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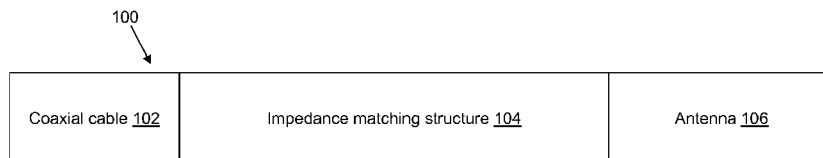


Fig. 1

(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.



WO 2015/138050 A1

MICROWAVE ABLATION ANTENNA SYSTEM

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims priority to U.S. Patent Application No. 14/202,786 that was filed March 10, 2014, the entire contents of which is hereby incorporated by reference.

BACKGROUND

[0002] 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.

[0003] 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

[0004] 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.

[0005] 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.

[0006] 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

[0007] Illustrative embodiments of the disclosed subject matter will hereafter be described referring to the accompanying drawings, wherein like numerals denote like elements.

[0008] Fig. 1 depicts a block diagram of a microwave ablation (MWA) antenna system in accordance with an illustrative embodiment.

[0009] Fig. 2 depicts a side cross sectional view of an MWA antenna system of Fig. 1 in accordance with an illustrative embodiment.

[0010] Fig. 3a 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.

[0011] Fig. 3b 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.

[0012] Fig. 3c 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.

[0013] Fig. 3d 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.

[0014] 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.

[0015] 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.

[0016] Fig. 6 depicts a side cross sectional view of a second MWA antenna system of Fig. 1 in accordance with an illustrative embodiment.

[0017] 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.

[0018] 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.

[0019] Fig. 9 depicts a block diagram of a transmitter incorporating the MWA antenna system of Fig. 1 in accordance with an illustrative embodiment.

[0020] Fig. 10 depicts a side cross sectional view of a third MWA antenna system in accordance with an illustrative embodiment.

[0021] Fig. 11 depicts a side cross sectional view of a fourth MWA antenna system in accordance with an illustrative embodiment.

[0022] 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.

[0023] 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.

[0024] 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.

[0025] 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

[0026] 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.

[0027] With reference to Fig. 2, a side cross-sectional view of a first antenna system 100a is shown in accordance with an illustrative embodiment. First antenna system 100a may include coaxial cable 102, a first impedance matching structure 104a, and a first antenna 106a. First impedance matching structure 104a is configured to match the impedance of coaxial cable 102 to an impedance of first antenna 106a.

[0028] 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.

[0029] 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.

[0030] First antenna 106a 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 106a acts similar to a monopole antenna. First antenna 106a may include a feed connector 210 and a plurality of helical turns 212. First antenna 106a is formed of a conductive material. The plurality of helical turns 212 have an electrical length of half a wavelength at a selected operating frequency. 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.

[0031] 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 106a and coaxial cable 102 can be achieved using first impedance matching structure 104a.

[0032] First impedance matching structure 104a is mounted between coaxial cable 102 and a feed end 219 of feed connector 210 of first antenna 106a. First impedance matching structure 104a may include a first capacitive section 220, an inductive section 222, and a second capacitive section 224. First impedance matching structure 104a 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.

[0033] 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.

[0034] 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.

[0035] 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.

[0036] In an illustrative embodiment, insulating jacket 206 surrounds first antenna 106a. A cover 232 may extend across an end of insulating jacket 206 to enclose first antenna 106a. Insulating jacket 206 and cover 232 may be mounted to allow movement relative to first antenna 106a so that first antenna 106a is protected while antenna system 100a is inserted into a tissue and is exposed once inserted into the tissue.

[0037] Referring to Fig. 3a, the plurality of helical turns 212 of first antenna 106a 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 104a. 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.

[0038] 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.

[0039] In the illustrative embodiment, first impedance matching structure 104a 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.

[0040] 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.

[0041] 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.

[0042] The values of first capacitance 324, inductance 326, and second capacitance 328 are chosen to provide an impedance match between first antenna 106a and coaxial cable 102.

[0043] First length 306 of first capacitive section 220 may be estimated assuming a short transmission line approximation and using $C_1 \ln\left(\frac{b_1}{a}\right)/2\pi\epsilon_1$, 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 ϵ_1 is a permittivity of the dielectric material between center conductor 200 and second conductive material 226.

[0044] 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.

[0045] Third length 310 of second capacitive section 224 may be estimated assuming a short transmission line approximation and using $C_2 \ln\left(\frac{b_2}{a}\right)/2\pi\epsilon_2$, where C_2 is second capacitance 328, b_2 is inner diameter 318 of third conductive material 230, and ϵ_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.

[0046] Referring to Fig. 3b, a second antenna 106b 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 106b may be circular, square, elliptical, rectangular, etc. A base 331 of second antenna 106b is mounted to and extends from center conductor 200. To simplify fabrication, a cross section of second antenna 106b may be the same as that of center conductor 200. The input impedance at base 331 of second antenna 106b is used to design first impedance matching structure 104a.

[0047] Second antenna 106b 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 106b is approximately half a wavelength, an electric current at base 331 of second antenna 106b 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 106b and coaxial cable 102 can be achieved using first impedance matching structure 104a.

[0048] Referring to Fig. 3c, a third antenna 106c is a bent wire antenna formed of a conducting wire bent to form a number of bends, n . Third antenna 106c 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 106c acts similar to a monopole antenna. Third antenna 106c may include feed connector 210. The number of bends, n , are mounted to and extend from feed connector 210.

[0049] 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 104a. For example, the input impedance can be computed using CST Microwave Studio®, another electromagnetic simulation tool, or measured experimentally.

[0050] 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 106c and coaxial cable 102 can be achieved using first impedance matching structure 104a.

[0051] First impedance matching structure 104a 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. 3d, a second antenna system 100b is shown in accordance with an illustrative embodiment. Second antenna

system 100b may include coaxial cable 102, a second impedance matching structure 104b, and first antenna 106a.

[0052] Second impedance matching structure 104b is mounted between coaxial cable 102 and feed end 219 of feed connector 210 of first antenna 106a. Second impedance matching structure 104b may include a second inductive section 350 and a third capacitive section 352. Second impedance matching structure 104b 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.

[0053] 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.

[0054] 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.

[0055] Second impedance matching structure 104b 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 106a and coaxial cable 102.

[0056] 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.

[0057] Referring to Fig. 4, a comparison between simulated and measured input impedance, S_{11} , of first antenna system 100a 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} .

[0058] An operating frequency f_o of first antenna 106a was selected as 1.9 GHz. Design parameters for first antenna 106a 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 ϵ_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 ϵ_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.

[0059] Coaxial cable 102 consisted of 50 Ω UT-085C-LL semi-rigid coaxial cable with a maximum outer diameter of 2.197 mm. First antenna 106a 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 106a 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.

[0060] First curve 400 of the fabricated antenna was measured using a vector network analyzer when first antenna 106a 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 106a 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 S11 of this prototype is shown in second curve 402 and shows excellent impedance matching at 1.9 GHz. In both prototypes, the S11 measurements were stable as the insertion depth of first antenna 106a was changed indicating that no currents are excited on conductive shield 204.

[0061] Referring to Fig. 5, a simulated normalized SAR pattern of first antenna 106a 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 106a. 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 106a.

[0062] The balun is eliminated by using first antenna 106a 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 104a is used to achieve impedance matching between first antenna 106a and coaxial cable 102. The simulated SAR pattern of first antenna 106a verifies localized heating potential at the desired frequency of operation. First antenna system 100a offers a practical solution to decrease an overall diameter of coax-fed interstitial antennas and to reduce the invasiveness of the MWA treatment.

[0063] With reference to Fig. 6, a side cross-sectional view of a third antenna system 100c is shown in accordance with an illustrative embodiment. Third antenna system 100c may include coaxial cable 102, a third impedance matching structure 104c, and first antenna 106a. Third impedance matching structure 104c is configured to match the impedance of coaxial cable 102 to the impedance of first antenna 106a. Third impedance matching structure 104c may be formed from an extension of coaxial cable 102. Third impedance matching structure 104c 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 104c is mounted between coaxial cable 102 and feed end 219 of feed connector 210 of first antenna 106a.

[0064] Third dielectric material 602 surrounds second center conductor 600 along a length 604 of third impedance matching structure 104c, conductive shield 204 surrounds third dielectric material 602 along length 604 of third impedance matching structure 104c, and insulating jacket 206 surrounds conductive shield 204 along length 604 of third impedance matching structure 104c.

[0065] 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 104c 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.

[0066] Third impedance matching structure 104c may be modeled as a transformer. The characteristic impedance of third impedance matching structure 104c 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 ε 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 106a at feed end 219 of feed connector 210. The diameter of second center conductor 600 may be determined as $a' = \frac{b}{e^{\frac{Z' 2\pi \sqrt{\varepsilon}}{\mu}}}$.

[0067] Referring to Fig. 7, a simulated input impedance, S_{11} , of third antenna system 100c 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 106a was selected as 10 GHz. Design parameters for first antenna 106a 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 104c 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 S_{11} shown in curve 700 shows excellent impedance matching at 10 GHz.

[0068] Referring to Fig. 8, a simulated normalized SAR pattern of first antenna 106a of third antenna system 100c 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 106a. 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.

[0069] 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.

[0070] With reference to Fig. 10, a side cross-sectional view of a fourth antenna system 100d is shown in accordance with an illustrative embodiment. Fourth antenna system 100d may be used to perform MWA. Fourth antenna system 100d 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.

[0071] 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.

