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Hagness et al.

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(54) **MICROWAVE ABLATION ANTENNA SYSTEM WITH TAPERED SLOT BALUN**

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

(72) Inventors: **Susan C. Hagness**, Madison, WI (US); **Nader Behdad**, Oregon, WI (US); **Hung Thanh Luyen**, Madison, WI (US)

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

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(22) Filed: **Mar. 9, 2017**

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(51) **Int. Cl.**

A61B 18/18	(2006.01)
A61B 18/00	(2006.01)
H05B 6/72	(2006.01)

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

CPC ***A61B 18/1815*** (2013.01); *A61B 2018/00577* (2013.01); *A61B 2018/1838* (2013.01); *A61B 2018/1861* (2013.01); *A61B 2018/1892* (2013.01); *H05B 6/72* (2013.01)

(58) **Field of Classification Search**

CPC A61B 18/1815; A61B 2018/00577; A61B 2018/1838; A61B 2018/1861; A61B 2018/1892; H05B 6/705; H05B 6/72; H05B 6/664; H05B 6/701; H05B 6/702; H05B 6/70; H05B 6/64; H05B 6/6447; H05B 1/025; H01Q 13/08; H01Q 5/48

See application file for complete search history.

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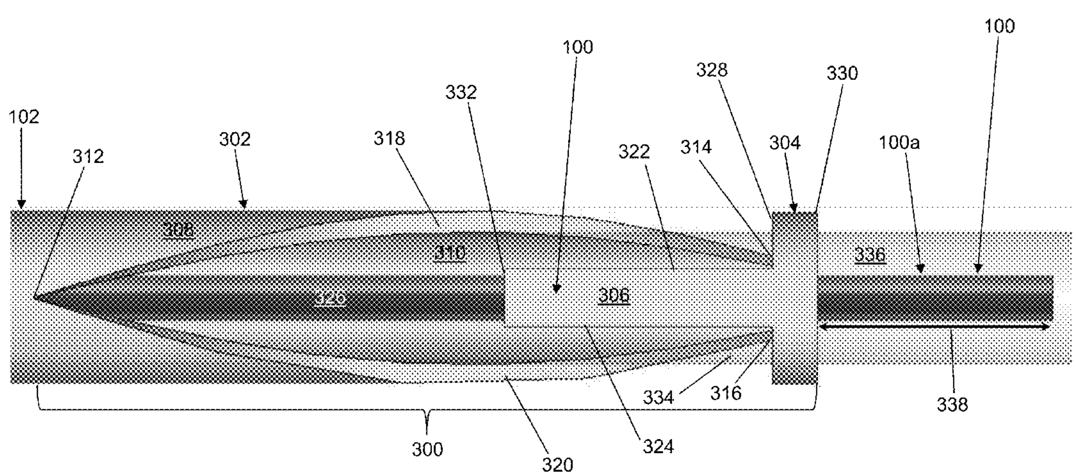
Primary Examiner — Jaymi E Della
Assistant Examiner — Rachel A. Vierra
(74) *Attorney, Agent, or Firm* — Bell & Manning, LLC

(57) **ABSTRACT**

A balun includes a center conductor, a dielectric material, a tapered wall, a ring, and a prong. The center conductor extends a length of the balun. The dielectric material surrounds the center conductor along the length of the balun. The tapered wall forms a portion of a tube between a first wall and a second wall. The first wall is opposite the second wall. The tapered wall is formed of a conductive material. The portion of the tube forms a slot exposing the dielectric material. The ring connects to the second wall of the tapered wall and is formed of the conductive material. The ring forms a tube surrounding the center conductor and the dielectric material. The prong connects to the ring to extend toward the first wall and is formed of the conductive material. The prong extends over a portion of the dielectric material exposed by the slot.

20 Claims, 28 Drawing Sheets



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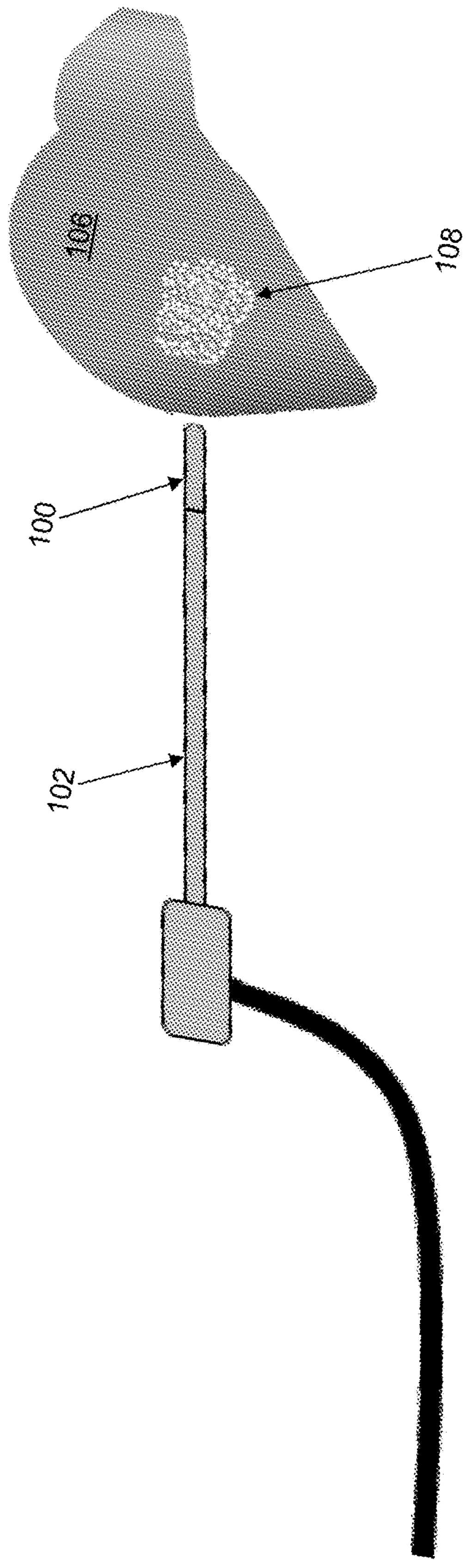


FIG. 1

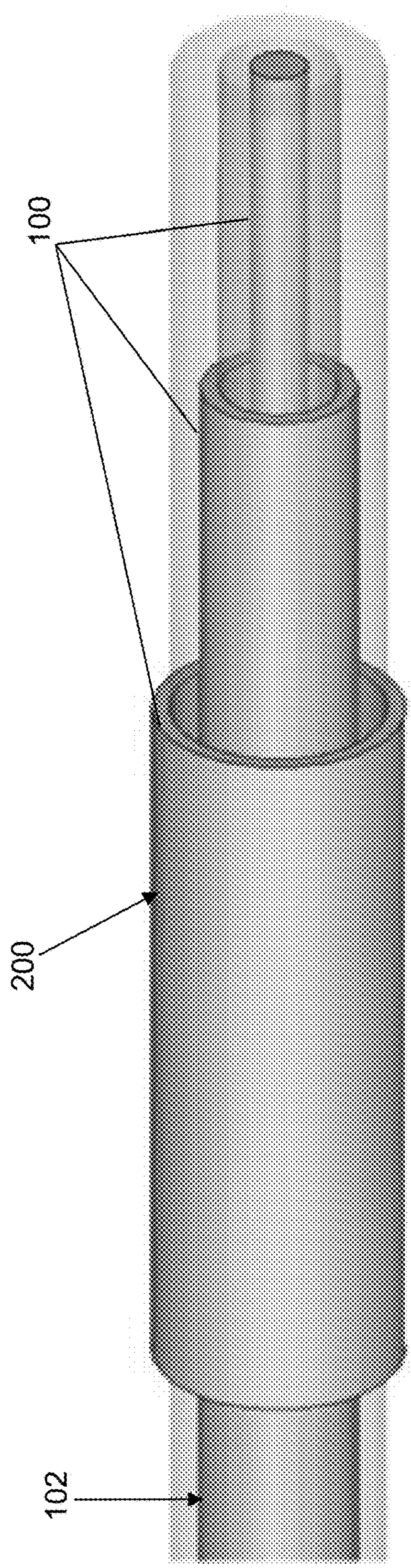
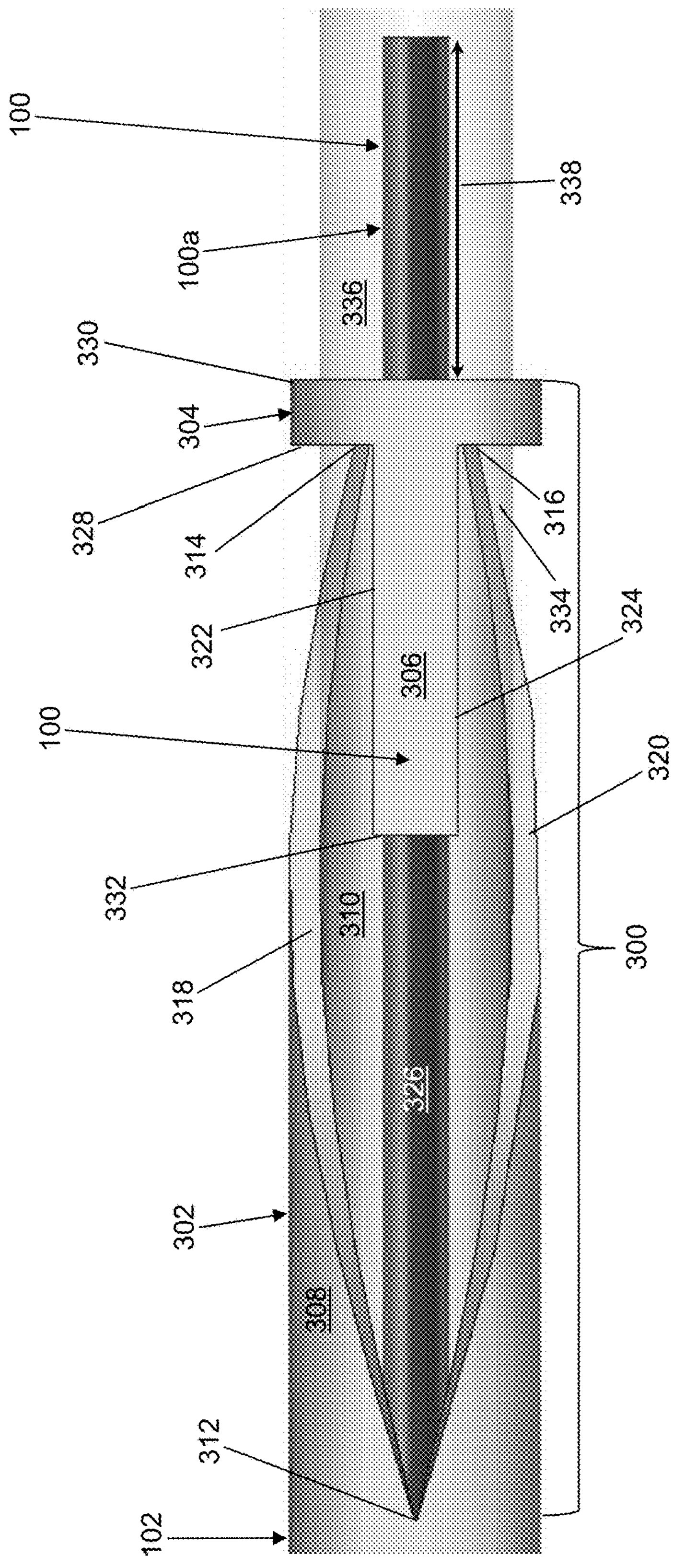


FIG. 2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100a
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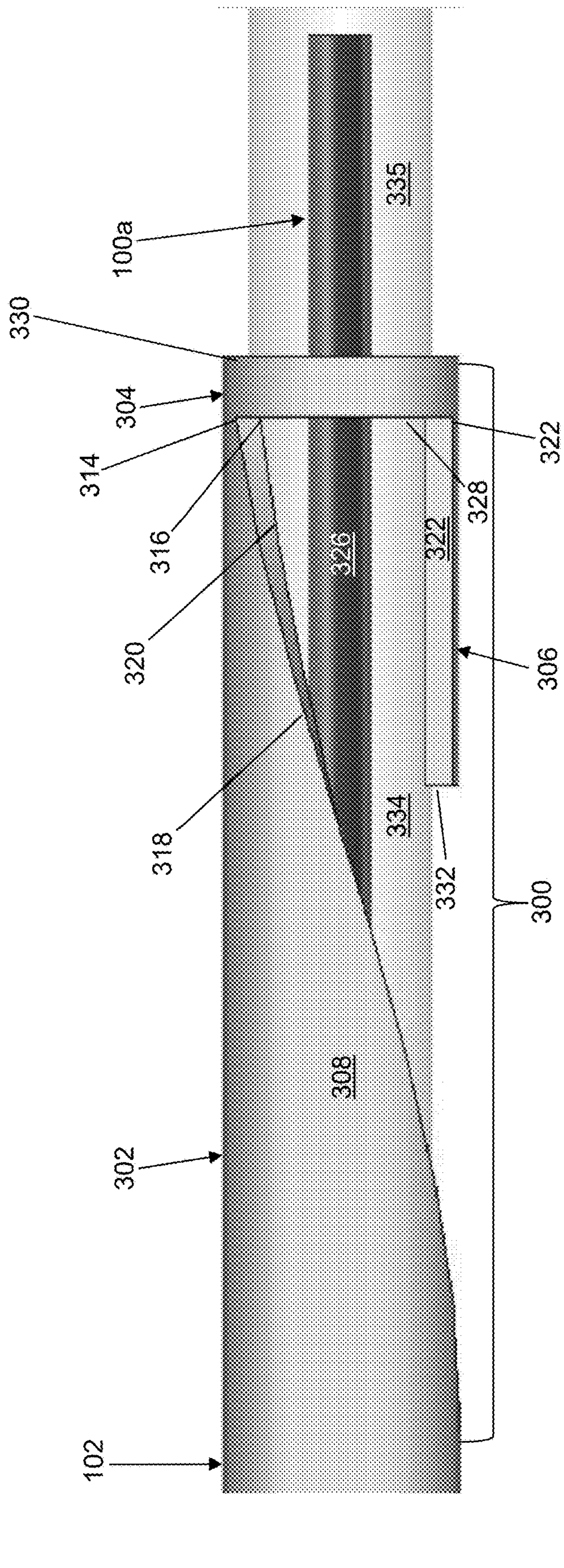
336
330
304
328
314
316
334
322
324
306
100
320
332
310
318
300
326
302
308
312
102

