material that surrounds the second dielectric material along the length of the capacitive section,
- wherein a portion of the second conductive shield that extends the length of the capacitive section surrounds the third conductive material; and

an inductive section located adjacent the capacitive section on a side of the capacitive section opposite the feed end of the feed connector of the antenna, the inductive section comprising

- a third dielectric material surrounding a portion of the second center conductor that extends the length of the inductive section,
- wherein a portion of the second conductive shield that extends the length of the inductive section surrounds the third dielectric material,

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

2. The antenna system of claim **1**, wherein the selected operating frequency is greater than or equal to 300 megahertz and less than or equal to 300 gigahertz.

3. The antenna system of claim **2**, wherein the selected operating frequency is greater than or equal to 300 megahertz and less than or equal to 6 gigahertz.

4. The antenna system of claim **1**, wherein an insulating material surrounds the conductive shield along the length of the coaxial cable.

5. The antenna system of claim **4**, wherein the insulating material further surrounds the second conductive shield along the length of the impedance matching structure.

6. The antenna system of claim **5**, wherein the insulating material further surrounds the length of the base fed monopole type antenna.

7. The antenna system of claim **6**, wherein a cover extends across an end of the insulating material to enclose the base fed monopole type antenna.

8. The antenna system of claim **7**, wherein the insulating material and the cover are moveable relative to the conductor so that, when inserted into the surrounding tissue, the conductor is exposed to the surrounding tissue.

9. The antenna system of claim **1**, wherein the feed connector of the antenna extends directly from and in alignment with the second center conductor, wherein the feed connector mounts the conductor to the second center conductor.

10. The antenna system of claim **1**, wherein a diameter of the second center conductor is smaller than a diameter of the center conductor of the coaxial cable along the length of the inductive section.

11. The antenna system of claim **10**, wherein the diameter of the second center conductor along the length of the inductive section is determined as

$$a' = \frac{b}{e^{z' 2\pi \sqrt{\frac{\varepsilon}{\mu}}}},$$

where a' is the diameter of the second center conductor, L is an inductance of the inductive section selected to match the impedance, b is an inner diameter of the conductive shield, μ is a permeability of the third dielectric material, and ε is a permittivity of the third dielectric material.

12. The antenna system of claim **1**, wherein a dielectric constant of the third dielectric material is less than a dielectric constant of the second dielectric material, and is less than a dielectric constant of the first dielectric material.

13. The antenna system of claim **12**, wherein the third dielectric material has a dielectric constant approximately equal to one.

14. The antenna system of claim **12**, wherein a length of the third dielectric material along the length of the inductive section is determined as

$$\ell = 2\pi L / \mu \ln\left(\frac{b}{a}\right),$$

where L is an inductance of the inductive section selected to match the impedance, μ is a permeability of the third dielectric material, b is an inner diameter of the second conductive shield, and a is a diameter of the second center conductor.

15. The antenna system of claim **1**, wherein the inductive section is connected between the capacitive section and the coaxial cable.

16. The antenna system of claim **1**, wherein the impedance matching structure further comprises:

a second capacitive section connected between the inductive section and the coaxial cable, wherein the second center conductor extends through the second capacitive section, the second capacitive section comprising

a fourth dielectric material surrounding a portion of the second center conductor that extends the length of the second capacitive section; and

a fourth conductive material that surrounds the fourth dielectric material along the length of the second capacitive section,

wherein a portion of the second conductive shield that extends the length of the second capacitive section surrounds the fourth conductive material.

17. The antenna system of claim **1**, wherein the conductive shield and the second conductive shield have a constant outer diameter.

18. The antenna system of claim **1**, wherein a length of the capacitive section is determined as

$$\ell = C \ln\left(\frac{b}{a}\right) \Big/ (2\pi\varepsilon),$$

where C is a capacitance of the capacitive section selected to match the impedance, b is an inner diameter of the third conductive material, and a is a diameter of the second center conductor, and ε is a permittivity of the second dielectric material.

19. The antenna system of claim **1**, wherein a dielectric constant of the second dielectric material is greater than a dielectric constant of the first dielectric material.

20. A transmitter comprising:

an antenna system comprising

a coaxial cable comprising

a center conductor extending a length of the coaxial cable made of a first conductive material;

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

a conductor surrounding the first dielectric material along the length of the coaxial cable made of a second conductive material;

a base fed monopole type antenna comprising a conductor having an electrical length of half a wavelength at a selected operating frequency for the antenna system,

wherein the conductor is configured to radiate an electromagnetic wave into surrounding tissue when the antenna system is used; and

an impedance matching structure comprising

a second center conductor located between an end of the center conductor of the coaxial cable and a feed connector of the antenna as a continuous extension of the first conductive material of the center conductor of the coaxial cable;

a second conductive shield that is a continuous extension of the second conductive material of the conductive shield of the coaxial cable;

a capacitive section located adjacent a feed end of the feed connector of the antenna, the capacitive section comprising

a second dielectric material surrounding a portion of the second center conductor that extends the length of the capacitive section; and

a third conductive material that surrounds the second dielectric material along the length of the capacitive section,

wherein a portion of the second conductive shield that extends the length of the capacitive section surrounds the third conductive material; and

an inductive section located adjacent the capacitive section on a side of the capacitive section opposite the feed end of the feed connector of the antenna, the inductive section comprising

a third dielectric material surrounding a portion of the second center conductor that extends the length of the inductive section,

wherein a portion of the second conductive shield that extends the length of the inductive section surrounds the third dielectric material,

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

a signal generator configured to generate a signal at the selected operating frequency; and a connector configured to connect a second end of the coaxial cable opposite the end of the center conductor to the signal generator to receive the generated signal.

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