[0072] 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.

[0073] 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.

[0074] With reference to Fig. 11, a side cross-sectional view of a fifth antenna system 100e is shown in accordance with an illustrative embodiment. Fifth antenna system 100e may be used to perform MWA. Fifth antenna system 100e 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.

[0075] With reference to Fig. 12, a front cross-sectional view of a first two-wire balanced cable 1000a is shown in accordance with an illustrative embodiment. First two-wire balanced cable 1000a may include dielectric material 1004, a first conductive line 1006a, a second conductive line 1008a, and floating shield 1010. Dielectric material 1004 has a radius 1200. First conductive line 1006a and second

conductive line 1008a are formed of rectangular strips having a width 1202 and separated by a distance 1204.

[0076] With reference to Fig. 13, a front cross-sectional view of a second two-wire balanced cable 1000b is shown in accordance with an illustrative embodiment. Second two-wire balanced cable 1000b may include dielectric material 1004, a first conductive line 1006b, a second conductive line 1008b, and floating shield 1010. Dielectric material 1004 has radius 1200. First conductive line 1006b and second conductive line 1008b are formed of circular wires having a diameter 1300 and separated by a distance 1302.

[0077] Referring to Fig. 14, a simulated input impedance, S_{11} , of fourth antenna system 100d 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 1000a. Design parameters for first two-wire balanced cable 1000a 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 100c in liver tissue. The simulated S_{11} shown in curve 1400 shows excellent impedance matching at 10 GHz.

[0078] 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 1000a. The maximum SAR level in the area immediately outside of floating shield 1010 of first two-wire balanced cable 1000a 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.

[0079] 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.

[0080] 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.

[0081] The foregoing description of illustrative embodiments of the disclosed subject matter has been presented for purposes of illustration and of description. It is not intended to be exhaustive or to limit the disclosed subject matter to the precise form disclosed, and modifications and variations are possible in light of the above teachings or may be acquired from practice of the disclosed subject matter. The embodiments were chosen and described in order to explain the principles of the disclosed subject matter and as practical applications of the disclosed subject matter to enable one skilled in the art to utilize the disclosed subject matter in various embodiments and with various modifications as suited to the particular use contemplated. It is intended that the scope of the disclosed subject matter be defined by the claims appended hereto and their equivalents.

WHAT IS CLAIMED IS:

1. An antenna system comprising:
a coaxial cable comprising
a center conductor extending a length of the coaxial cable;
a dielectric material surrounding the center conductor along the length of the coaxial cable; and
a conductive shield surrounding the dielectric material along the length of the coaxial cable;
an antenna comprising a conductor having an electrical length of half a wavelength at a selected operating frequency; and
an impedance matching structure comprising a second center conductor mounted between an end of the center conductor of the coaxial cable and a feed end of the antenna;
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 antenna is a base fed monopole antenna.
3. The antenna system of claim 1, wherein the electrical length is selected to operate the antenna in a second resonance mode at the selected operating frequency.
4. 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.
5. The antenna system of claim 1, wherein the dielectric material is polytetrafluoroethylene.
6. The antenna system of claim 1, wherein an insulating material surrounds the conductive shield along the length of coaxial cable.
7. The antenna system of claim 1, wherein the second center conductor extends directly from the center conductor of the coaxial cable.

8. The antenna system of claim 1, wherein the impedance matching structure further comprises a second dielectric material surrounding the second center conductor along a length of the second center conductor.

9. The antenna system of claim 8, wherein a diameter of the second center conductor is smaller than a diameter of the center conductor of the coaxial cable.

10. The antenna system of claim 9, wherein the diameter of the second center conductor is determined as $a' = \frac{b}{e^{Z' 2\pi \sqrt{\frac{\epsilon}{\mu}}}}$, where $Z' = \sqrt{Z_0 Z_{in}}$, where Z_0 is the impedance of the coaxial cable, Z_{in} is the impedance of the antenna, b is an inner diameter of the conductive shield, μ is a permeability of the second dielectric material, and ϵ is a permittivity of the second dielectric material.

11. The antenna system of claim 9, wherein the impedance matching structure further comprises a second conductive shield surrounding the second dielectric material along the length of the second center conductor.

12. The antenna system of claim 11, wherein the second conductive shield extends directly from the conductive shield of the coaxial cable.

13. The antenna system of claim 11, wherein an insulating material surrounds the conductive shield along the length of the coaxial cable and the second conductive shield along the length of the second center conductor.

14. The antenna system of claim 8, wherein the second dielectric material has a dielectric constant approximately equal to one.

15. The antenna system of claim 1, wherein the impedance matching structure comprises:

an inductive section connected to and extending from the end of the center conductor of the coaxial cable; and

a capacitive section connected to and extending from the feed end of the antenna;

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

16. The antenna system of claim 15, wherein the capacitive section comprises:

- a second dielectric material surrounding the second center conductor along a length of the capacitive section;

- a second conductive material surrounding the second dielectric material along the length of the capacitive section; and

- the conductive shield surrounding the second conductive material along the length of the capacitive section;

- wherein the inductive section comprises:

- a third dielectric material surrounding the second center conductor along a length of the inductive section; and

- the conductive shield surrounding the third dielectric material along the length of the inductive section.

17. The antenna system of claim 1, wherein the impedance matching structure comprises:

- a first capacitive section connected to and extending from the end of the center conductor of the coaxial cable;

- an inductive section; and

- a second capacitive section connected to and extending from the feed end of the antenna;

- wherein the inductive section is connected between the first capacitive section and the second capacitive section, wherein the second center conductor extends through the first capacitive section, the inductive section, and the second capacitive section.

18. The antenna system of claim 17, wherein the first capacitive section comprises:

- a second dielectric material surrounding the second center conductor along a length of the first capacitive section;

a second conductive material surrounding the second dielectric material along the length of the first capacitive section; and

the conductive shield surrounding the second conductive material along the length of the first capacitive section.

19. The antenna system of claim 18, wherein the inductive section comprises:
a third dielectric material surrounding the second center conductor along a length of the inductive section; and

the conductive shield surrounding the third dielectric material along the length of the inductive section.

20. A transmitter 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 conductor surrounding the dielectric material along the length of the coaxial cable;

an antenna comprising a conductor having an electrical length of half a wavelength at a selected operating frequency; and

an impedance matching structure comprising a second center conductor mounted between an end of the center conductor of the coaxial cable and a feed end of the antenna, 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.