FIG. 3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100a
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316
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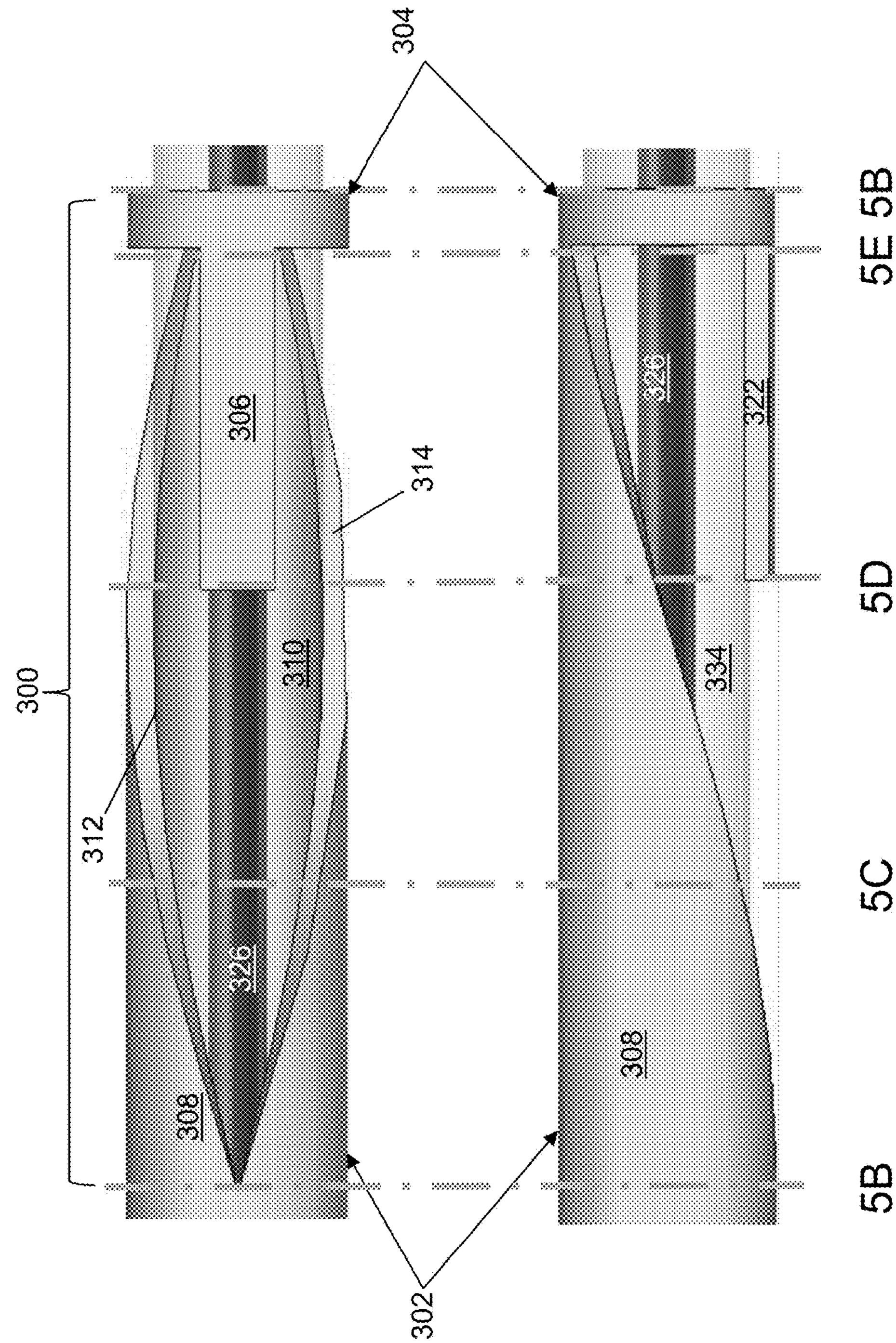
318
326
322
328
322
306
334
332
300
308
302
102

FIG. 4


304
300
306
314
322
326
312
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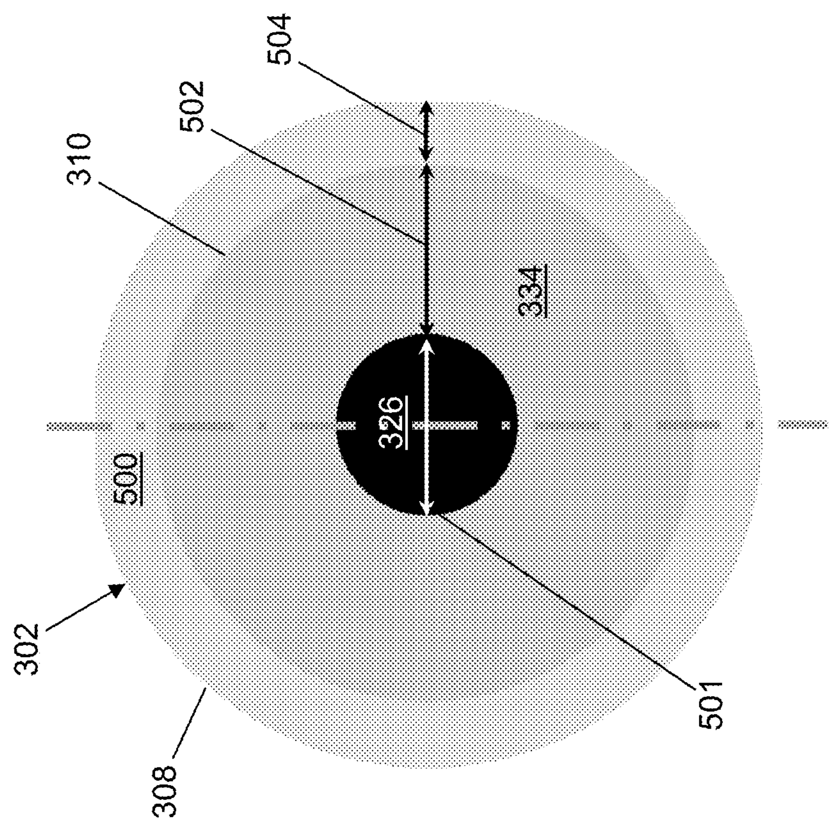
334
326
308
308
302
5B
5E
5B
5D
5C
5B

FIG. 5A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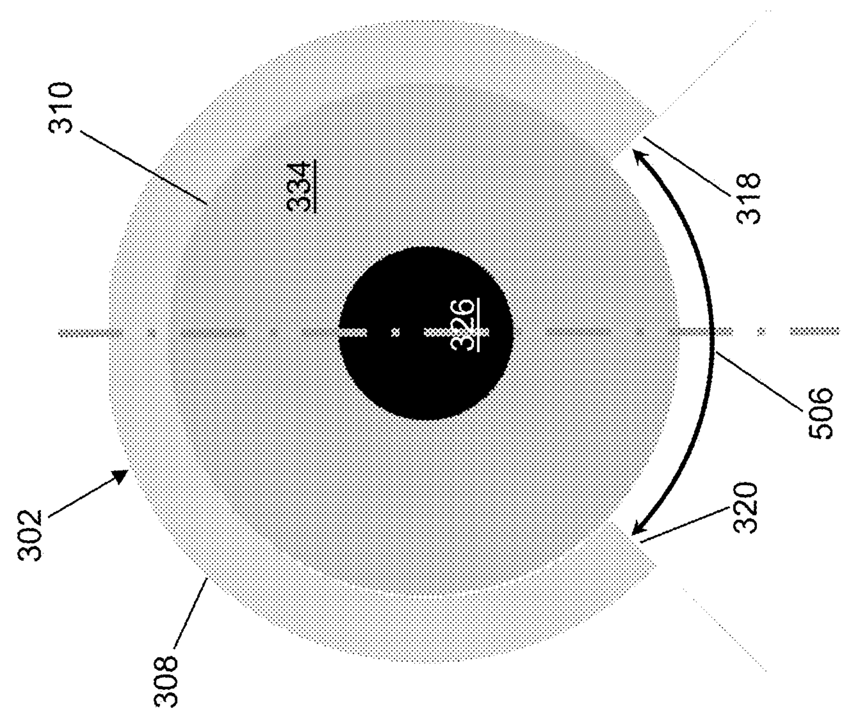
326
334
501
502
504

FIG. 5B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318
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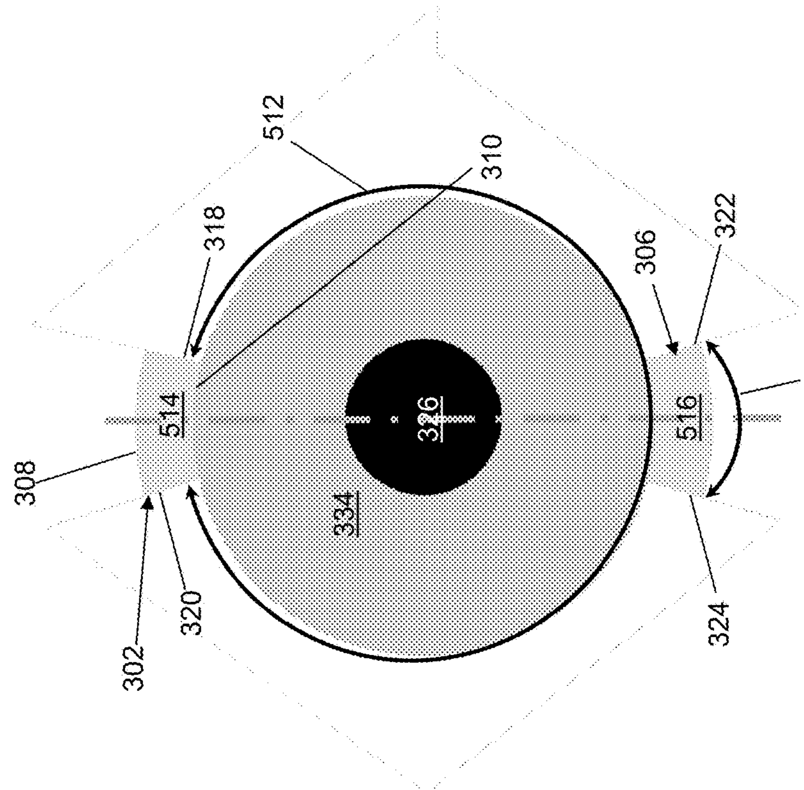
320

FIG. 5C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318
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322
514
326
516
510
308
334
302
320
324

FIG. 5E

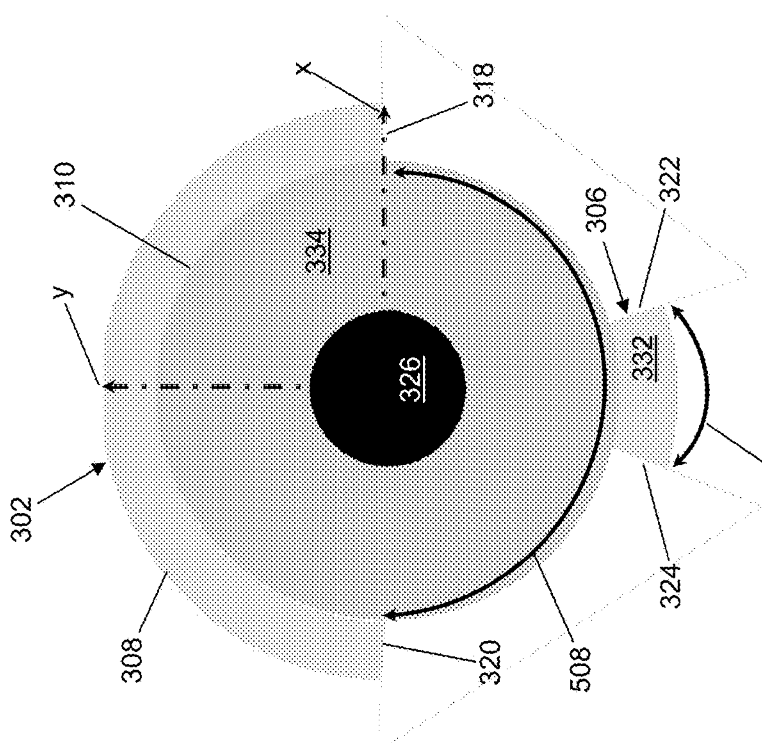
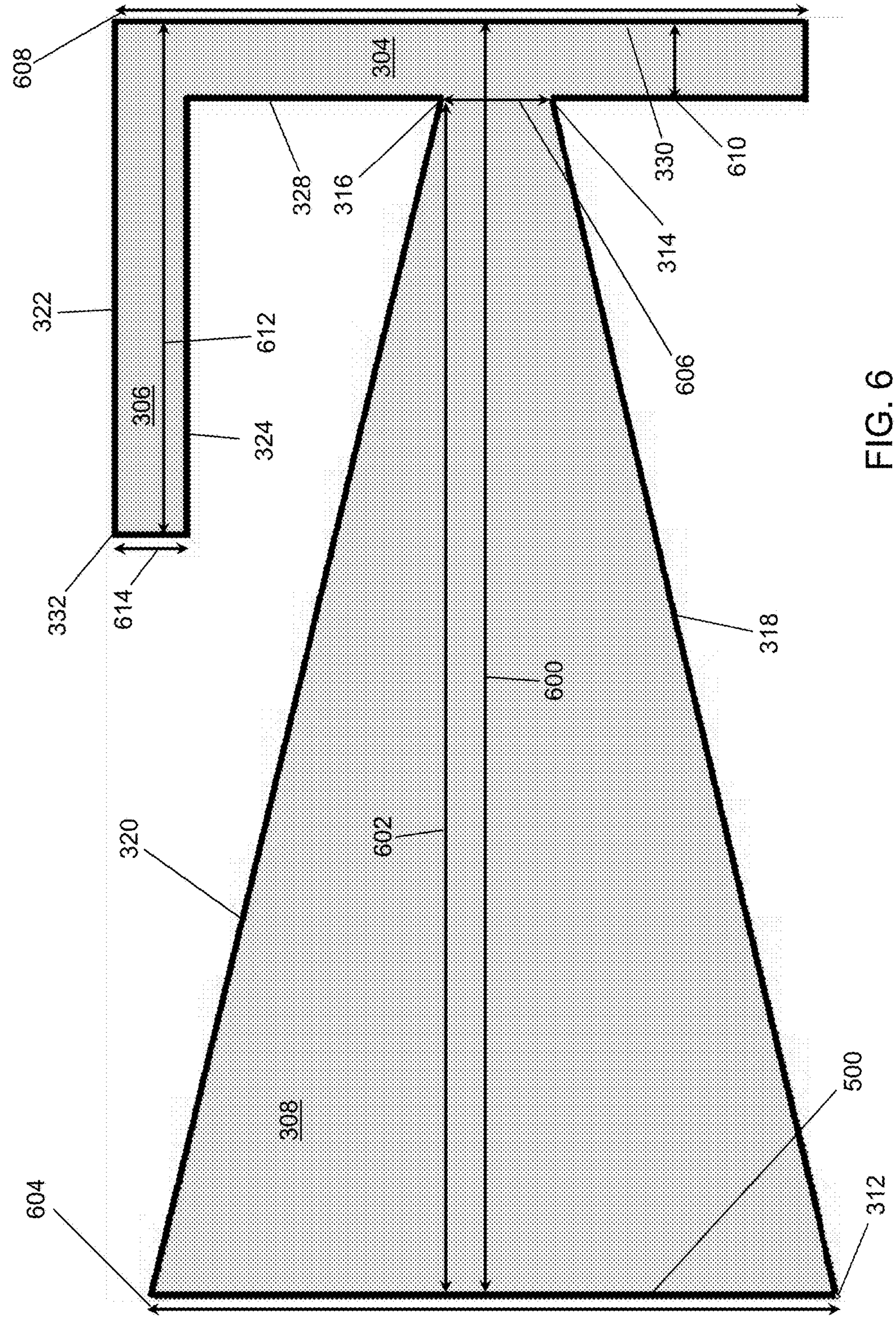

x
318
310
y
334
306
322
326
332
302
510
308
320
508
324

FIG. 5D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308
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314
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318
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322
324
328
330
332
500
600
602
604
606
608
610
612
614