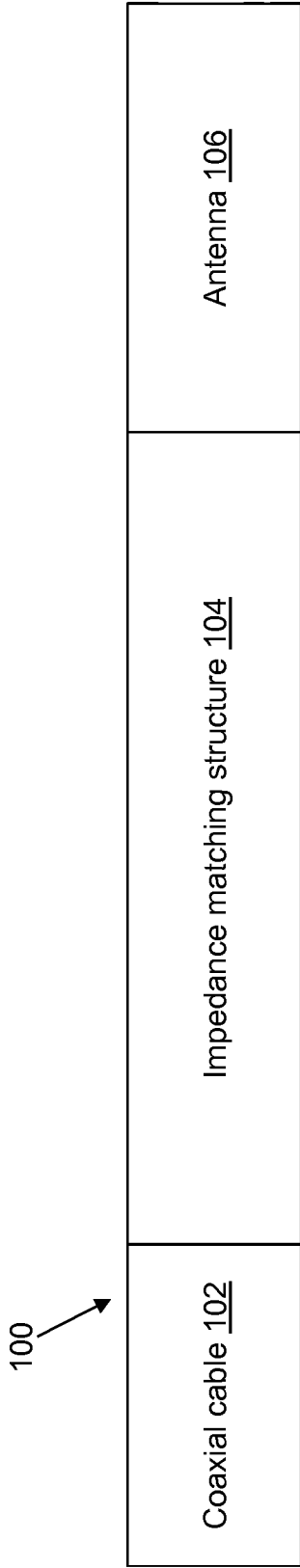


Fig. 1

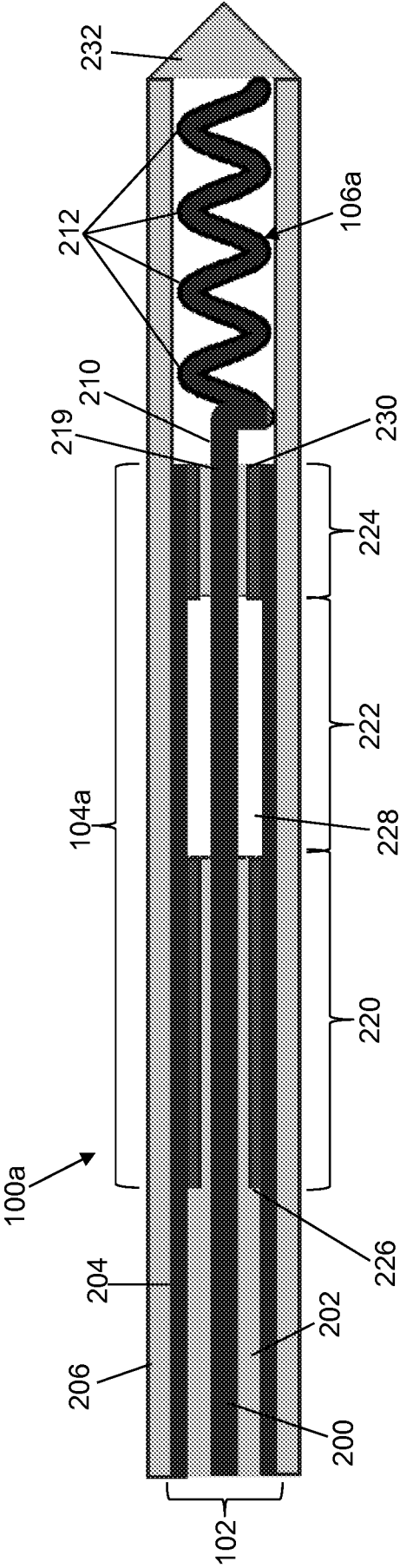


Fig. 2

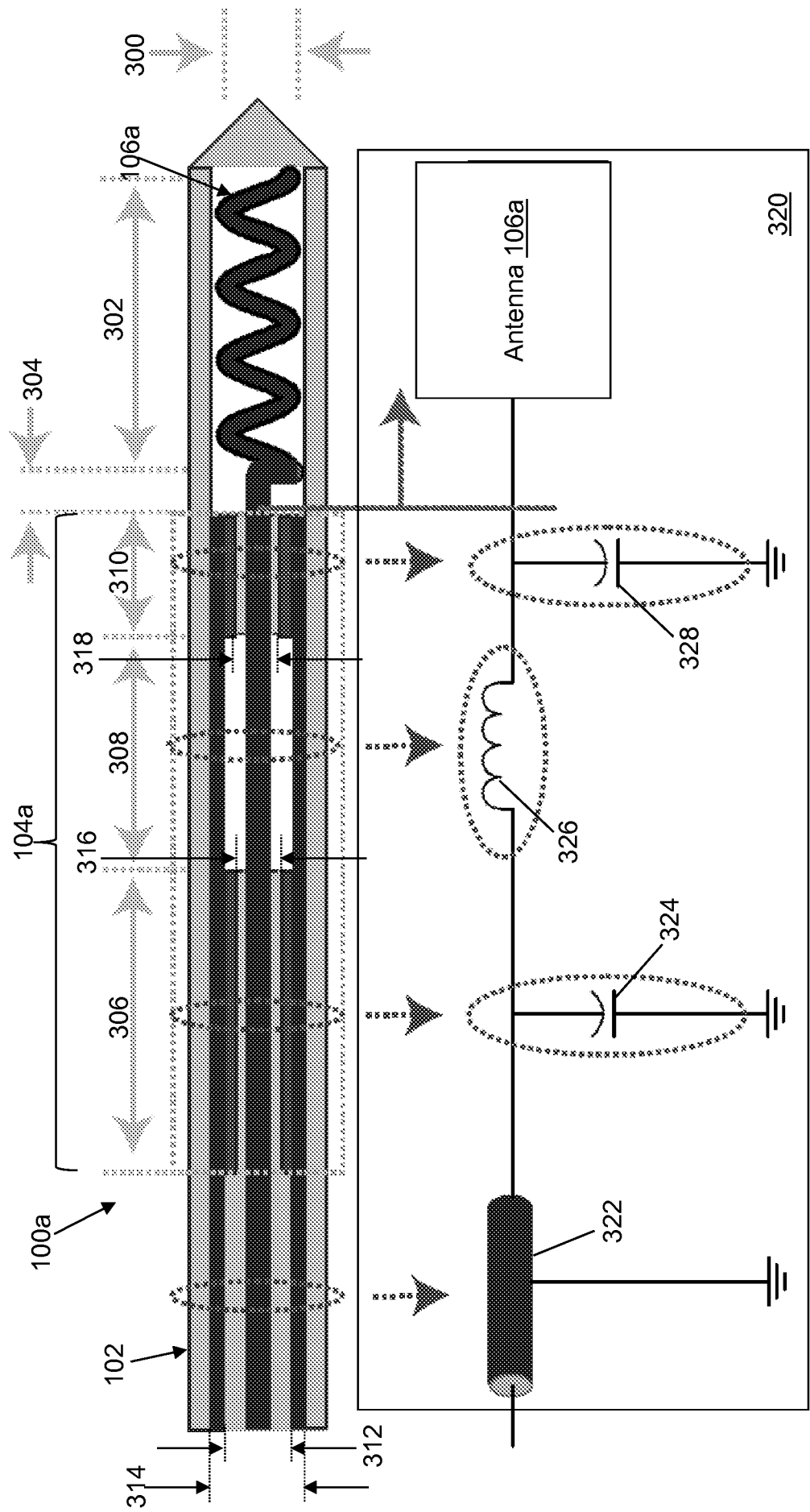


Fig. 3a

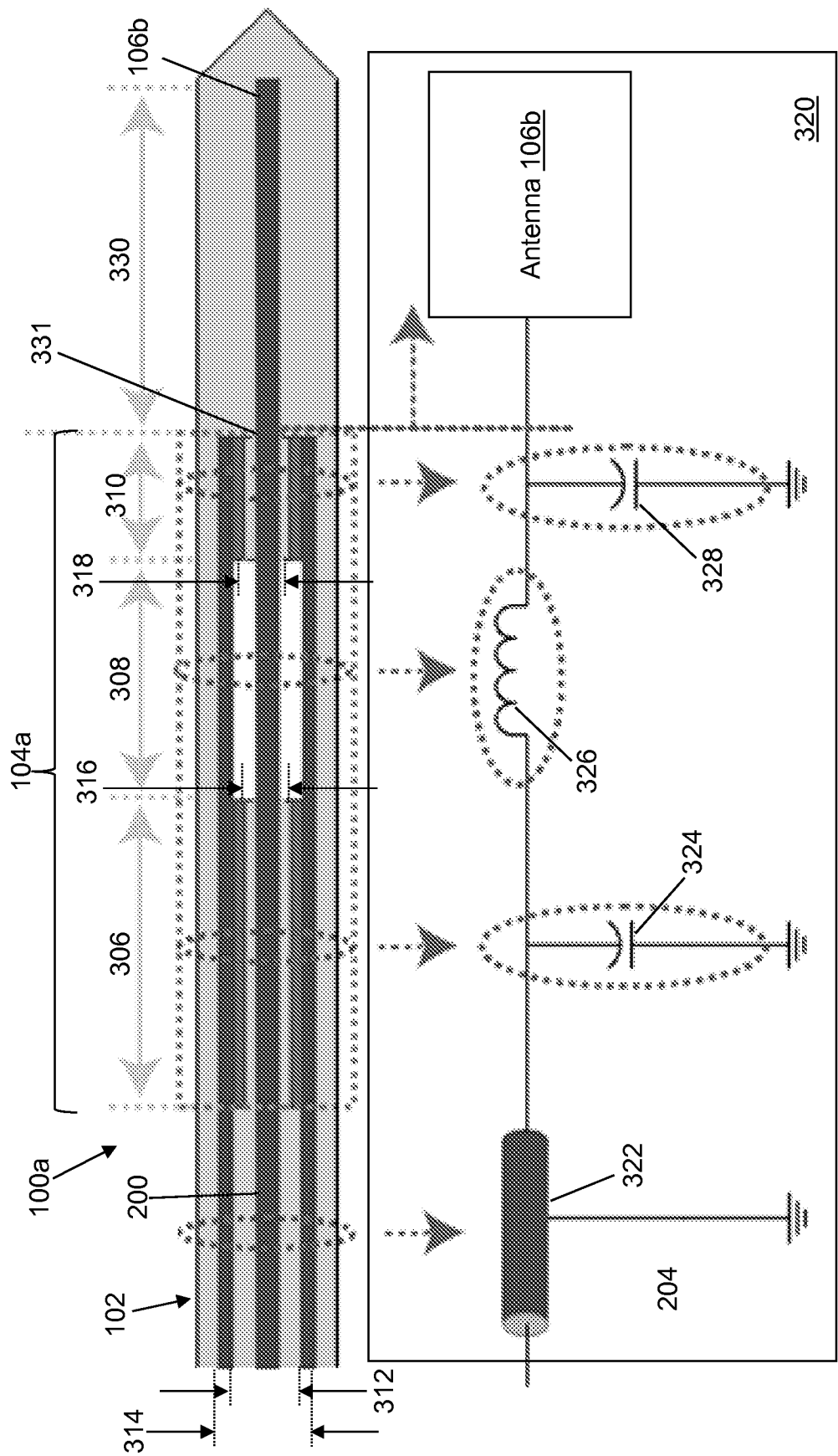


Fig. 3b

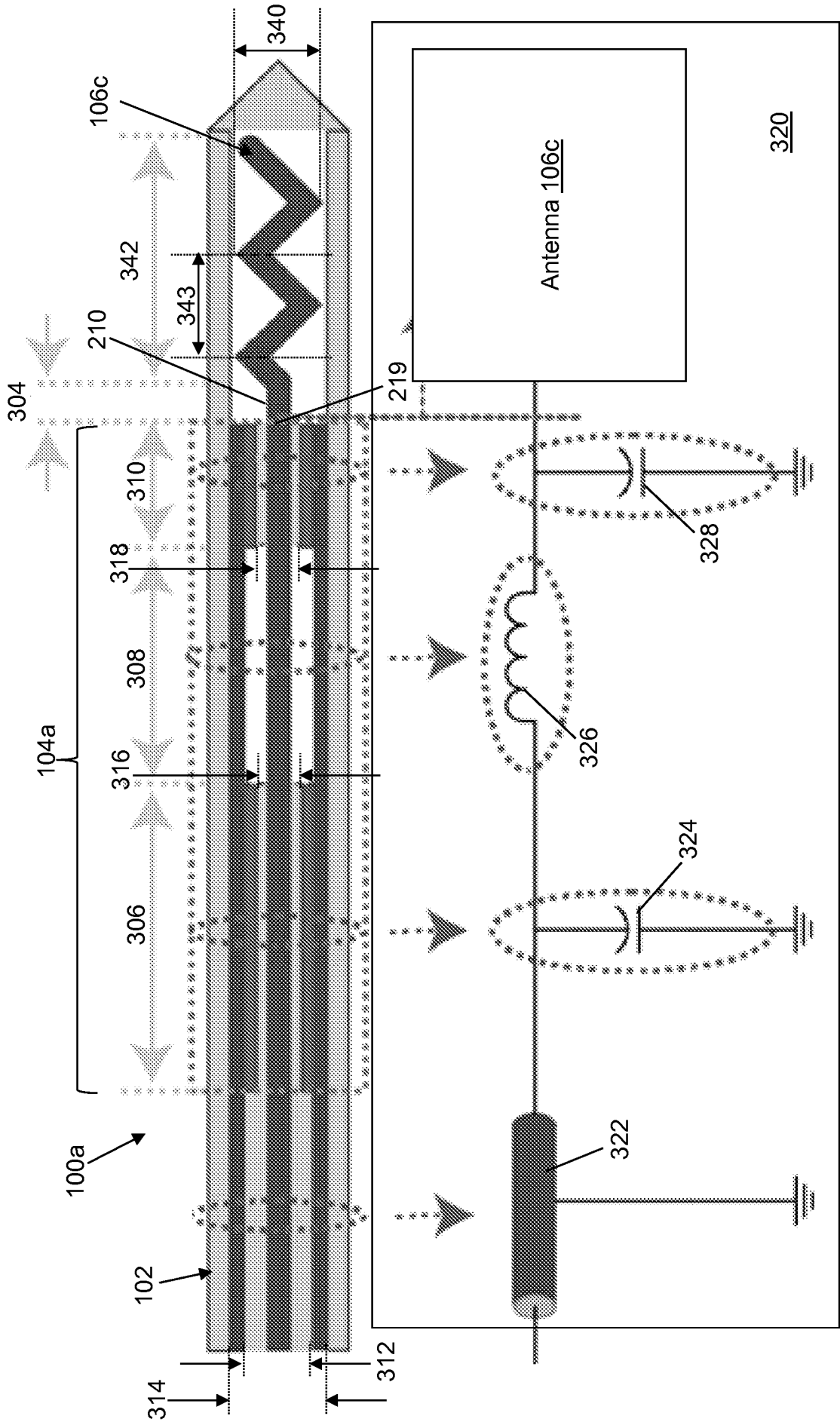


Fig. 3c

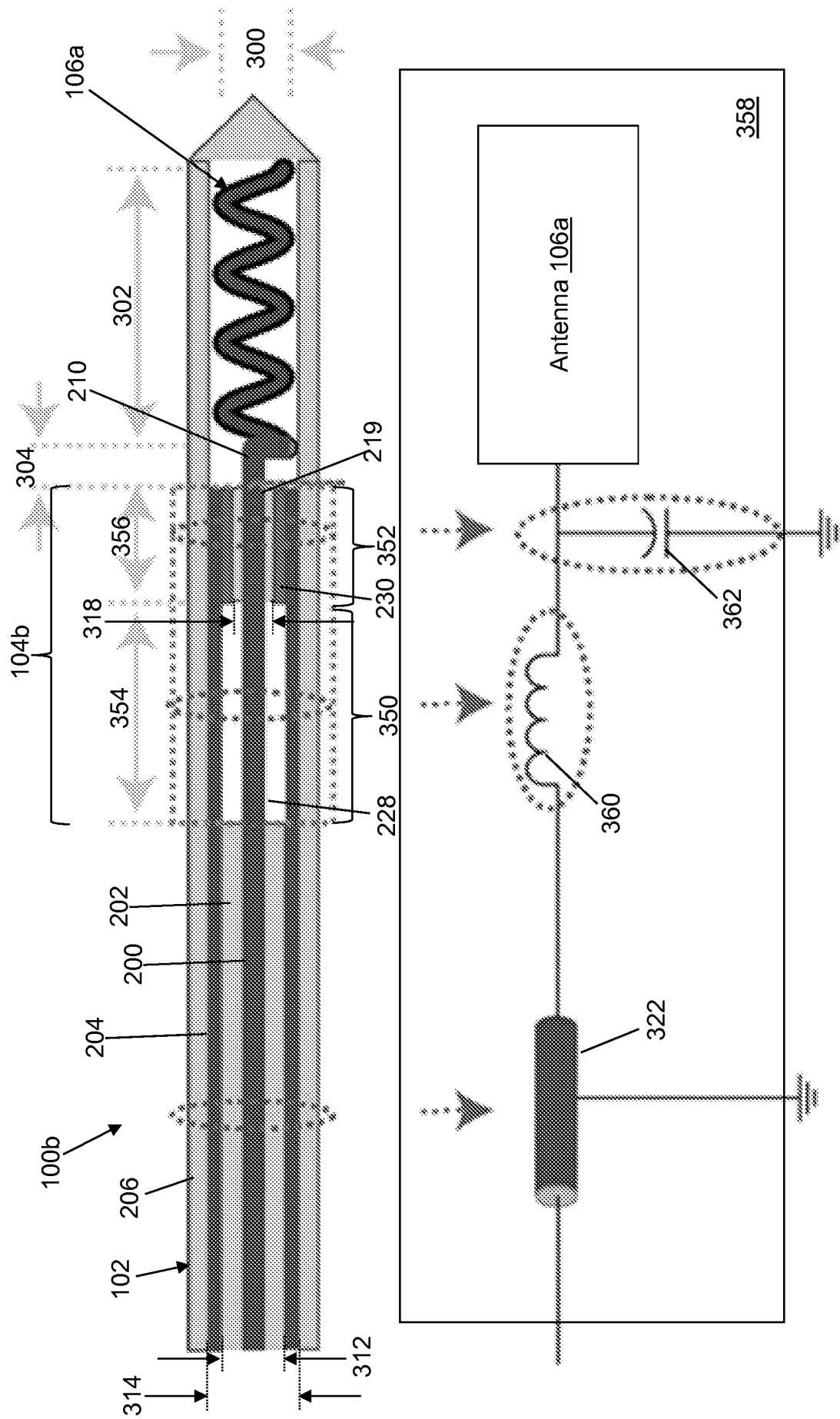


Fig. 3d

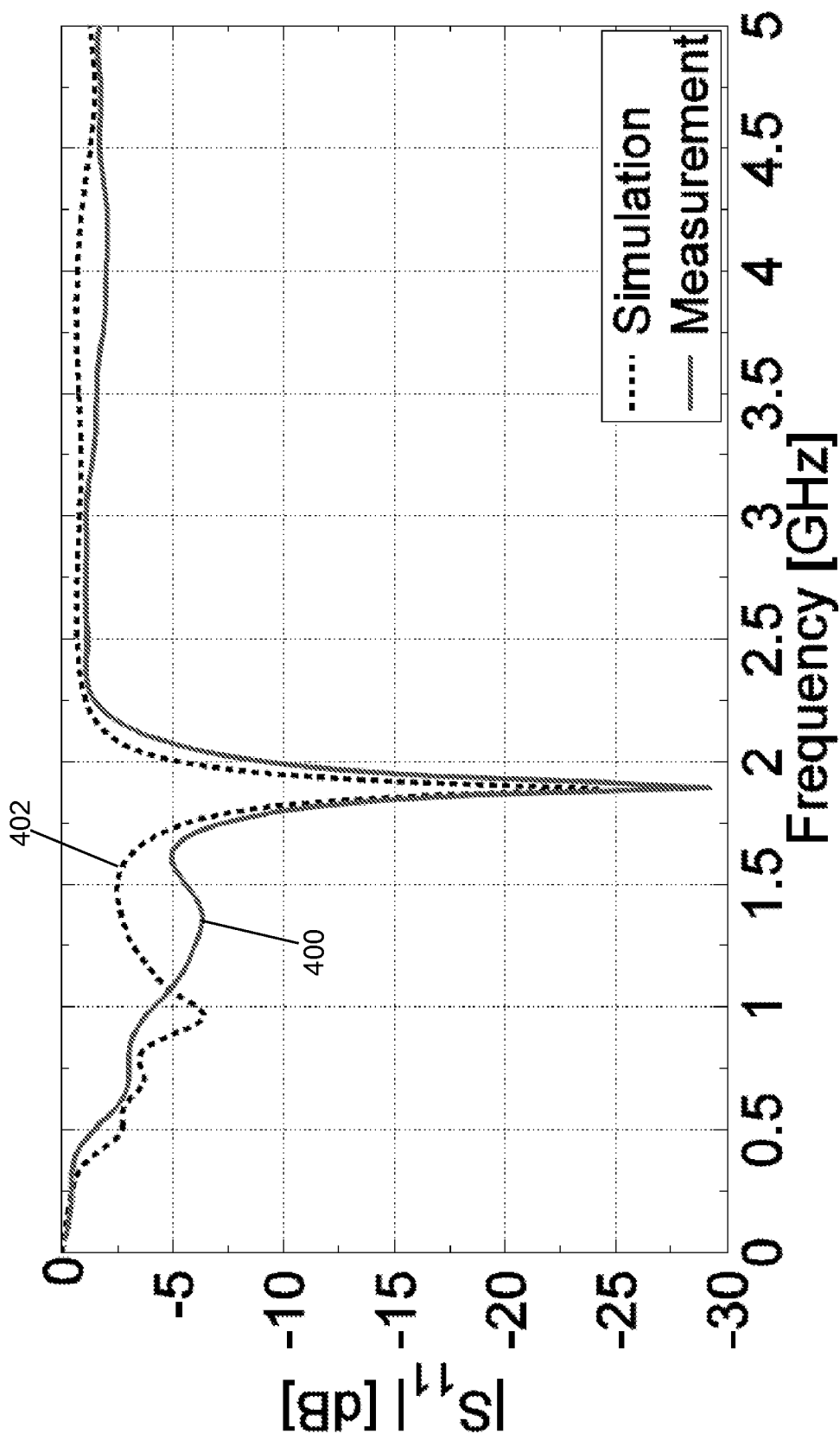


Fig. 4

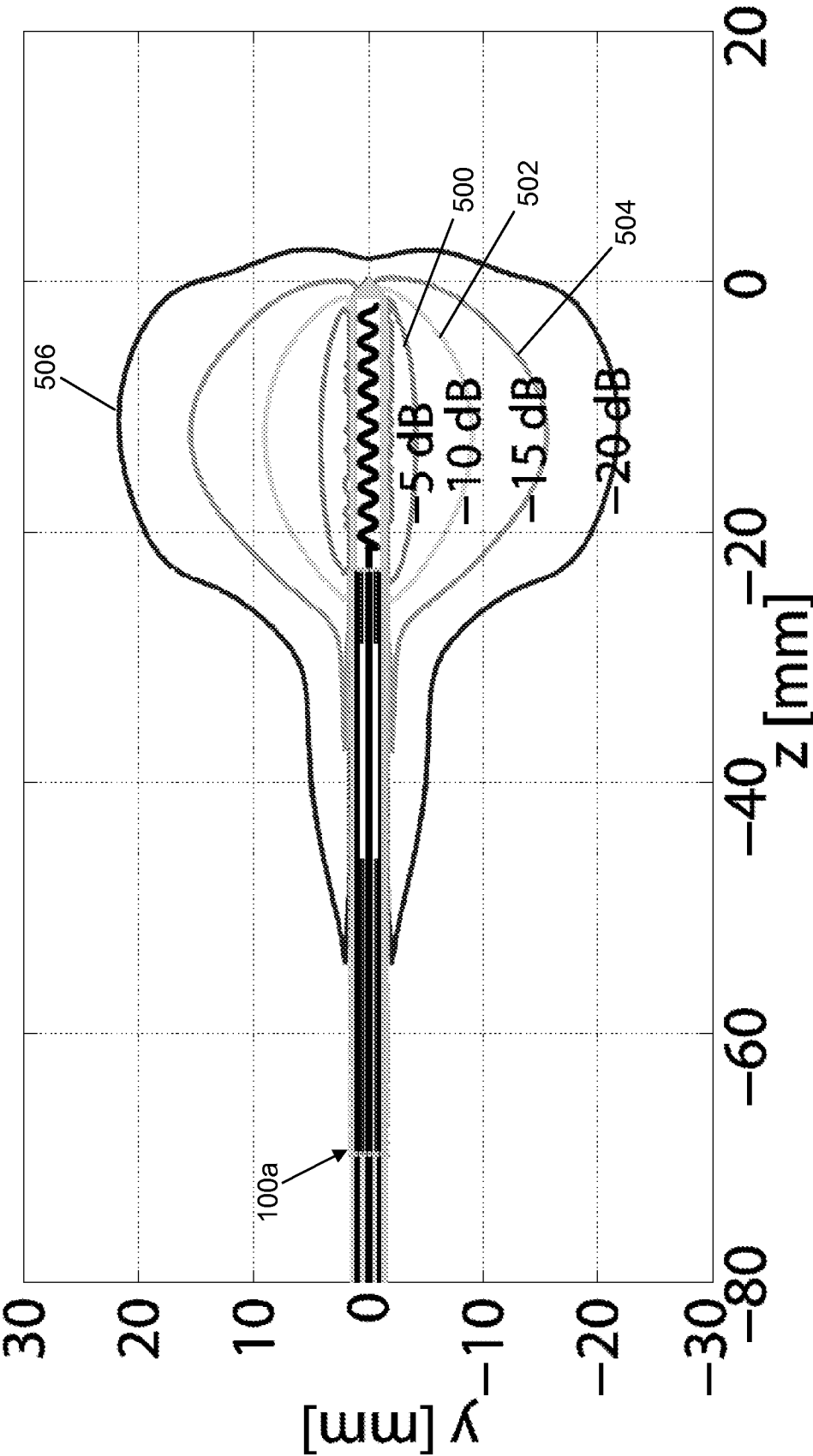


Fig. 5

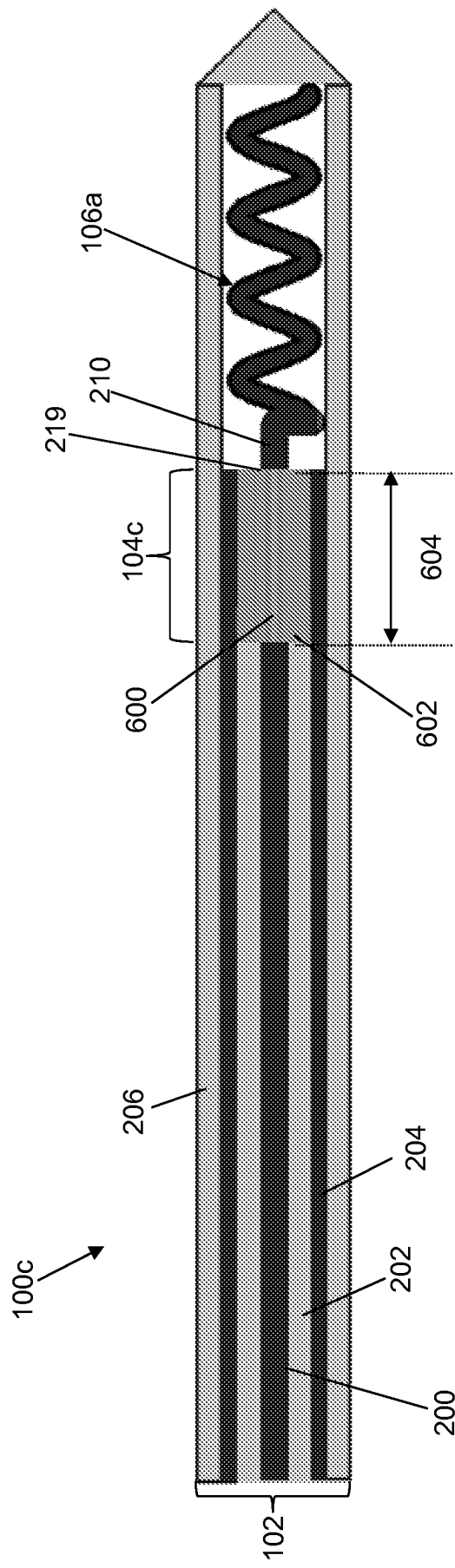


Fig. 6

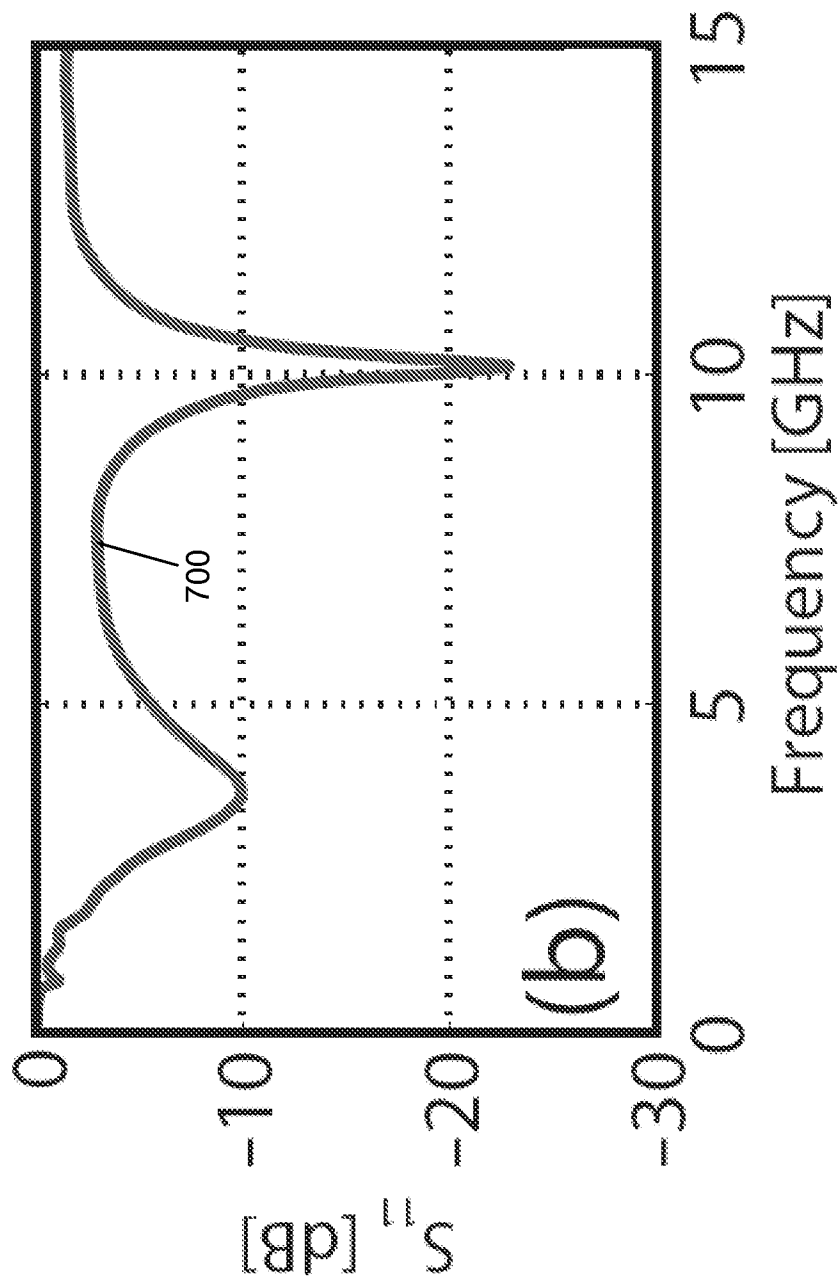