FIG. 6

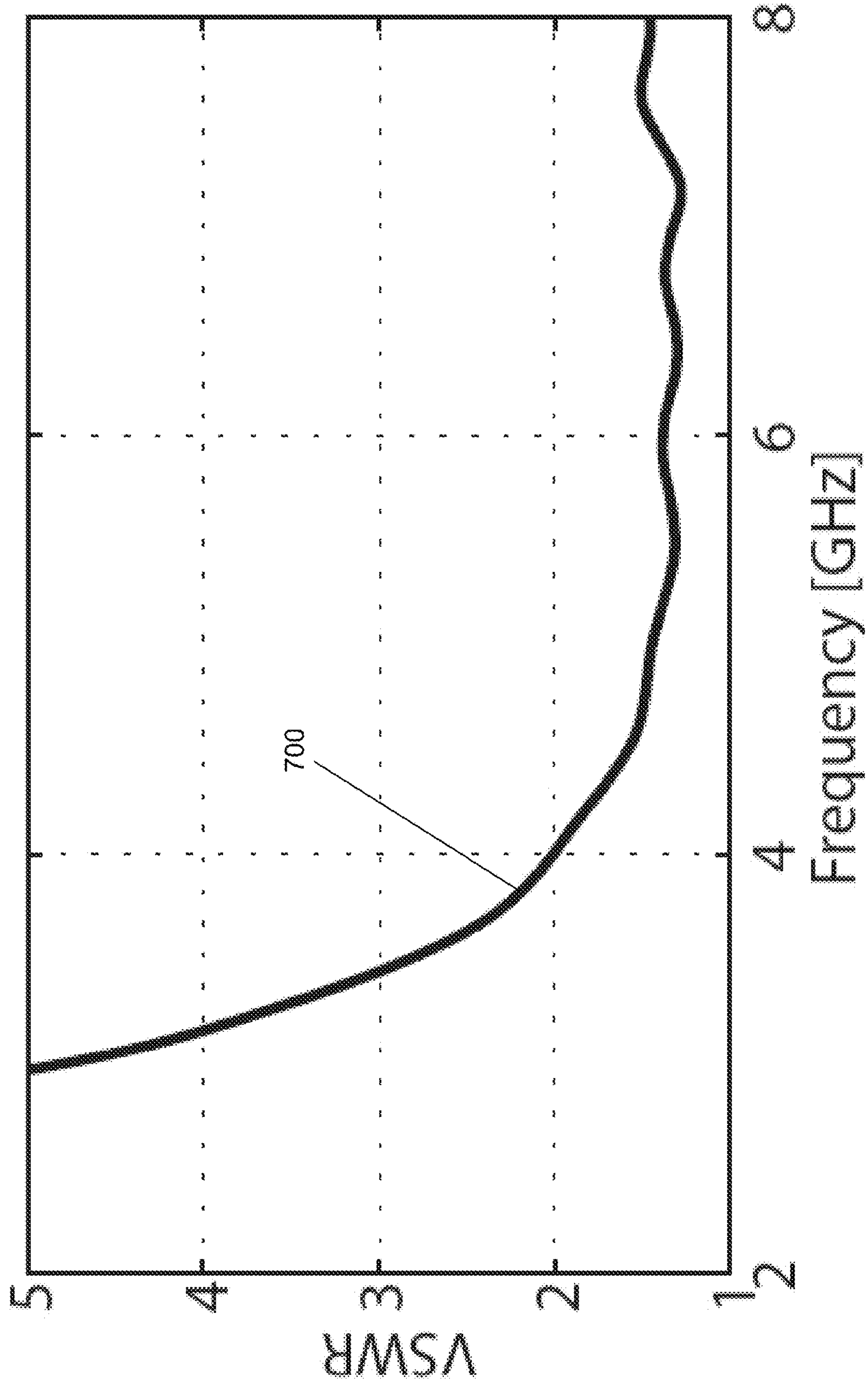


FIG. 7

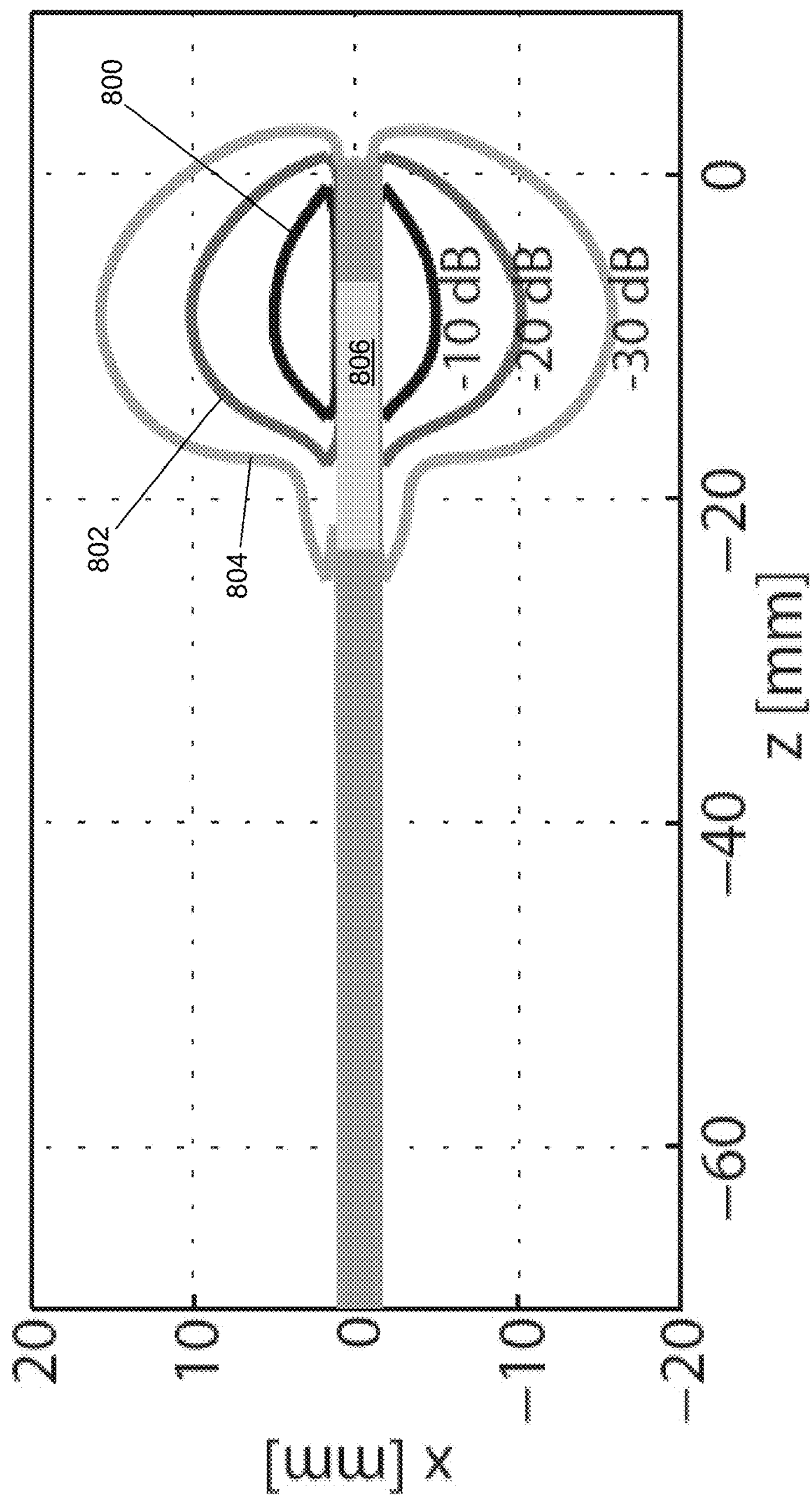
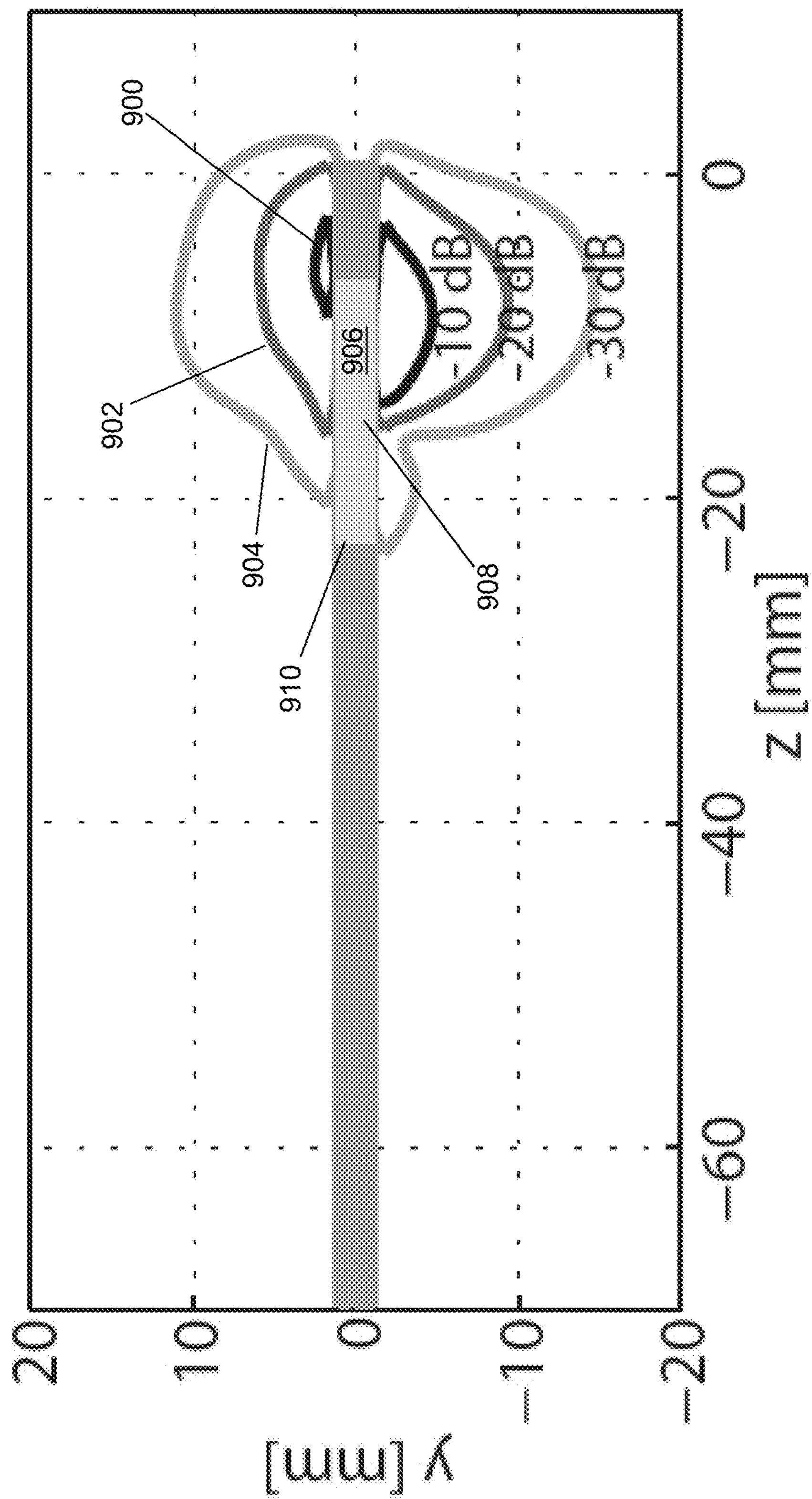


FIG. 8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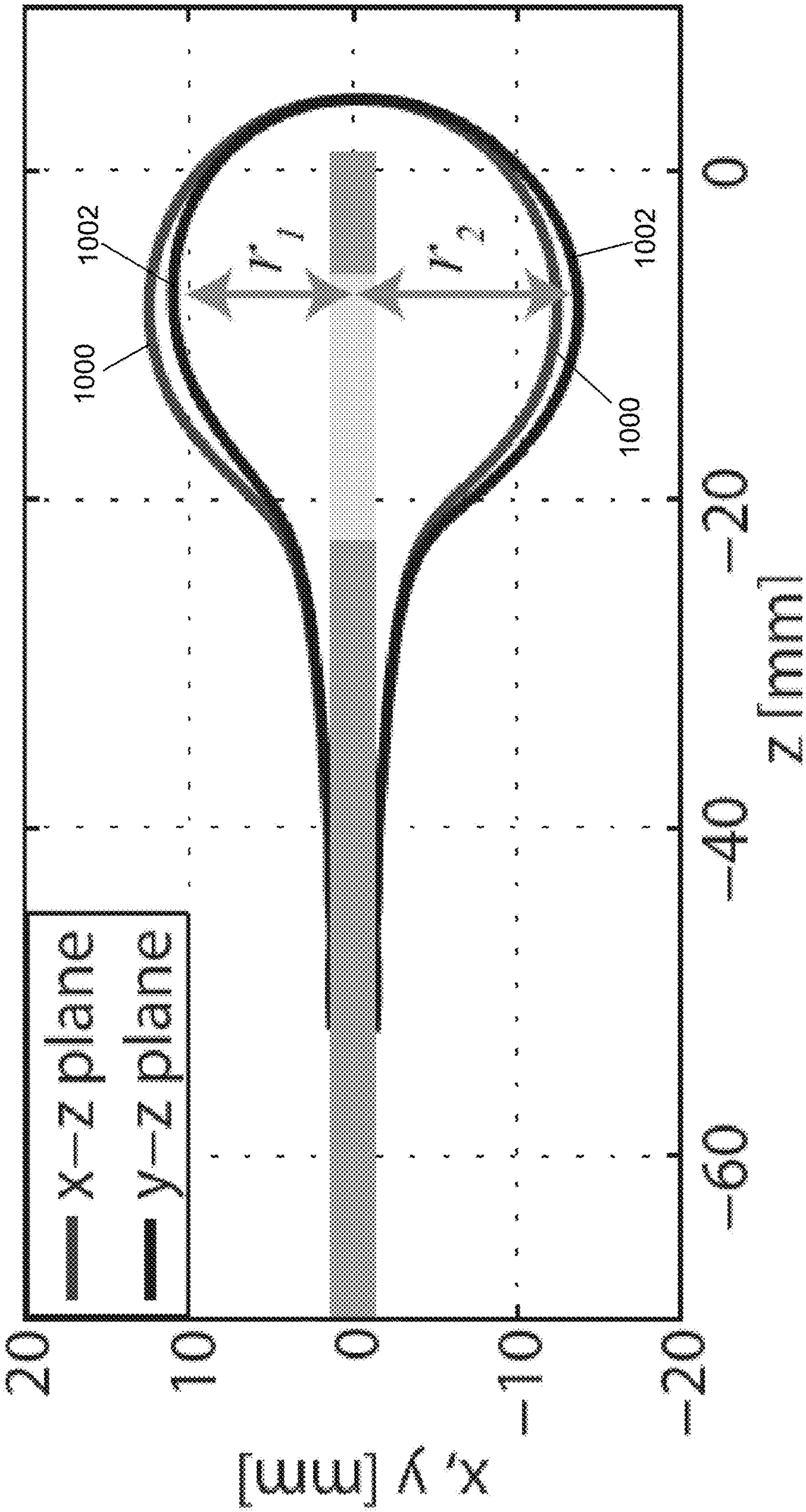
902
904
906
908
910
−10 dB
−20 dB
−30 dB
0
−20
−40
−60
z [mm]
20
10
0
−10
−20
y [mm]

FIG. 9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y–z plane
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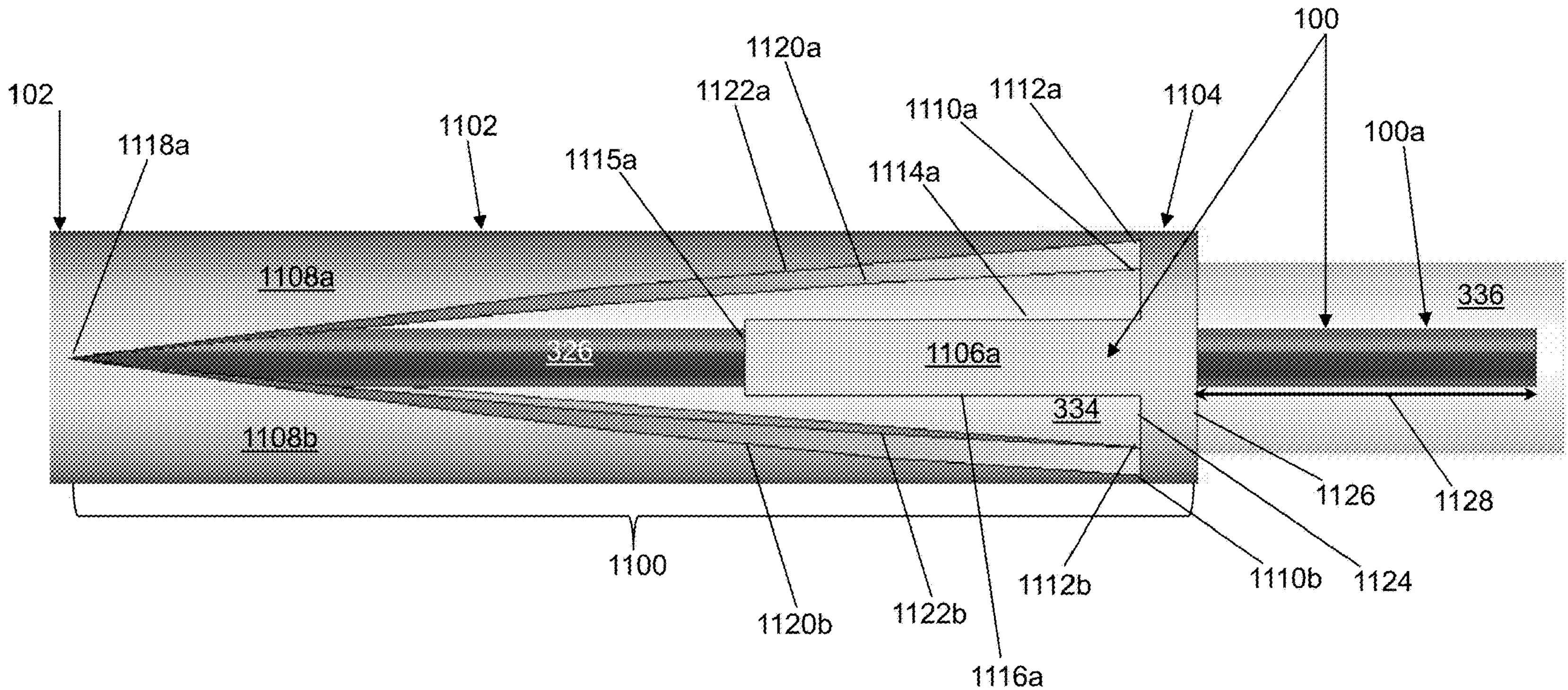
1002
1000
1002
r^*_1
r^*_2
20
10
0
−10
−20
x, y [mm]
−60
−40
−20
0
z [mm]

FIG. 10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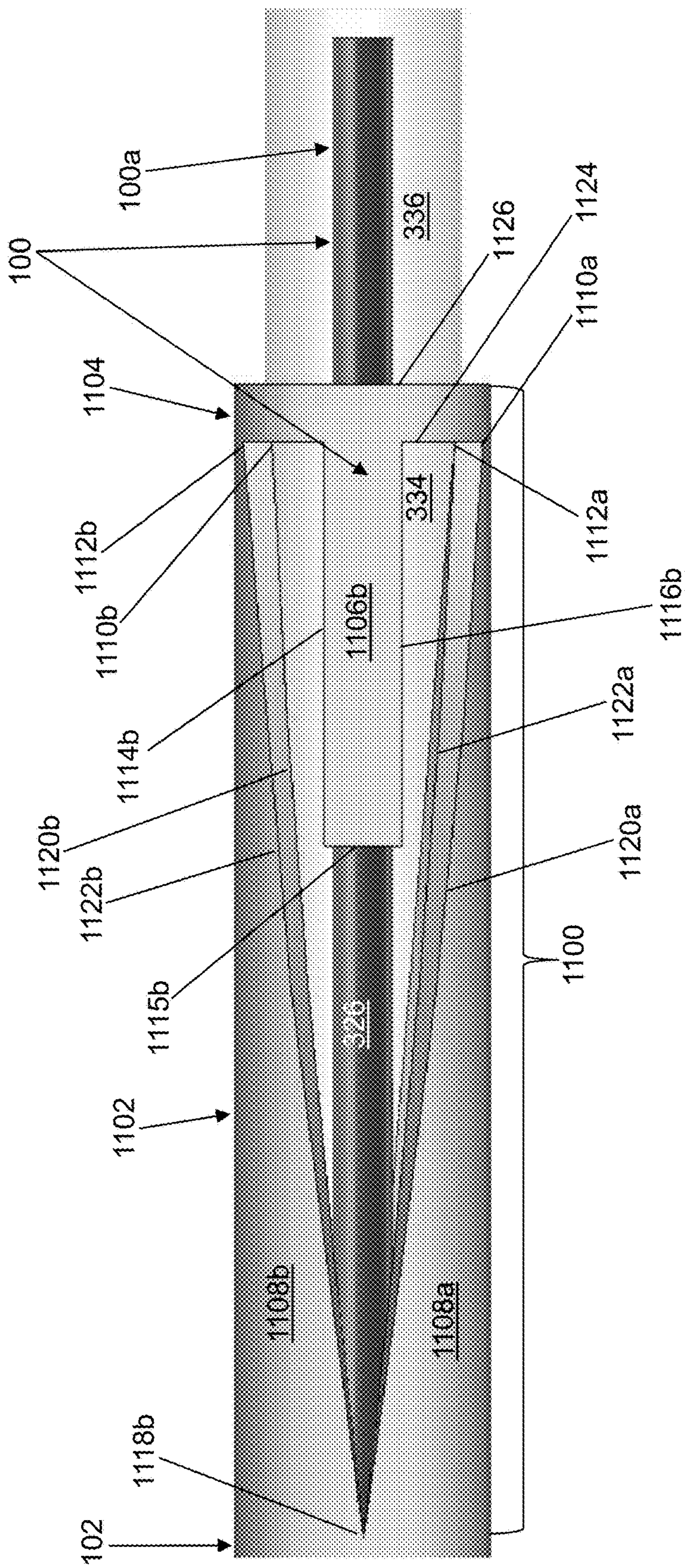
1102
1108a
1115a
1122a
1120a
1110a
1112a
1114a
1104
100
100a
336
326
1106a
334
1108b
1126
1128
1100
1120b
1122b
1116a
1112b
1110b
1124

FIG. 11



100a
336
1126
1124
100
1110a
1104
1112b
334
1112a
1110b
1106b
1116b
1114b
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1115b
1100
326
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1108b
1108a
1118b
102

FIG. 12

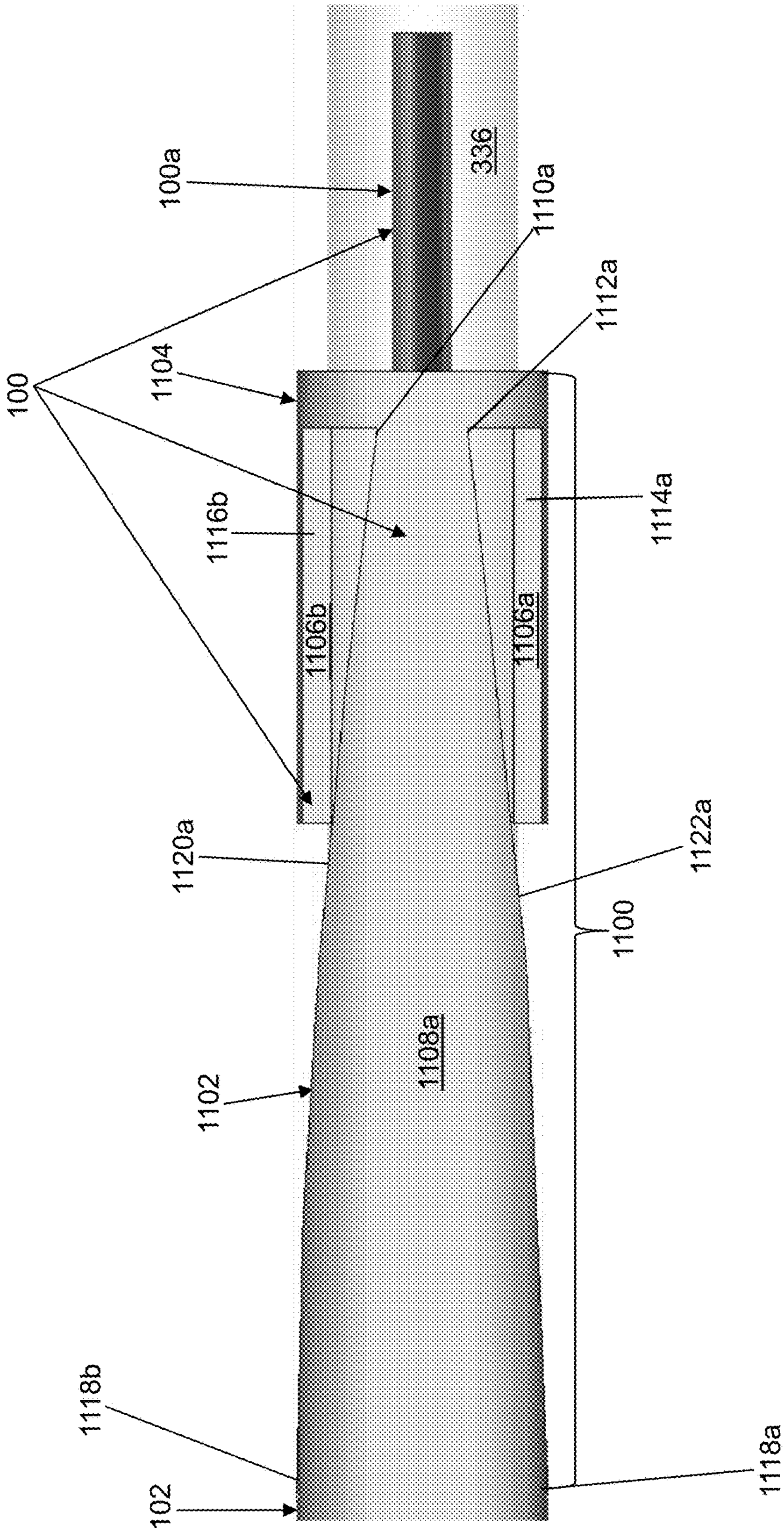

336
100a
1110a
1112a
100
1104
1116b
1114a
1106b
1106a
1120a
1122a
1100
1108a
1102
1118b
1118a
102

FIG. 13

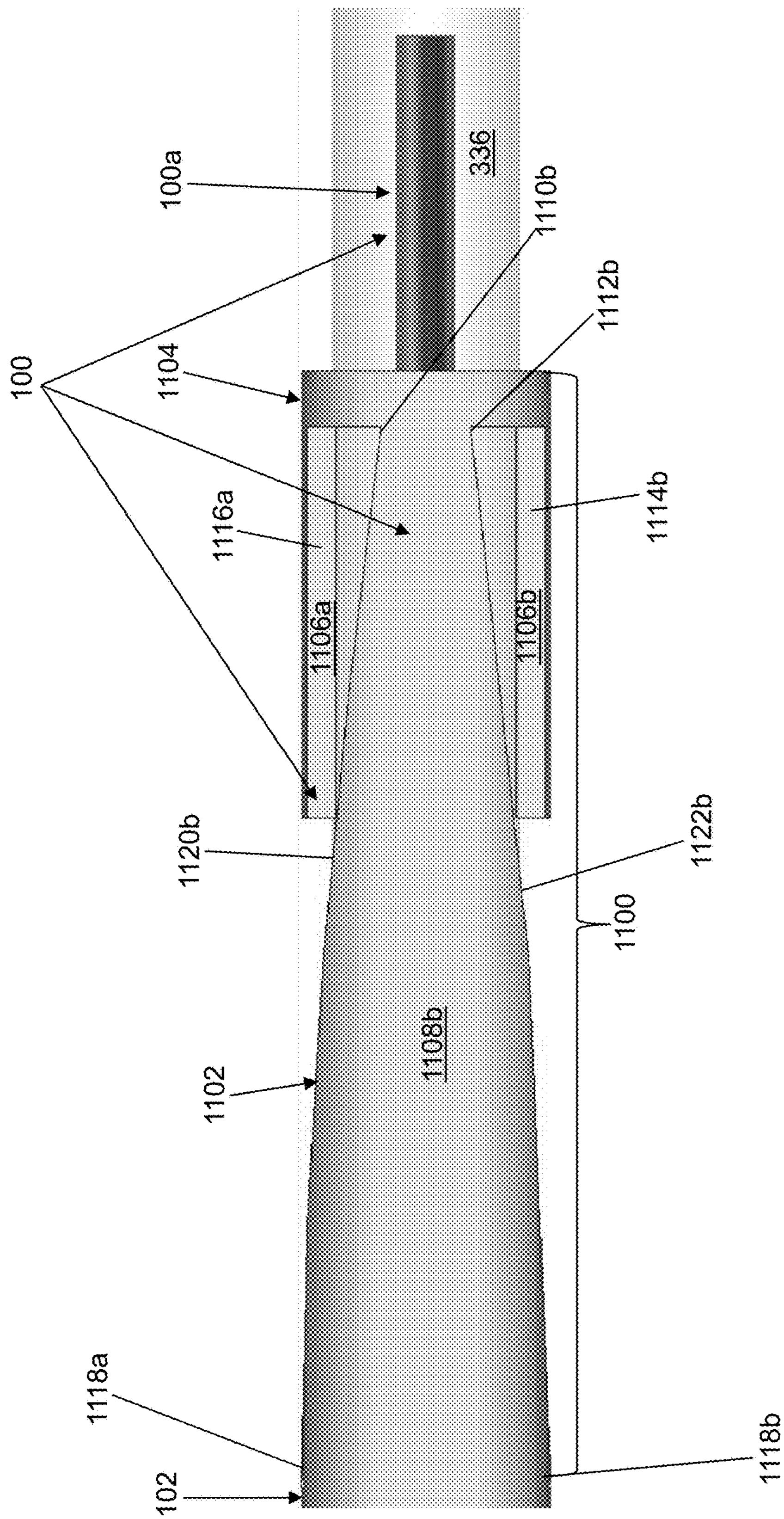
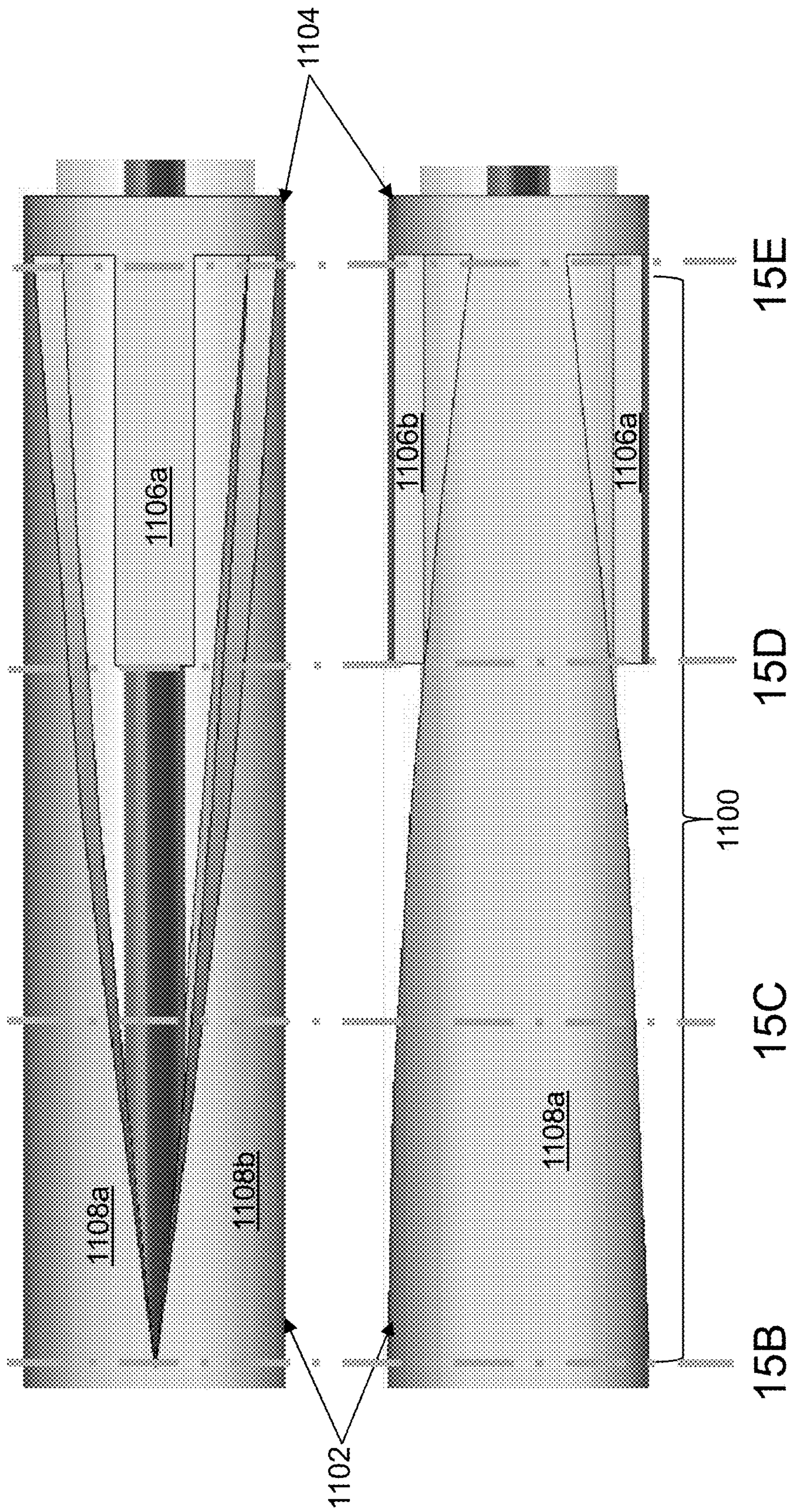

100a
336
1110b
1112b
100
1104
1116a
1114b
1106a
1106b
1120b
1122b
1100
1108b
1102
1118a
102
1118b