Fig. 7

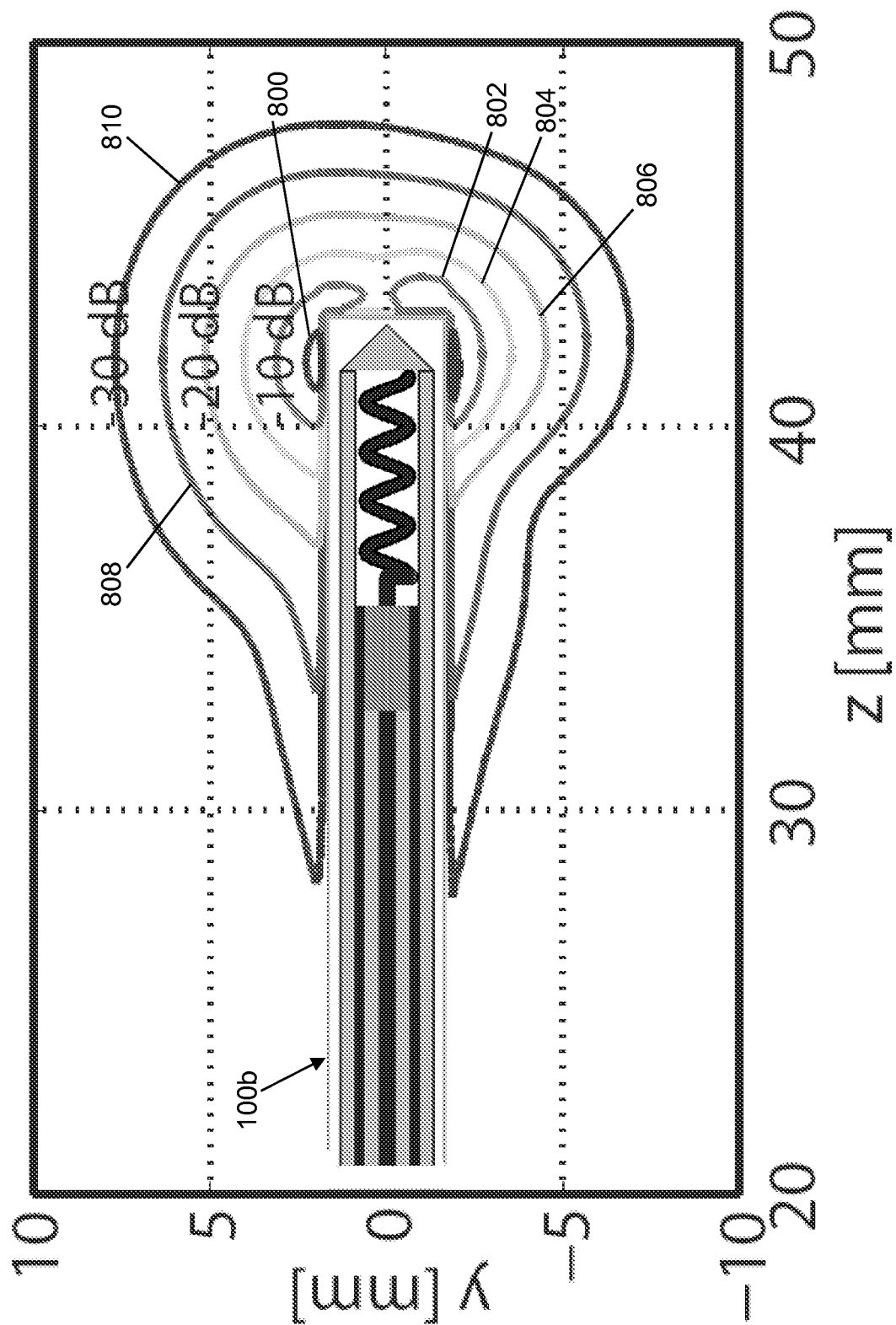


Fig. 8

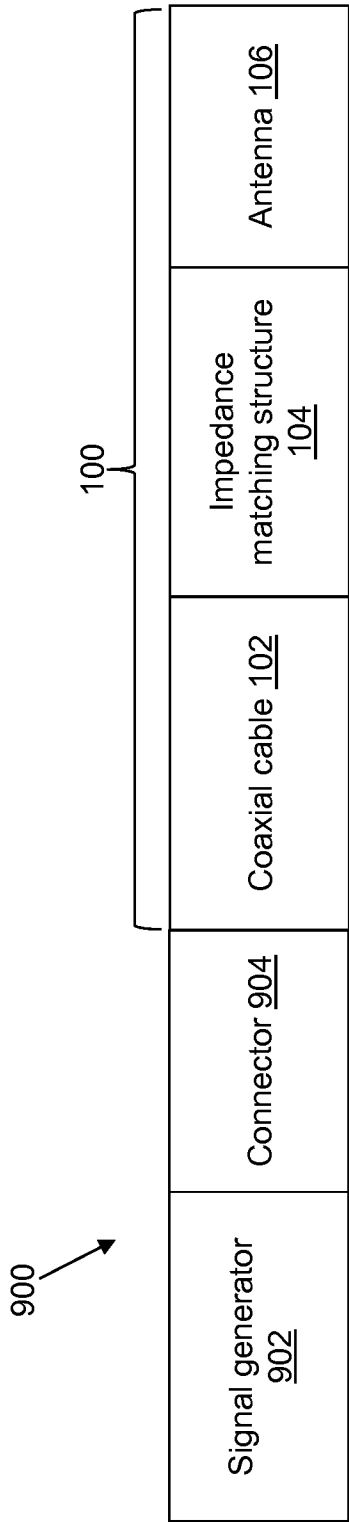


Fig. 9

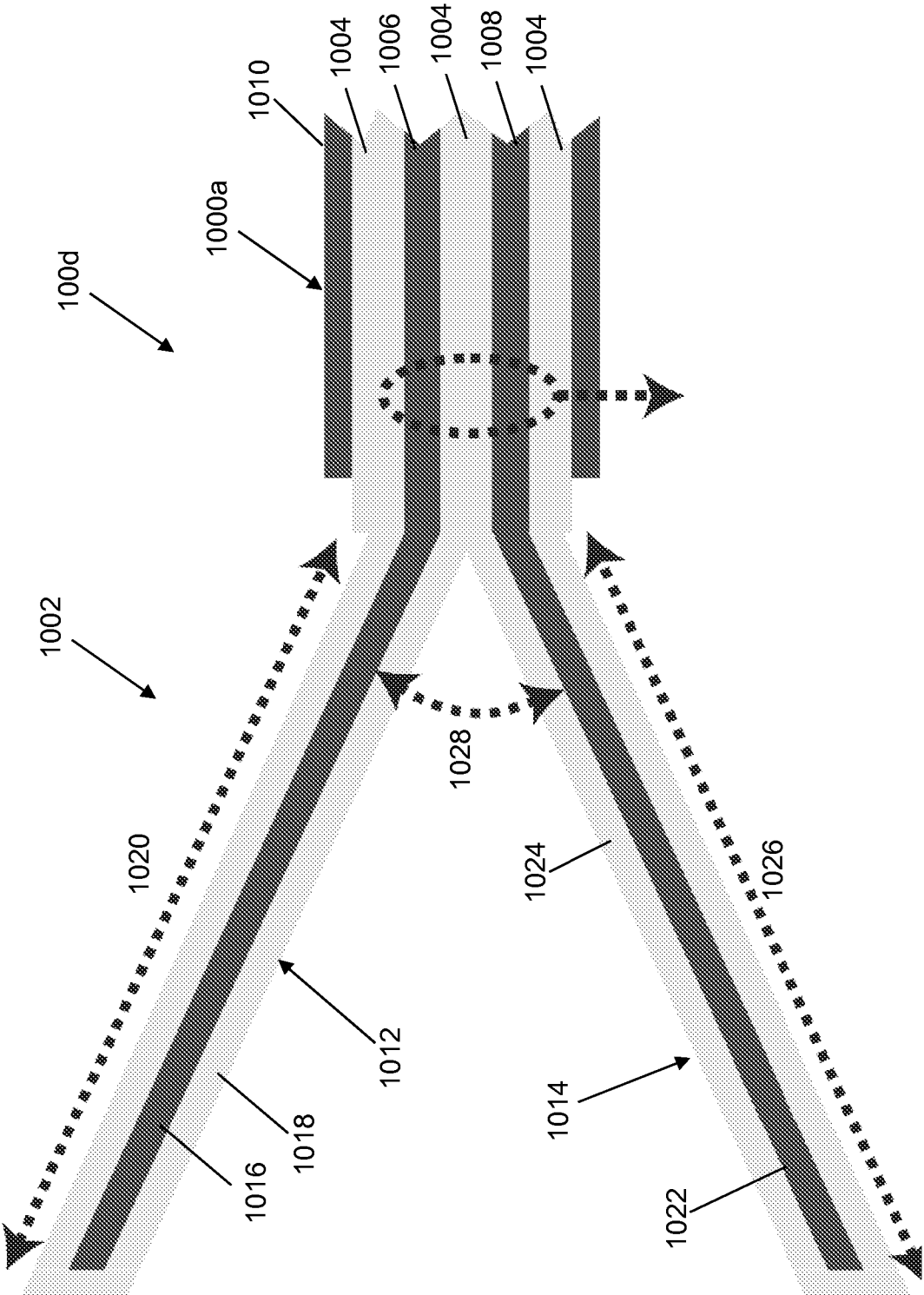


Fig. 10

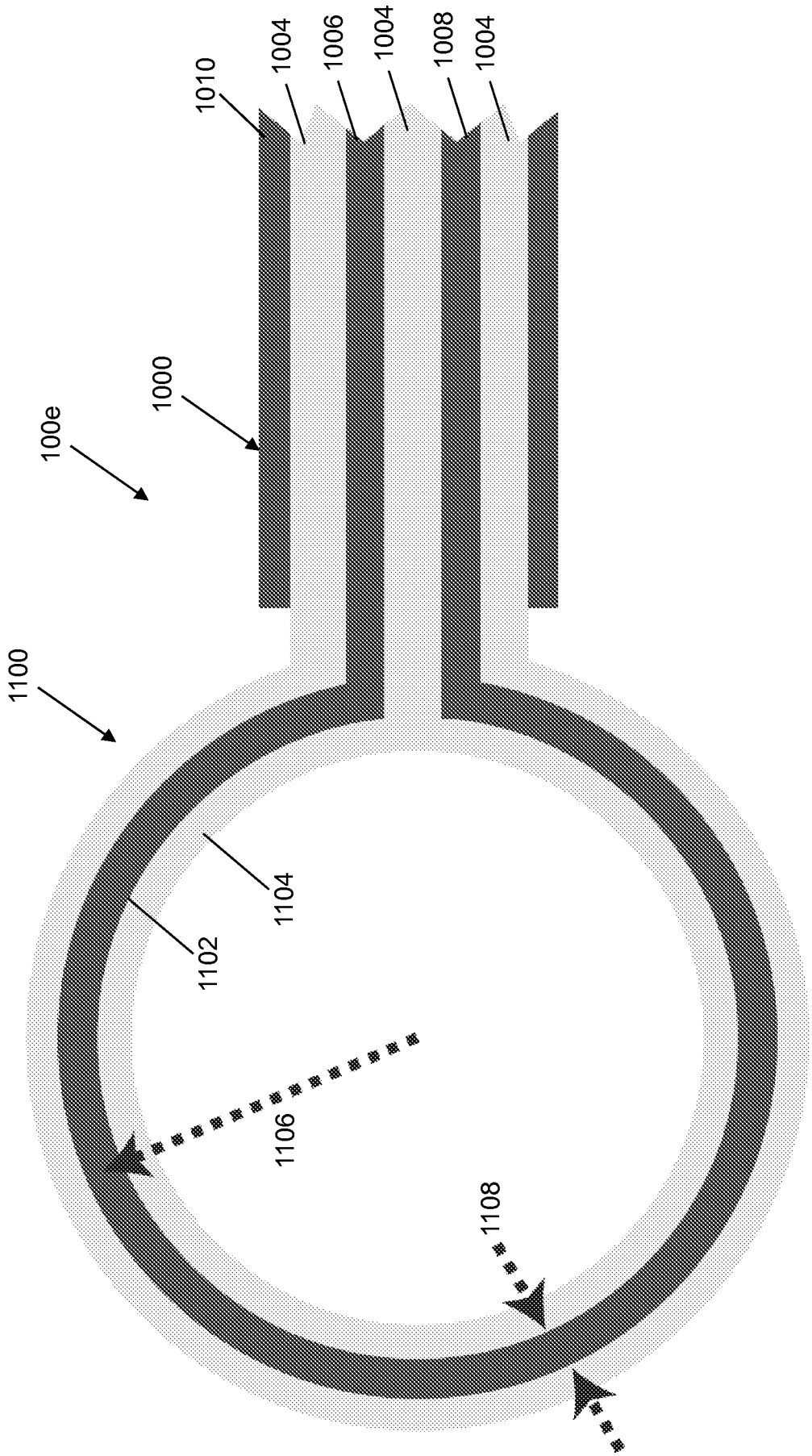


Fig. 11

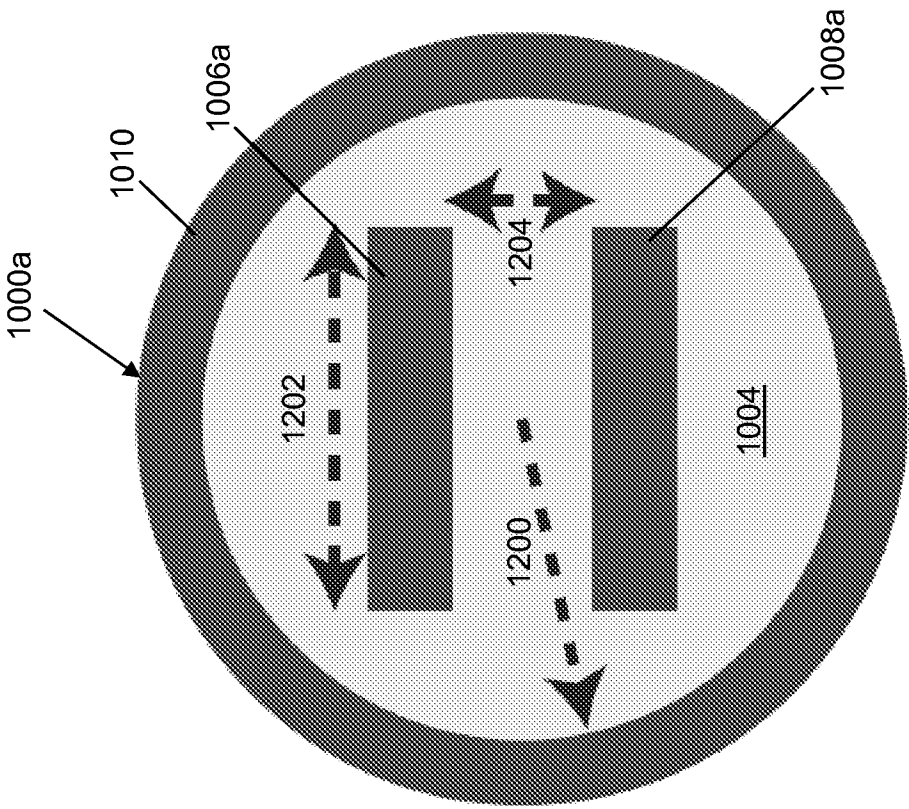


Fig. 12

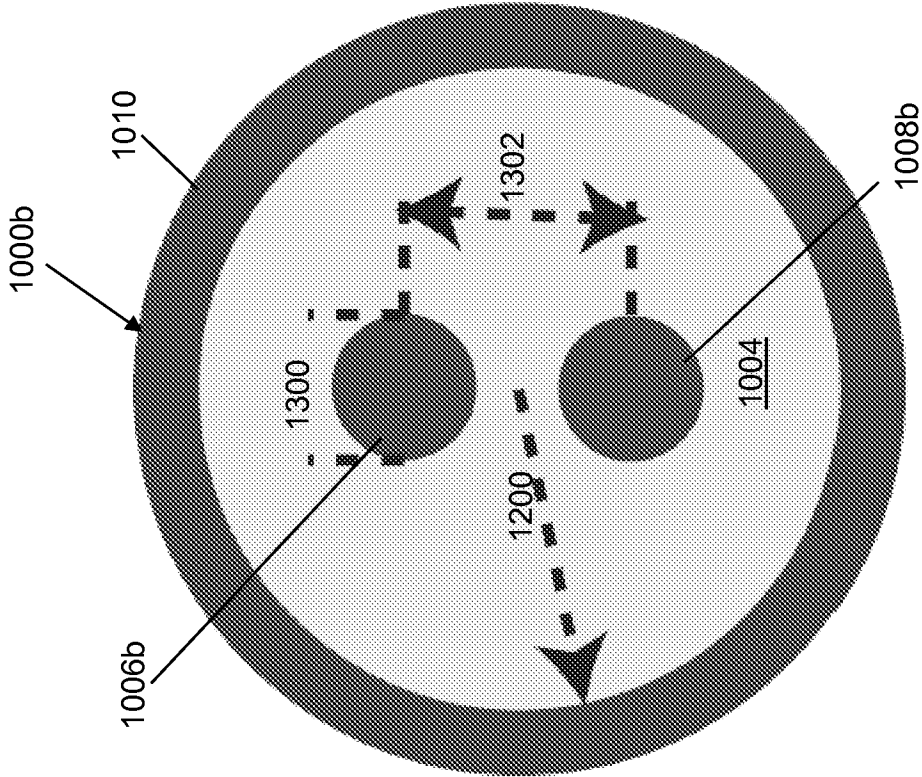


Fig. 13

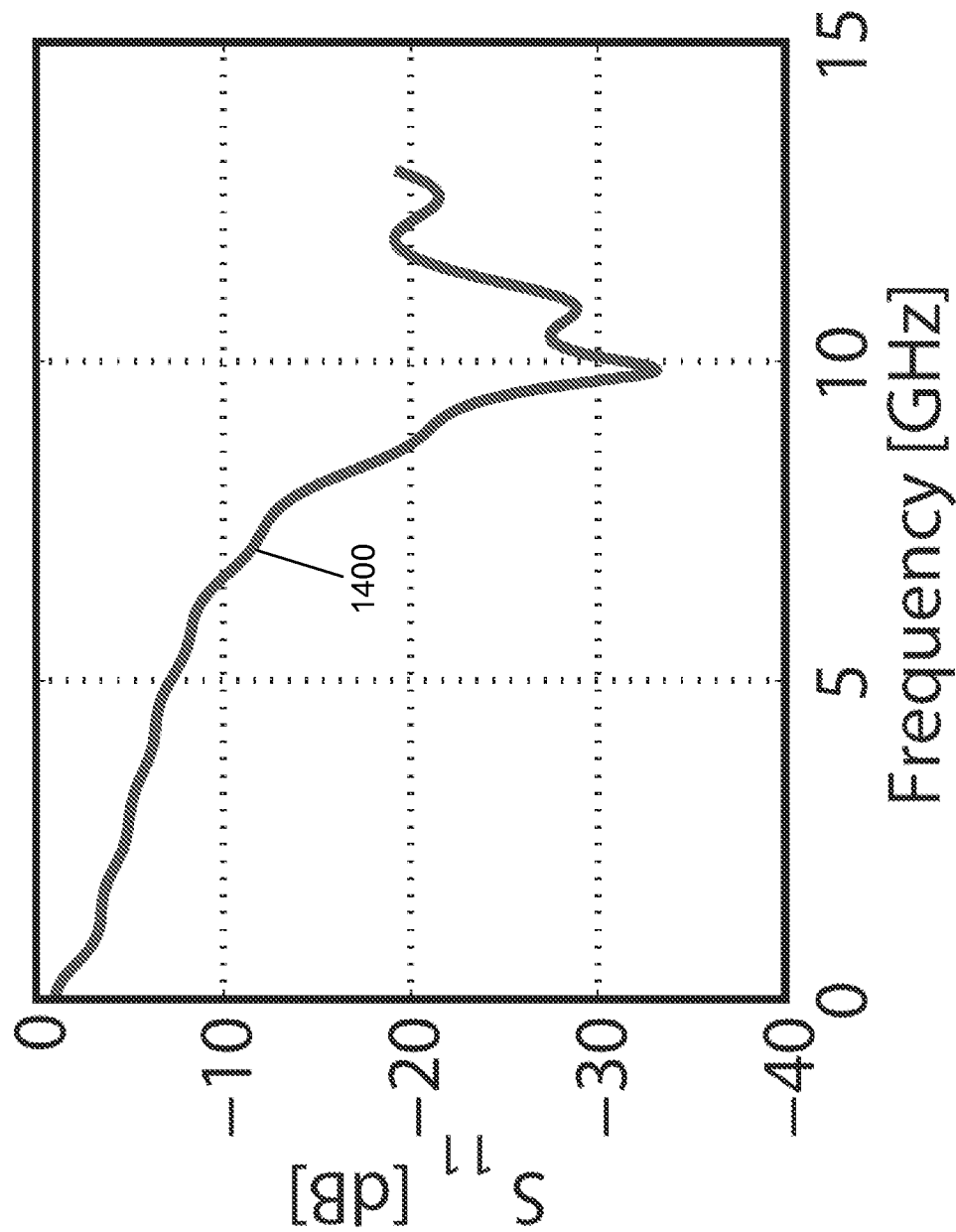


Fig. 14

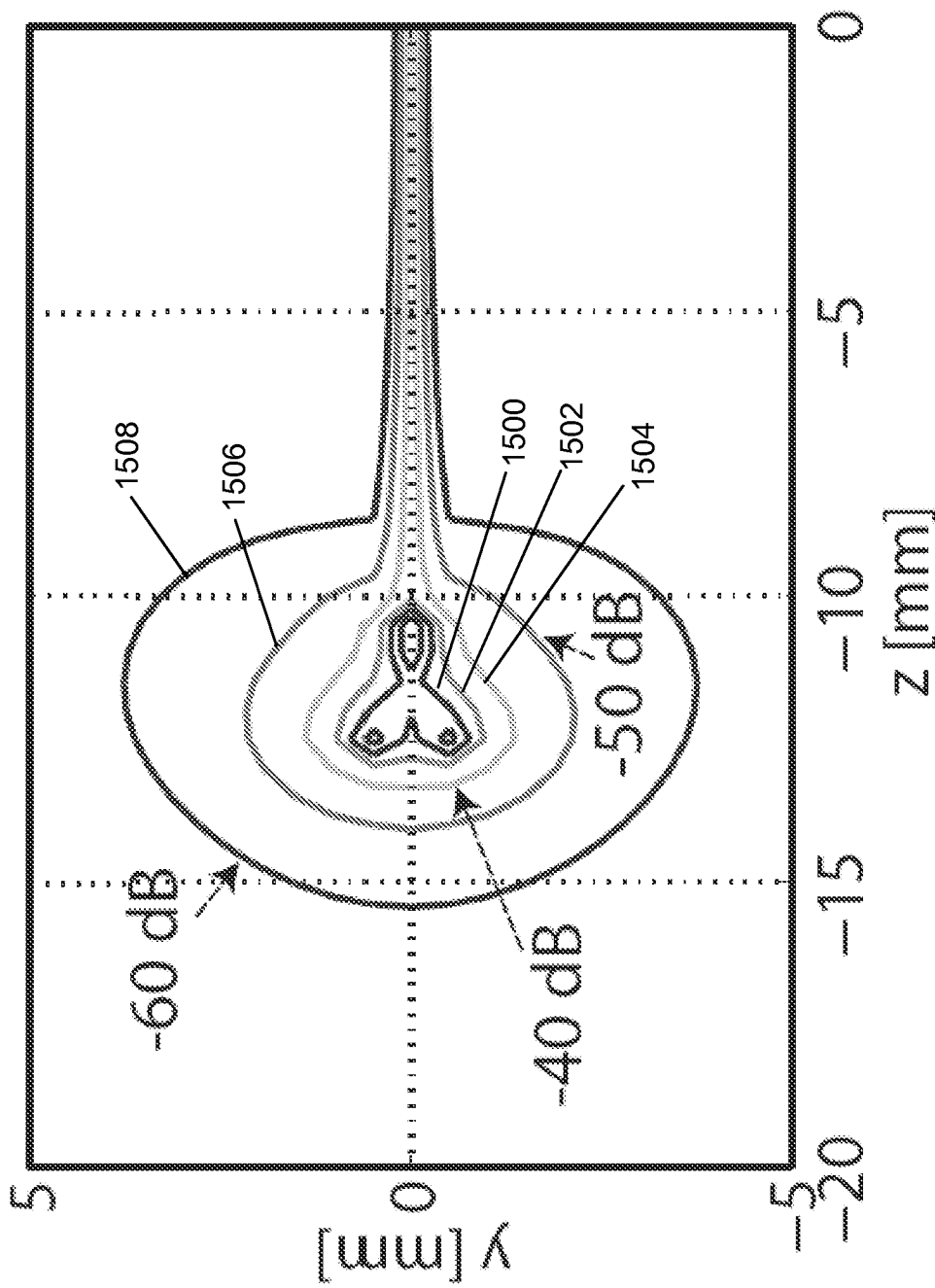


Fig. 15

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2015/012615**A. CLASSIFICATION OF SUBJECT MATTER****A61B 18/18(2006.01)i, G01R 29/10(2006.01)i**

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

A61B 18/18; A61B 18/14; A61B 18/04; H01Q 9/16; A61F 2/00; H01B 11/18; A61B 6/00; H01B 11/12; A61N 1/06; G01R 29/10

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) & Keywords: coaxial cable, center conductor, dielectric material, conductive shield, antenna, impedance matching structure**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JP 2004-311334 A (MURATA MFG CO., LTD.) 4 November 2004 See abstract; paragraphs [0024]-[0051]; and figures 1a-2.	1-14, 20
A		15-19
A	US 8414570 B2 (TURNER et al.) 9 April 2013 See column 8, line 52-column 11, line 21; and figures 1-4.	1-20
A	JP 2008-142467 A (MURATA MFG CO., LTD.) 26 June 2008 See abstract; paragraphs [0021]-[0029]; and figure 1.	1-20
A	US 2011-0238060 A1 (LEE, JR. et al.) 29 September 2011 See paragraphs [0040]-[0055]; and figures 5-8.	1-20
A	US 2010-0097284 A1 (BRANNAN et al.) 22 April 2010 See paragraphs [0032]-[0041], [0052], [0053]; and figures 1-8.	1-20
A	US 7194297 B2 (TALPADE et al.) 20 March 2007 See column 6, line 10 - column 8, line 25; and figures 3a-4.	1-20
A	US 8280525 B2 (RUSIN et al.) 2 October 2012 See column 3, line 22-column 5, line 13; and figures 1-3C.	1-20



Further documents are listed in the continuation of Box C.



See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

29 April 2015 (29.04.2015)

Date of mailing of the international search report

01 May 2015 (01.05.2015)

Name and mailing address of the ISA/KR

International Application Division
Korean Intellectual Property Office
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Republic of Korea

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CHANG, Bong Ho

Telephone No. +82-42-481-3353



INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2015/012615

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