FIG. 14



1104
1106a
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1106a
1108a
1108b
1108a
1100
1102
15E
15D
15C
15B

FIG. 15A

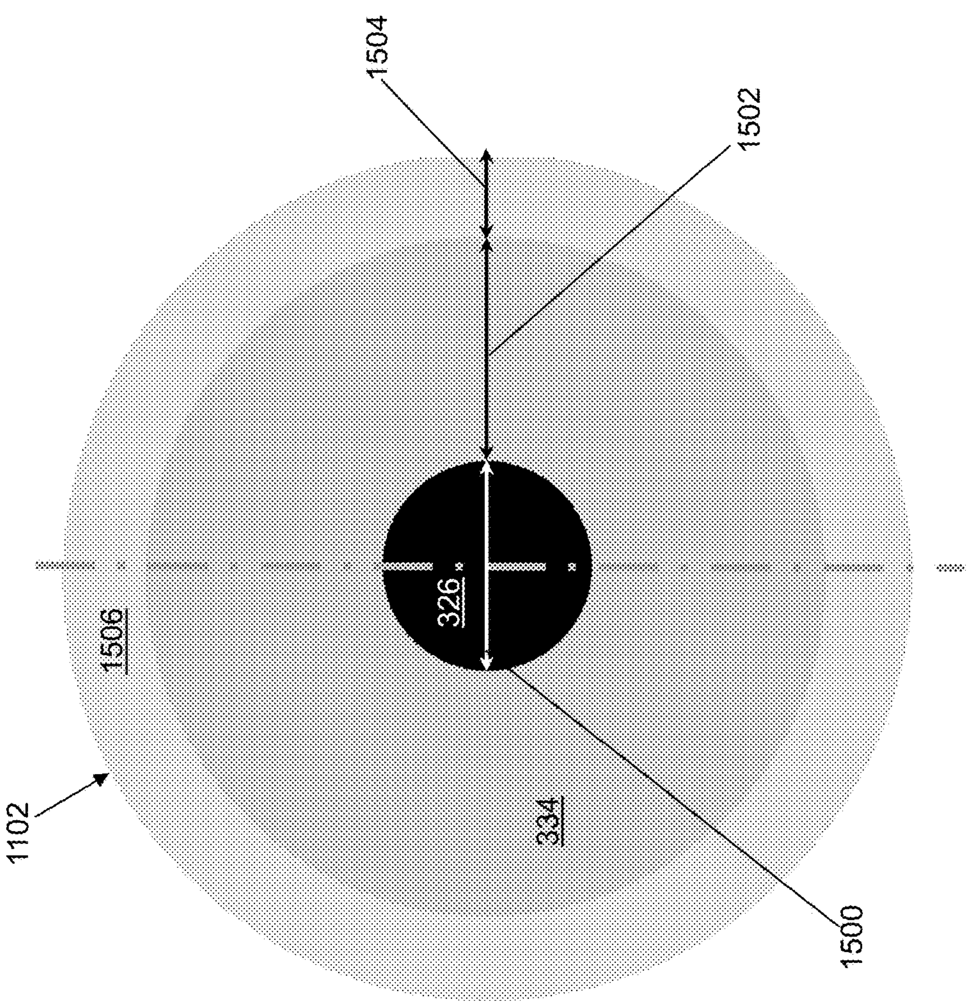
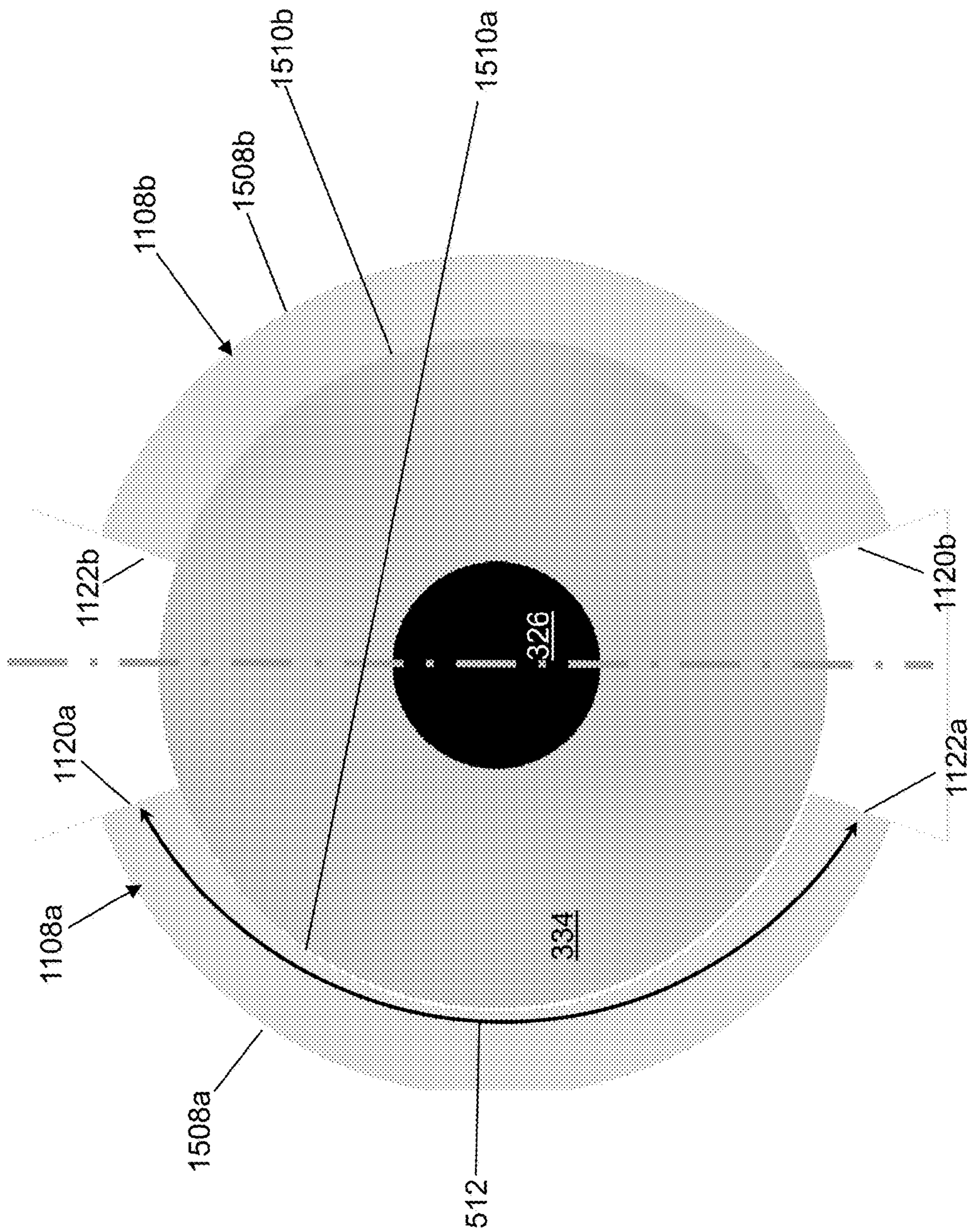


FIG. 15B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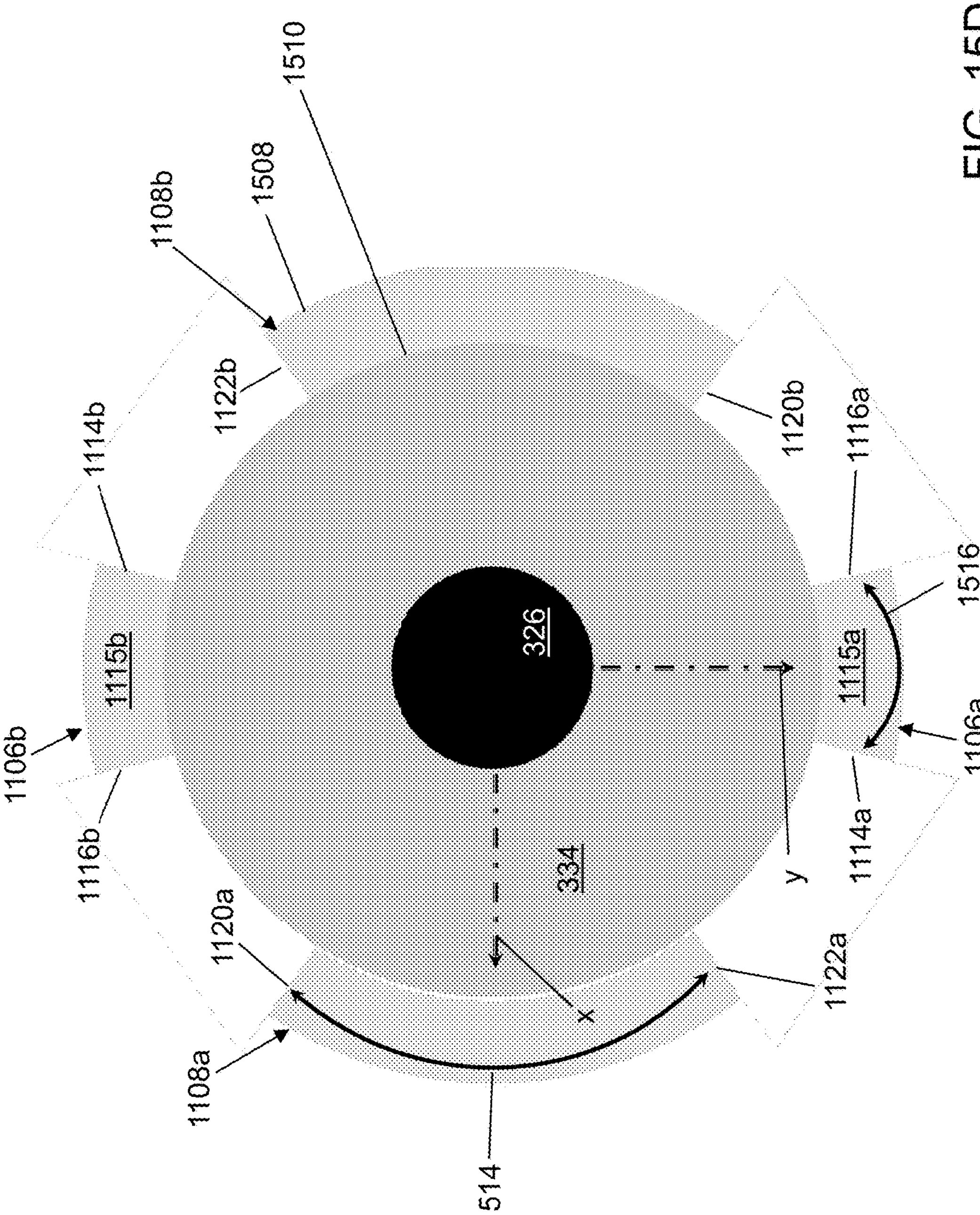
1508a
1512
326
334
1122a
1120b

FIG. 15C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1114b
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1516
326
1115b
1115a
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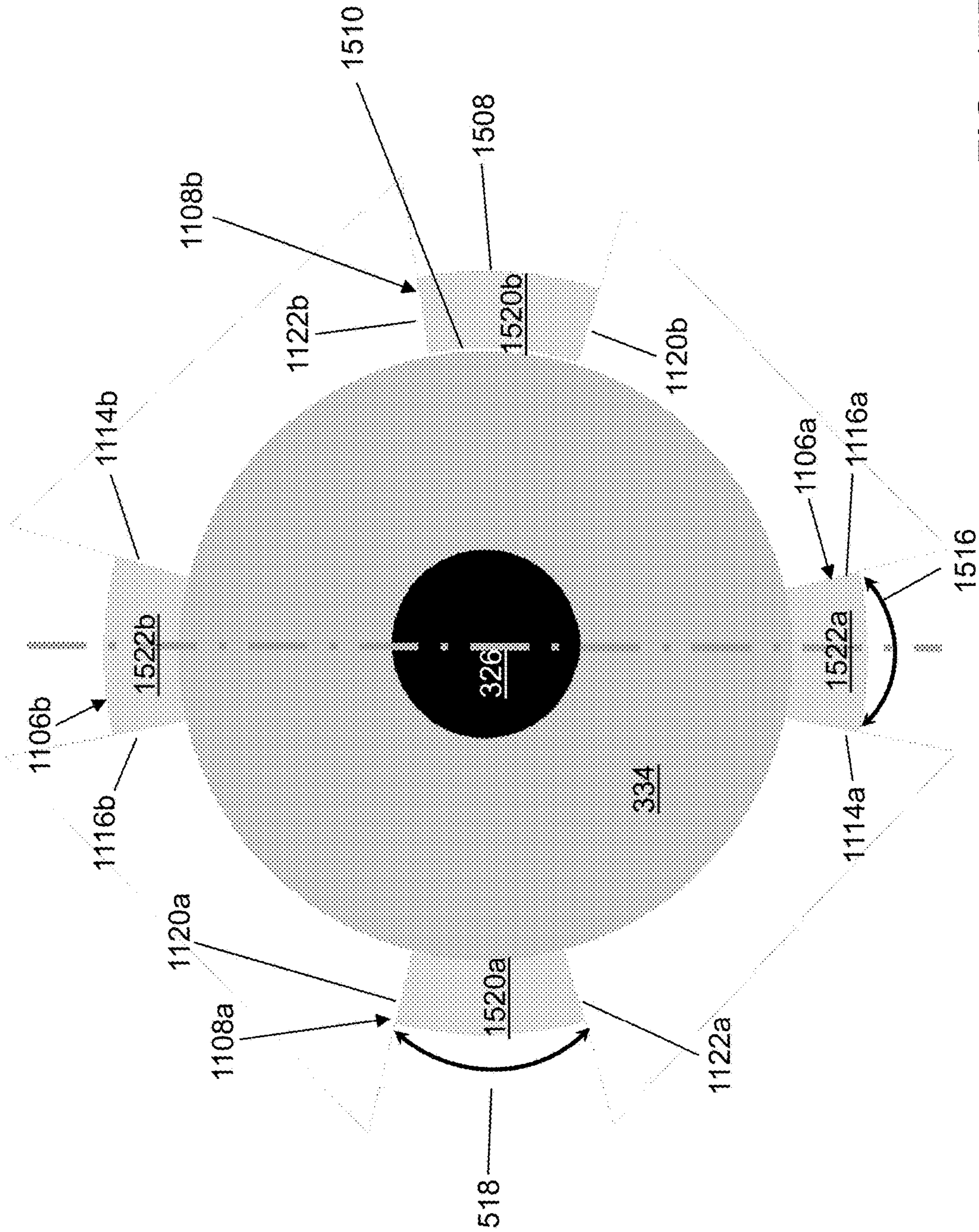
1116b
1114a
334
y
1120a
1122a
x
1108a
1514

FIG. 15D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1120b
1114b
1106a
1116a
1516
1522b
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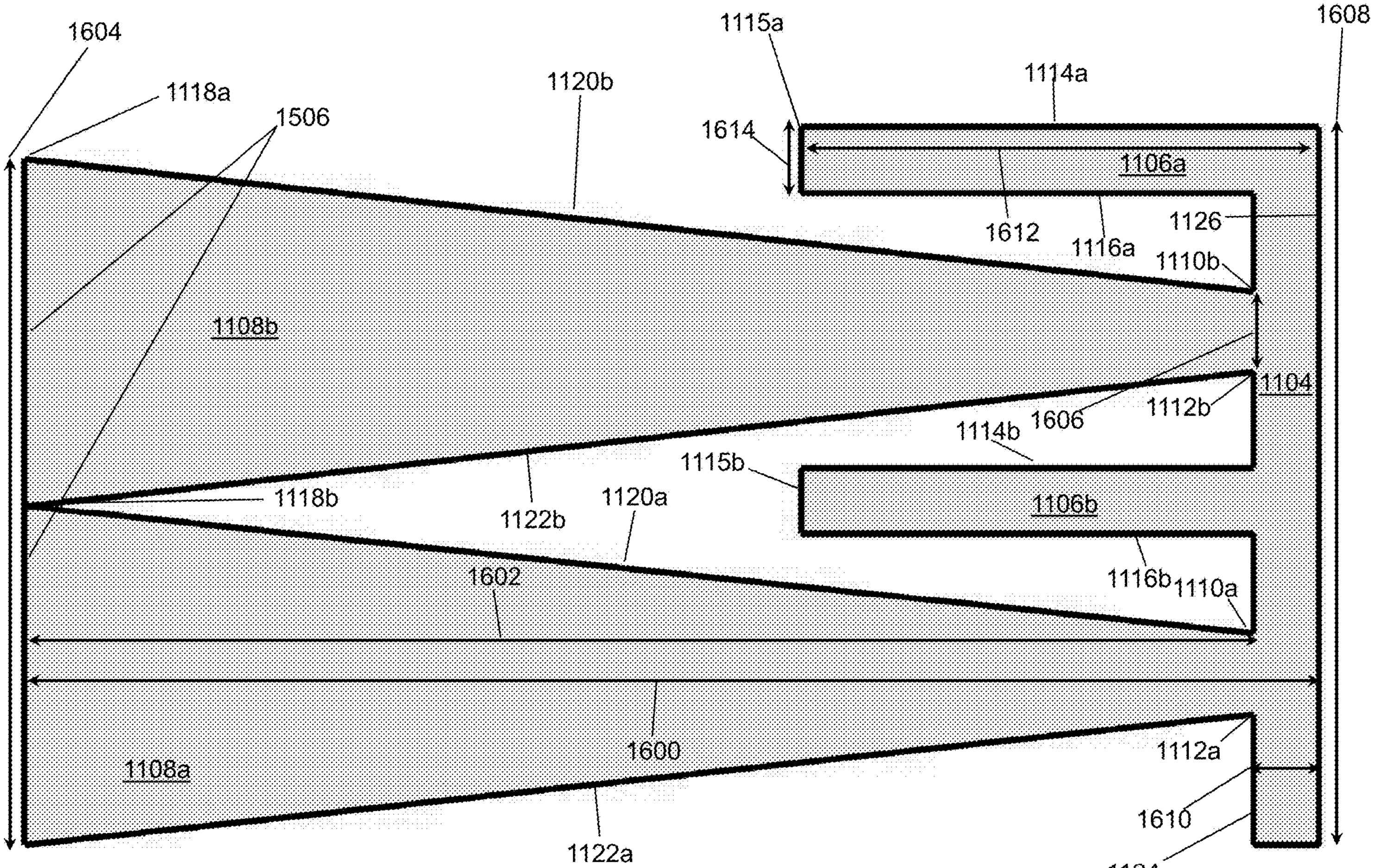
334
1106b
1116b
1114a
1120a
1520a
1108a
1122a
1518

FIG. 15E


1604
1118a
1506
1120b
1115a
1114a
1608
1614
1106a
1612
1116a
1126
1110b
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1104
1606
1112b
1114b
1115b
1106b
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1600
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1112a
1610
1122a
1124

FIG. 16

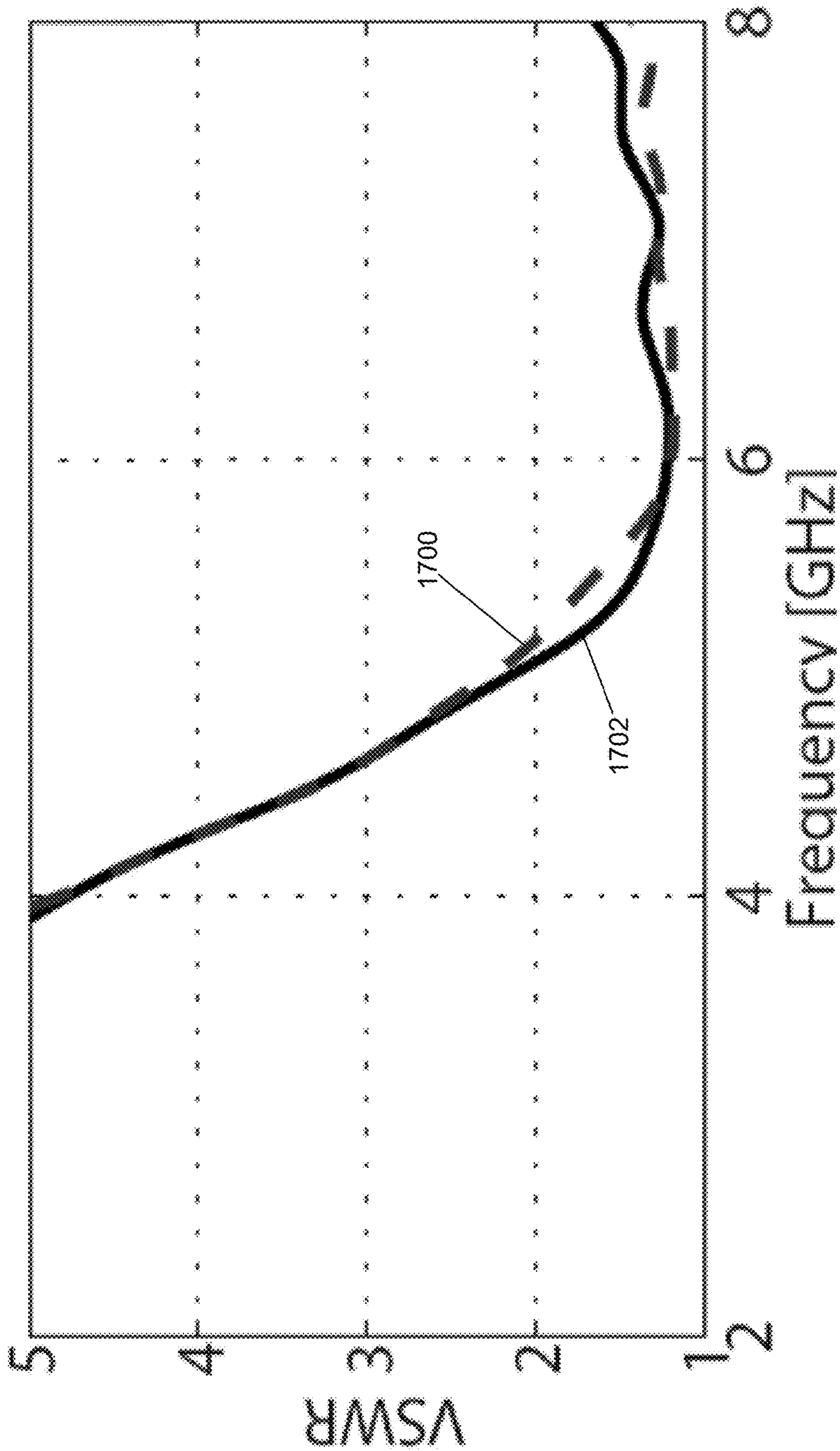


FIG. 17

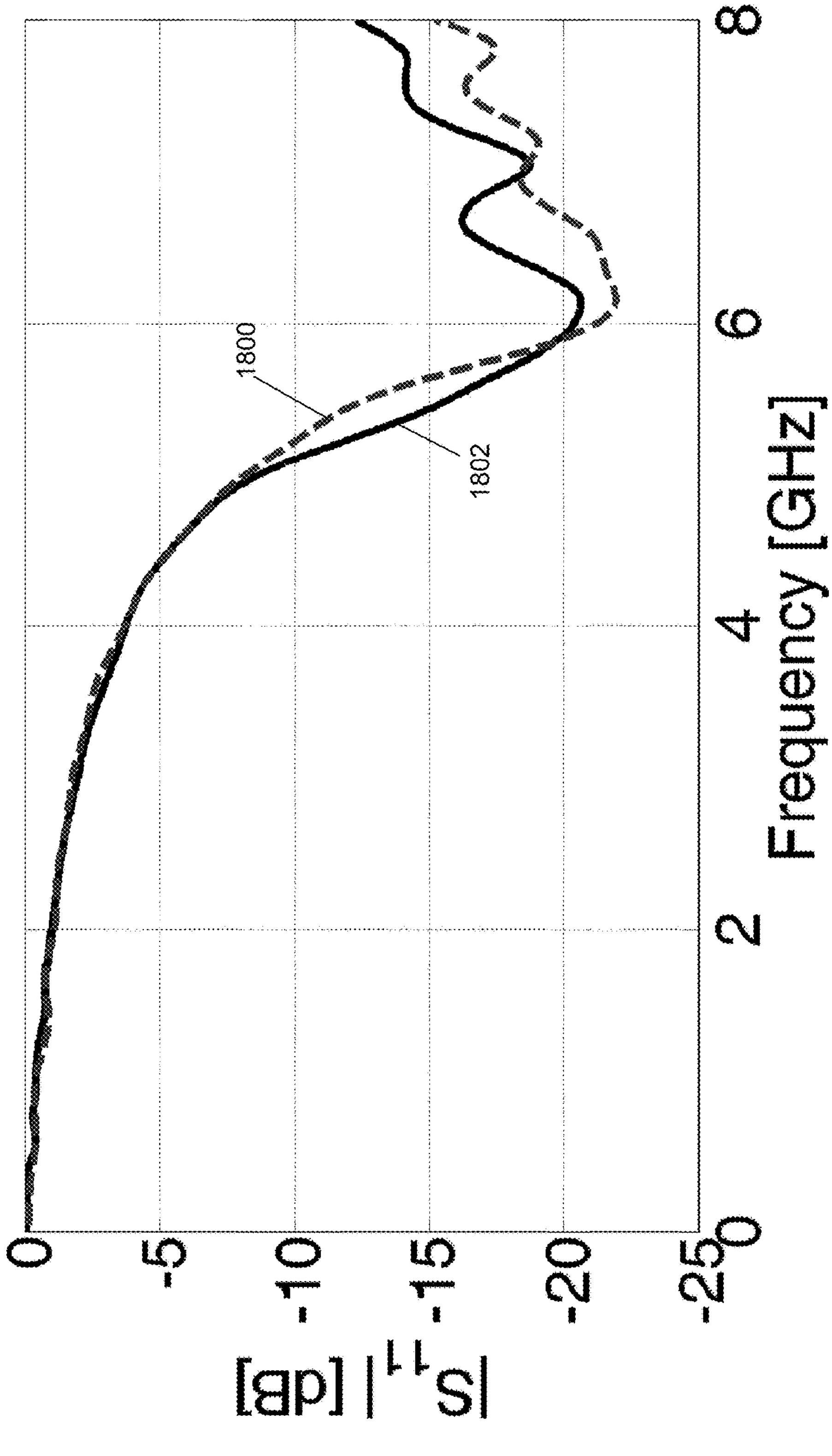


FIG. 18

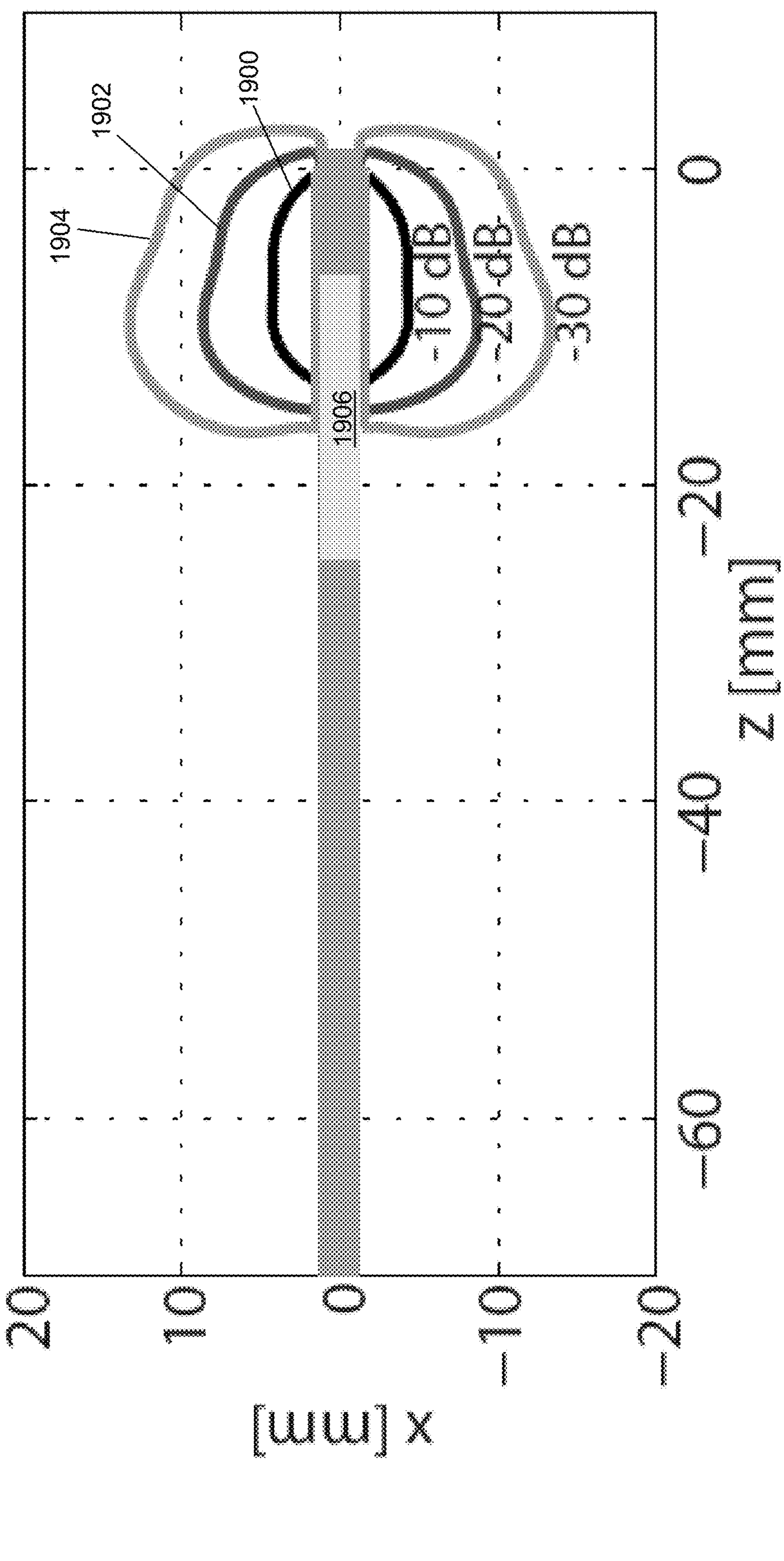

1900
1902
1904
1906
−10 dB
−20 dB
−30 dB
z [mm]
x [mm]
0
−20
−40
−60
20
10
0
−10
−20

FIG. 19

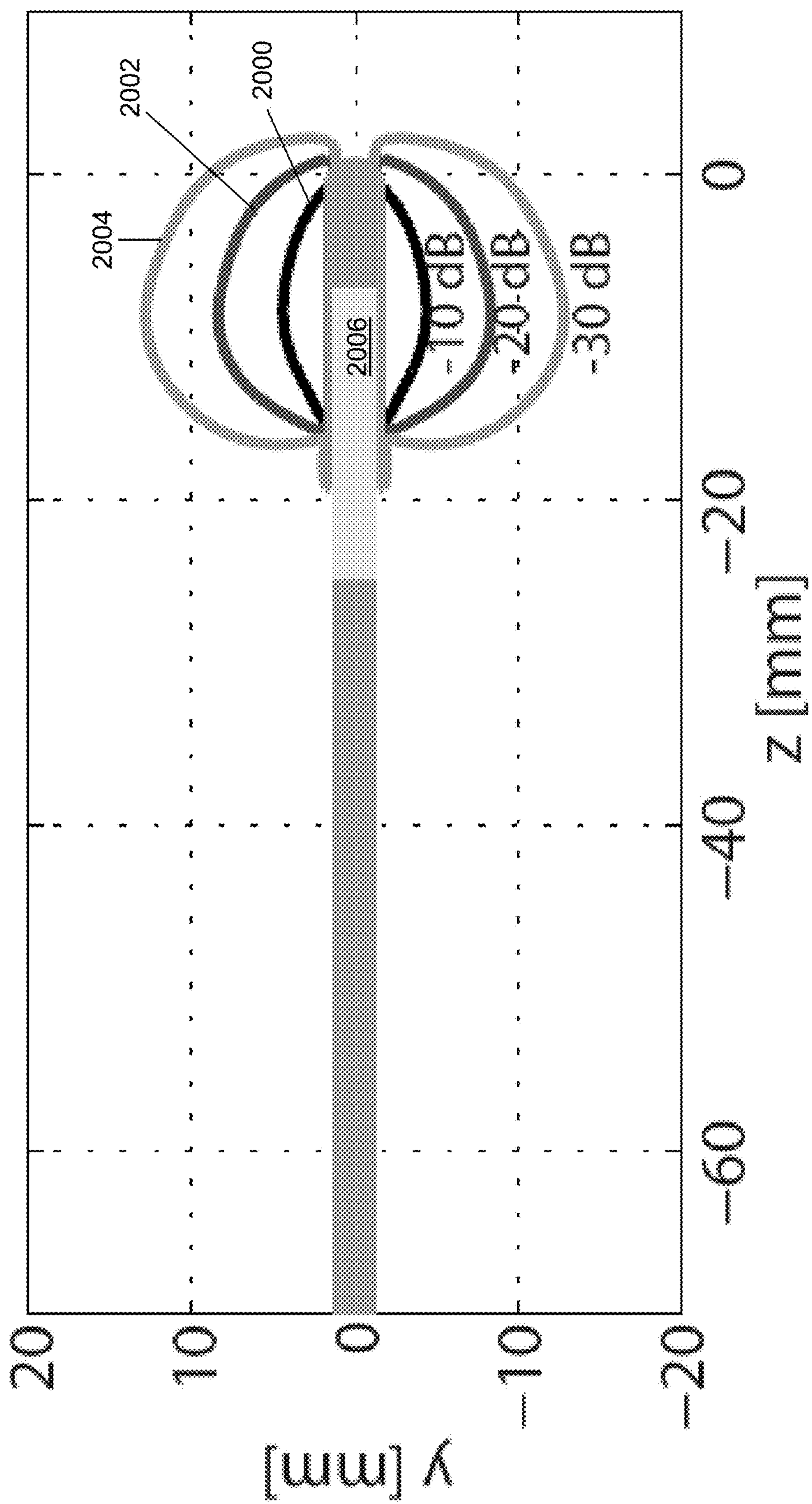

2000
2002
2004
2006
−10 dB
−20 dB
−30 dB
20
10
0
−10
−20
y [mm]
0
−20
−40
−60
z [mm]

FIG. 20

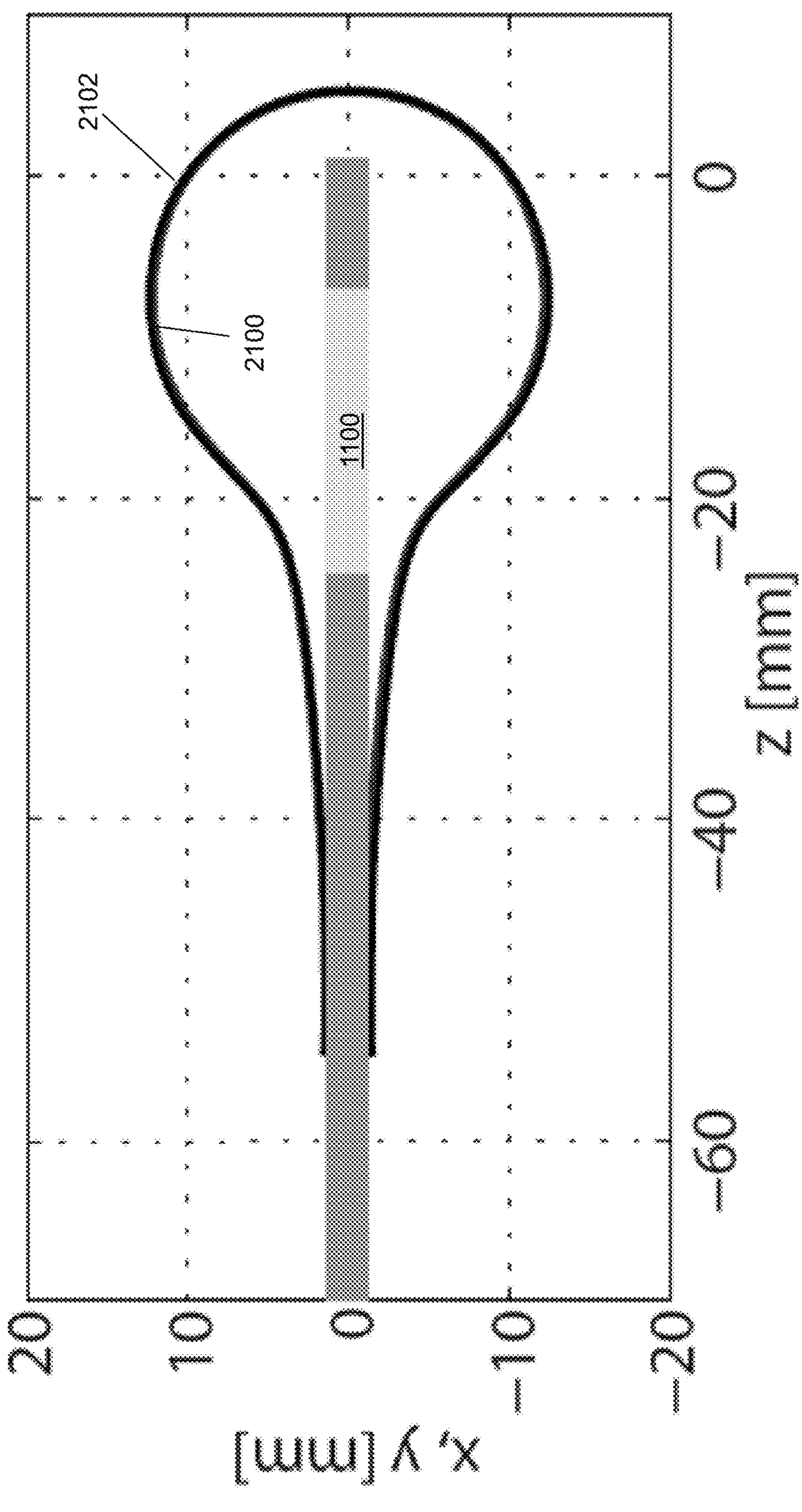
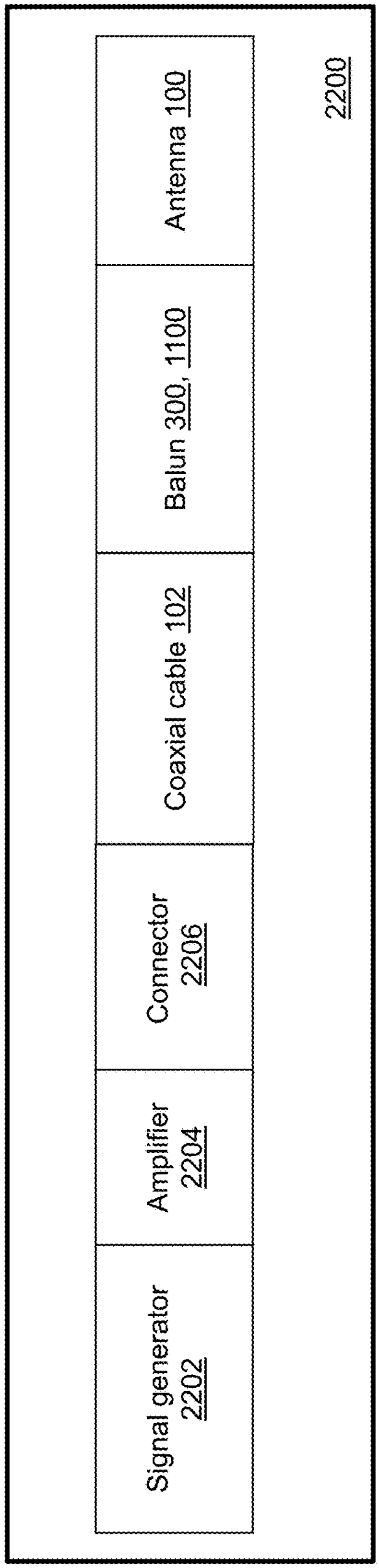


FIG. 21



Antenna 100
Balun 300, 1100
Coaxial cable 102
Connector 2206
Amplifier 2204
Signal generator 2202
2200

FIG. 22

MICROWAVE ABLATION ANTENNA SYSTEM WITH TAPERED SLOT BALUN

REFERENCE TO GOVERNMENT RIGHTS

This invention was made with government support under ECCS-1406090 awarded by the National Science Foundation. The government has certain rights in the invention.

BACKGROUND

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

SUMMARY

A balun is provided that includes, but is not limited to, a center conductor, a dielectric material, a tapered wall, a ring, and a prong. The center conductor extends a length of the balun. The dielectric material surrounds the center conductor along the length of the balun. The tapered wall forms a portion of a tube between a first wall and a second wall. The first wall is opposite the second wall. The tapered wall is formed of a conductive material. The portion of the tube forms a slot exposing the dielectric material. The ring connects to the second wall of the tapered wall and is formed of the conductive material. The ring forms a tube surrounding the center conductor and the dielectric material. The prong connects to the ring to extend toward the first wall and is formed of the conductive material. The prong extends over a portion of the dielectric material exposed by the slot.

An antenna system is provided. The antenna system includes, but is not limited to, a coaxial cable, a first dipole arm, and a balun. 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 first dipole arm connects to the center conductor. The balun connects between an end of the coaxial cable and the first dipole arm. The balun includes, but is not limited to, a second center conductor, a second dielectric material, a tapered wall, a ring, and a prong. The second center conductor extends a length of the balun and connects to and extends from the center conductor between the center conductor and the first dipole arm. The second dielectric material surrounds the second center conductor along the length of the balun. The tapered wall forms a portion of a tube between a first wall and a second wall, wherein the first wall is opposite the second wall. The first wall is connected to the conductive shield. The tapered wall is formed of a conductive material. The portion of the tube forms a slot exposing the second dielectric material. The ring connects to the second wall of the tapered wall and is formed of the conductive material. The ring forms a tube surrounding the second center conductor and the second dielectric material. The prong connects to the ring to extend toward the first wall and is formed of the conductive material. The prong extends over a portion of the second dielectric material exposed by the slot and forms a second dipole arm.

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

BRIEF DESCRIPTION OF THE DRAWINGS

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

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

FIG. **2** depicts an MWA antenna system with a prior balun design in accordance with an illustrative embodiment.

FIG. **3** depicts a top view of an MWA antenna system with a first balun in accordance with an illustrative embodiment.

FIG. **4** depicts a right side view of the MWA antenna system of FIG. **3** in accordance with an illustrative embodiment.

FIG. **5**A depicts the top and right side views of the MWA antenna system of FIGS. **3** and **4** aligned in accordance with an illustrative embodiment.

FIGS. **5**B-**5**E depict cross sectional views of the MWA antenna system at cross section locations illustrated in FIG. **5**A in accordance with an illustrative embodiment.

FIG. **6** depicts a top view of the MWA antenna system of FIGS. **3** and **4** unrolled and placed on a flat surface in accordance with an illustrative embodiment.

FIG. **7** shows a voltage standing wave ratio as a function of frequency of a simulated MWA antenna system illustrated in FIGS. **3** and **4** in accordance with an illustrative embodiment.

FIG. **8** shows a normalized specific absorption rate (SAR) pattern of the MWA antenna system of FIGS. **3** and **4** in the x-z plane in accordance with an illustrative embodiment.

FIG. **9** shows a normalized SAR pattern of the MWA antenna system of FIGS. **3** and **4** in the y-z plane in accordance with an illustrative embodiment.

FIG. **10** shows a 50° Celsius contour after 5 minutes of ablation using the MWA antenna system of FIGS. **3** and **4** with 20 Watts of input power in the x-z and y-z planes in accordance with an illustrative embodiment.

FIG. **11** depicts a top view of an MWA antenna system with a second balun in accordance with an illustrative embodiment.

FIG. **12** depicts a bottom view of the MWA antenna system of FIG. **11** in accordance with an illustrative embodiment.

FIG. **13** depicts a right side view of the MWA antenna system of FIG. **11** in accordance with an illustrative embodiment.

FIG. **14** depicts a left side view of the MWA antenna system of FIG. **11** in accordance with an illustrative embodiment.

FIG. **15**A depicts the top and right side views of the MWA antenna system of FIGS. **11** and **13** aligned in accordance with an illustrative embodiment.

FIGS. **15**B-**15**E depict cross sectional views of the MWA antenna system at cross section locations illustrated in FIG. **15**A in accordance with an illustrative embodiment.

FIG. **16** depicts a top view of the MWA antenna system of FIGS. **11-14** unrolled and placed on a flat surface in accordance with an illustrative embodiment.

FIG. **17** shows a simulated and a measured voltage standing wave ratio as a function of frequency of the MWA antenna system illustrated in FIGS. **11-14** in accordance with an illustrative embodiment.

FIG. **18** shows a comparison between a simulated and a measured input reflection coefficient, S_{11}, of the MWA antenna system of FIGS. **11-14** in accordance with an illustrative embodiment.

FIG. **19** shows a normalized SAR pattern of the MWA antenna system of FIGS. **11-14** in the x-z plane in accordance with an illustrative embodiment.

FIG. **20** shows a normalized SAR pattern of the MWA antenna system of FIGS. **11-14** in the y-z plane in accordance with an illustrative embodiment.

FIG. **21** shows a 50° Celsius contour after 5 minutes of ablation using the MWA antenna system of FIGS. **11-14** with 20 Watts of input power in the x-z and y-z planes in accordance with an illustrative embodiment.

FIG. **22** depicts a block diagram of an MWA system including the balun of FIGS. **3** and **4** or of FIGS. **11-14** in accordance with an illustrative embodiment.

DETAILED DESCRIPTION

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

Typically, interstitial antennas used for MWA are implemented using coaxial cables. When a balanced antenna (antenna **100**) is fed by an unbalanced transmission line (coaxial cable **102**), unwanted electric currents are excited on the outer conductor of coaxial cable **102**. If not properly suppressed, the currents can result in undesired heating and ablation of healthy tissue along the insertion path of antenna **100**. A balanced to unbalanced transformer (balun) may be implemented to suppress the currents.

With reference to FIG. **2**, a widely used solution for choking the undesired outer surface currents for coaxially fed MWA antennas is to use a coaxial balun **200**. Coaxial balun **200** includes a cylindrical conductor with a circular cross section that encompasses coaxial cable **102**. The cylindrical conductor and the outer conductor of coaxial cable **102** constitute a new coaxial transmission line for the outer surface currents. By properly choosing a length of coaxial balun **200** and terminating its proximal end with a short circuit or an open circuit, a high impedance is presented at its distal end to effectively choke the outer surface currents. However, this coaxial balun **200** increases an overall diameter, and therefore, invasiveness of antenna **100**.

With reference to FIG. **3**, a top view of antenna **100** with a first balun **300** is shown in accordance with an illustrative embodiment. With reference to FIG. **4**, a right side view of antenna **100** with first balun **300** is shown in accordance with an illustrative embodiment. Antenna **100** may be a dipole antenna formed by a first dipole arm **100*a*** and a second dipole arm **306**. Second dipole arm **306** may also be referred to herein as a prong. In the illustrative embodiment, second dipole arm **306** has a rectangular shape though other shapes may be used. Because second dipole arm **306** may be integrally formed with the remaining components of first balun **300**, second dipole arm **306** is also referred to herein as a portion of first balun **300**. First balun **300** is connected between coaxial cable **102** and first dipole arm **100*a*** of antenna **100**.

Antenna **100** is formed of a conductive material. As understood by a person of skill in the art, the wavelength of operation, λ_0, of antenna **100** is defined as $\lambda_0=c/F_0$, where c is the speed of light in an environment in which antenna **100** is used, such as a body tissue, and f_0 is the selected operating frequency. For illustration, f_0 may be between 500 MHz and 30 GHz. A cross section of first dipole arm **100*a*** may be circular, square, elliptical, rectangular, etc.

Coaxial cable **102** may include any length of coaxial cable having any characteristic impedance. Coaxial cable **102** may include a center conductor extending a length of coaxial cable **102**, a dielectric material surrounding the center conductor along the length of coaxial cable **102**, a conductive shield surrounding the dielectric material along the length of coaxial cable **102**, and an insulating jacket surrounding the conductive shield along the length of coaxial cable **102** as understood by a person of skill in the art. The center conductor 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. The dielectric material may include foamed polyethylene, solid polyethylene, polyethylene foam, polytetrafluoroethylene, air, air space polyethylene, vacuum, alumina, etc. For illustration, the dielectric material may include any low loss dielectric materials having a permittivity relative to a vacuum within the range of 1-10. The conductive shield may be formed of a solid or braided conductive material such as copper, steel, aluminum, silver plated copper, silver plated copper clad steel, etc. The insulating jacket (also known as an outer sheath) can be made from many different insulating materials such as polyvinyl chloride, polytetrafluoroethylene, another plastic material, etc.

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 (Ω) or may 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 balun **300** may include a tapered wall **302**, a ring **304**, and second dipole arm **306** that forms a prong connected to and extending from ring **304**. First balun **300** is formed of a conductive material. For example, tapered wall **302**, ring **304**, and second dipole arm **306** may be formed of the same material as the conductive shield of coaxial cable **102**. First balun **300** may be created by tapering the conductive shield of a portion of coaxial cable **102** to a wall that connects to ring **304** and removing the material on each side of second dipole arm **306** except where it connects to ring **304** to form a slot and to make a smooth transition from a coaxial line to a parallel wire line.

Tapered wall **302** forms a portion of a cylindrical tube between a first wall **500** (shown referring to FIGS. **5**B and **6**) and a second wall **514** (shown referring to FIG. **5**E). First wall **500** is opposite second wall **514**. Tapered wall **302** surrounds a balun dielectric material **334**. Balun dielectric material **334** may surround a balun center conductor **326**. Balun center conductor **326** may be an extension of the center conductor of coaxial cable **102**. First dipole arm **100***a* may be an extension of balun center conductor **326**.

The portion of the cylindrical tube forms a slot exposing balun dielectric material **334**. Balun dielectric material **334** may be the same material and/or an extension of the dielectric material that surrounds the center conductor of coaxial cable **102**. A second dielectric material **336** may further surround first dipole arm **100***a*. Second dielectric material **336** may be the same material as and/or an extension of balun dielectric material **334**.

Tapered wall **302** has an exterior surface **308** and an interior surface **310**. The slot formed by tapered wall **302** starts at a slot end point **312** and extends to a first end point **314** and a second end point **316** on either side of second wall **514**. A first slot wall **318** extends from slot end point **312** to first end point **314**. A second slot wall **320** extends from slot end point **312** to second end point **316**.

Second dipole arm **306** extends from a first dipole arm wall **332** that is closest to slot end point **312** to a second dipole arm wall **516** (shown referring to FIG. **5**E) that mounts (connects) second dipole arm **306** to ring **304**. First dipole arm wall **332** is opposite second dipole arm wall **516**. A first arm wall **322** of second dipole arm **306** extends from first dipole arm wall **332** to second dipole arm wall **516**. A second arm wall **324** of second dipole arm **306** extends from first dipole arm wall **332** to second dipole arm wall **516**. First arm wall **322** and second arm wall **324** are on opposite sides of second dipole arm **306**. Second dipole arm **306** forms a semicircular prong.

Ring **304** is connected to second wall **514** of tapered wall **302** and to second dipole arm wall **516** of second dipole arm **306**. Ring **304** forms a short cylindrical tube surrounding balun center conductor **326** and balun dielectric material **334**. Ring **304** has an inner ring wall **328** and an outer ring wall **330**. Second dipole arm **306** is connected to inner ring wall **328** of ring **304**, extends towards first wall **500**, and is located in the slot created by tapered wall **302**. Second dipole arm **306** and first dipole arm **100***a* extend in opposite directions relative to ring **304**. Second wall **514** of tapered wall **302** also connects to inner ring wall **328**.

Tapered wall **302** and balun center conductor **326** form a balanced parallel-wire line to feed antenna **100** that includes first dipole arm **100***a* and second dipole arm **306**. Second dipole arm **306** is placed in the slot formed by tapered wall **302** and is connected to tapered wall **302** through ring **304** at second dipole arm wall **516**. At its operating frequency, first balun **300** provides balanced currents for antenna **100**. As a result, unbalanced currents flowing back on an outer surface of the conductive shield of coaxial cable **102** are minimized.

First balun **300** may be formed by removing a portion of the conductive shield of coaxial cable **102** to form the slot leaving tapered wall **302**, second dipole arm **306**, and ring **304**. For example, a laser may be used to remove the portion of the conductive shield of coaxial cable **102**. Thus, first balun **300** may be formed from a portion of coaxial cable **102**. As another example, first balun **300** may be etched from a hollow tube of conductive material such as copper and electrically connected to an inner surface of the conductive shield of coaxial cable **102**.

A cover (insulating jacket or outer sheath) (not shown) may enclose first dipole arm **100***a* and first balun **300**. The cover may be mounted to allow movement relative to first dipole arm **100***a* and first balun **300** so that first dipole arm **100***a* and first balun **300** are protected while inserted into a tissue, but can be exposed once inserted into the tissue.

With reference to FIG. **5**A, the top and right side views of FIGS. **3** and **4** are aligned to show cross section locations of first balun **300** shown with reference to FIGS. **5**B to **5**E. With reference to FIG. **5**B, a cross section of first balun **300** taken at slot end point **312** and indicated as **5**B in FIG. **5**A is shown in accordance with an illustrative embodiment. Balun center conductor **326** has a diameter **501**. Balun dielectric material **334** has a dielectric width **502** that surrounds balun center conductor **326**. First wall **500** of tapered wall **302** has a conductor width **504** that surrounds balun dielectric material **334** between exterior surface **308** and interior surface **310**. A cross section of first balun **300** taken at outer ring wall **330** of ring **304** and also indicated as **5**B in FIG. **5**A is identical to that taken at slot end point **312** except that wall **500** of tapered wall **302** is replaced with outer ring wall **330** of ring **304**.

With reference to FIG. **5**C, a cross section of first balun **300** taken at a point as indicated by **5**C in FIG. **5**A is shown in accordance with an illustrative embodiment. A first arc length **506** defines a slot arc length between first slot wall **318** and second slot wall **320** of tapered wall **302**.

With reference to FIG. **5**D, a cross section of first balun **300** taken at first dipole arm wall **332** as indicated by **5**D in FIG. **5**A is shown in accordance with an illustrative embodiment. A second arc length **508** defines a slot arc length between first slot wall **318** and second slot wall **320** of tapered wall **302** for a cross section taken at first dipole arm wall **332**. A prong arc length **510** defines an arc length between first arm wall **322** and second arm wall **324** of second dipole arm **306**.

With reference to FIG. **5**E, a cross section of first balun **300** taken at second wall **514** of tapered wall **302** and at second dipole arm wall **516** as indicated by **5**E in FIG. **5**A is shown in accordance with an illustrative embodiment. A third arc length **512** defines a slot arc length between first slot wall **318** and second slot wall **320** at second wall **514** of tapered wall **302**.

With reference to FIG. **6**, a top view of first balun **300** unrolled and placed on a flat surface is shown in accordance with an illustrative embodiment. A total length **600** of first balun **300** is measured between first wall **500** of tapered wall **302** and outer ring wall **330** of ring **304**. A tapered wall length **602** of tapered wall **302** is measured between first wall **500** and second wall **514** of tapered wall **302**. A tapered wall circumference **604** defines a circumference of tapered wall **302** at slot end point **312**. A tapered wall height **606** is measured between first end point **314** and second end point **316** and defines a length of second wall **514** of tapered wall **302** that mounts to inner ring wall **328** of ring **304**. A ring circumference **608** defines a circumference of inner ring wall **328** and outer ring wall **330** of ring **304**. A ring width **610** defines a width of ring **304** measured between inner ring wall **328** and outer ring wall **330**. A prong length **612** is measured between first dipole arm wall **332** and outer ring wall **330** of ring **304** and includes ring width **610**. A prong width **614** defines a width of second dipole arm **306** measured between first arm wall **322** and second arm wall **324**. A dipole arm length **338** (shown referring to FIG. **3**) is measured as a length of first dipole arm **100***a*.

In the illustrative embodiment, when flattened, first slot wall **318** and second slot wall **320** have a linear slope. In alternative embodiments, when flattened, first slot wall **318** and second slot wall **320** may have different slopes that may be non-linear. For example, when flattened, first slot wall **318** and second slot wall **320** may form a concave or convex curve between slot end point **312** and first end point and between slot end point **312** and second end point **316**, respectively. First slot wall **318** and second slot wall **320** have a complementary shape.

Total length **600** may be selected from a range defined by

$$\frac{\lambda_0}{4} \text{ and } \frac{3\lambda_0}{2},$$

where λ_0 is the wavelength at the operating frequency of the signal carried by balun center conductor **326**. Tapered wall height **606**, ring width **610**, and prong width **614** may each be selected from a range defined by

$$\frac{d}{2} \text{ and } 2 \times d,$$

where d is diameter **501** of balun center conductor **326**. Tapered wall height **606**, ring width **610**, and/or prong width **614** may be equal. Prong length **612** and dipole arm length **338** are selected from a range defined by

$$\frac{\lambda_1}{4} \text{ and } \frac{\lambda_1}{2},$$

where λ_1 is an effective wavelength of an operating frequency of a signal carried by balun center conductor **326** in a medium defined by a tissue into which first balun **300** and first dipole arm **100***a* are at least partially inserted. Tapered wall circumference **604** and ring circumference **608** may be equal to $2\pi r$, where

$$r = \frac{d}{2} + d_d + d_c,$$

where d_d equals dielectric width **502**, and d_c equals conductor width **504**.

For illustration, the parameters of first balun **300** and first dipole arm **100***a* to achieve localized specific absorption rate (SAR) and heating patterns and a good impedance match between antenna **100** and coaxial cable **102** at 6 GHz were determined using full-wave electromagnetic (EM) simulations of the antennas and simplified thermal simulations. For example, the EM simulations of the antennas were conducted using CST Microwave Studio to design them to operate at 6 GHz in liver tissue. Dielectric properties of liver at room temperature were modeled using a 1-pole Cole Cole model presented for the frequency range from 0 to 8 GHz. Absorption of electromagnetic fields in tissue, calculated from the EM simulations, was scaled for an input power of 20 W to be the heat source in transient thermal simulations in CST Multiphysics Suite. The dimensions were determined as prong length **612** equal to 6.2 millimeters (mm), dipole arm length **338** equal to 7 mm, total length **600** equal to 16 mm, tapered wall height **606**, ring width **610**, and prong width **614** each equal to 0.5 mm, and tapered wall circumference **604** and ring circumference **608** each equal to $\pi \times 2.2$ mm, the outer circumference of coaxial cable **102**. Coaxial cable **102** was selected as 50-Ω UT-085C semi-rigid cable. Copper tubing was used for first balun **300**. Polytetrafluoroethylene was used for balun dielectric material **334**.

Referring to FIG. **7**, a voltage standing wave ratio (VSWR) curve **700** computed from the simulation results is shown. VSWR curve **700** shows a value less than two from four GHz to over eight GHz.

Referring to FIGS. **8** and **9**, a normalized specific absorption rate (SAR) pattern of antenna **100** with first balun **300** is shown in the x-z and y-z planes, respectively, where z is along an axis of balun center conductor **326**. The x-y planes define the cross sections of first balun **300** with the x-axis and the y-axis as indicated in FIG. **5**D. Referring to FIG. **8**, a −10 decibel (dB) curve **800** shows a SAR level reduced by 10 dB compared to a maximum SAR level. A −20 dB curve **802** shows a SAR level reduced by 20 dB compared to the maximum SAR level. A −30 dB curve **804** shows a SAR level reduced by 30 dB compared to the maximum SAR level. A region **806** indicates a location of first balun **300** for reference.

Referring to FIG. **9**, a −10 dB curve **900** shows a SAR level reduced by 10 dB compared to the maximum SAR level. A −20 dB curve **902** shows a SAR level reduced by 20 dB compared to the maximum SAR level. A −30 dB curve **904** shows a SAR level reduced by 30 dB compared to the maximum SAR level. A region **906** indicates a location of first balun **300** for reference. A proximal end **908** of second dipole arm **306** shows a reduction of approximately 20 dB in SAR level. A proximal end **910** of first balun **300** shows a reduction of approximately 30 dB in SAR level. The results indicate that the outer surface currents are effectively suppressed using first balun **300**, resulting in a compact SAR pattern with minimal tails along the shaft of coaxial cable **102**.

An asymmetric heating pattern results due to a lack of symmetry in the placement of second dipole arm **306** that is connected to tapered wall **302** in the y-z plane. As a result, the electromagnetic radiation is stronger on the lower side, where second dipole arm **306** is located, compared to an upper side where tapered wall **302** is located. Referring to FIG. **10**, a simulated 50° C. contour, used to predict a boundary of an ablation zone, is shown in the x-z and the y-z planes at the end of a five minute ablation using an input power of 20 Watts (W). An x-z ablation zone **1000** is symmetrical in the x-z plane. A y-z ablation zone **1002** is slightly asymmetrical in the y-z plane, as a result of the corresponding SAR pattern in these two cut planes. However, maximum lateral dimensions of the ablation zone in the two cut planes are the same and equal to 24 mm. In the y-z plane, the maximum lateral radius of the ablation zone is 10.75 mm for the upper side (r_i) and 13.25 mm for the lower side (r_2). While this degree of asymmetry is not significant, further modification of the antenna design to create a more asymmetric ablation zone can be implemented such as tilting first dipole arm **100***a* and second dipole arm **306** toward a lower half of the y-z plane or deploying a hemi-cylindrical metallic reflector to prevent EM radiation on the upper half of the y-z plane. Additionally, such asymmetrically enhanced heating may be desirable in certain clinical scenarios where tumors are highly asymmetric or where an antenna has to heat a tumor from a peripheral position because the central region of the tumor is inaccessible (e.g. blockage by other vital organs).

With reference to FIG. **11**, a top view of first dipole arm **100***a* with a second balun **1100** is shown in accordance with an illustrative embodiment. With reference to FIG. **12**, a bottom view of first dipole arm **100***a* with second balun **1100** is shown in accordance with an illustrative embodiment. With reference to FIG. **13**, a right side view of first dipole arm **100***a* with second balun **1100** is shown in accordance with an illustrative embodiment. With reference to FIG. **14**, a left side view of first dipole arm **100***a* with second balun **1100** is shown in accordance with an illustrative embodiment. Antenna **100** may be a dipole antenna formed by first dipole arm **100***a*, a second dipole arm **1106***a*, and a third dipole arm **1106***b*. Second balun **1100** is similar to first balun **300** except that two slots are formed instead of one forming a symmetric structure with two slots opposite each other and with second dipole arm **1106***a* and third dipole arm **1106***b* opposite each other circumferentially around second balun **1100**.

Second dipole arm **1106***a* and third dipole arm **1106***b* may each be referred to herein as a prong. Second dipole arm **1106***a* and third dipole arm **1106***b* are connected to a ring **1104** to form one arm of antenna **100** that again forms a dipole. Again, first dipole arm **100***a* is the second arm of the dipole.

In the illustrative embodiment, second dipole arm **1106***a* and third dipole arm **1106***b* have a rectangular shape though other shapes may be used. Because second dipole arm **1106***a* and third dipole arm **1106***b* may be integrally formed with the remaining components of second balun **1100**, second dipole arm **1106***a* and third dipole arm **1106***b* are also referred to herein as portions of second balun **1100**. Second balun **1100** is connected between coaxial cable **102** and first dipole arm **100***a* of antenna **100**.

Second balun **1100** may include a tapered wall **1102**, ring **1104**, second dipole arm **1106***a*, and third dipole arm **1106***b* that form prongs connected to and extending from ring **1104**. Second balun **1100** is formed of a conductive material. For example, tapered wall **1102**, ring **1104**, second dipole arm **1106***a*, and third dipole arm **1106***b* may be formed of the same material as the conductive shield of coaxial cable **102**. Second balun **1100** may be created by tapering the conductive shield of a portion of coaxial cable **102** to form two walls that connect to ring **1104** and removing the material on each side of second dipole arm **1106***a* and of third dipole arm **1106***b* except where each connects to ring **1104** to form two slots and to make a smooth transition from a coaxial line to a parallel wire line.

Tapered wall **1102** includes a first tapered wall **1108***a* and a second tapered wall **1108***b*. First tapered wall **1108***a* and second tapered wall **1108***b* are similar to tapered wall **302**. First tapered wall **1108***a* and second tapered wall **1108***b* form two portions of a cylindrical tube between a first wall **1506** (shown referring to FIGS. **15**B and **16**) and a second wall **1520***a* and a third wall **1520***b*, respectively (shown referring to FIG. **15**E). First wall **1506** is opposite second wall **1520***a* and third wall **1520***b*. First tapered wall **1108***a* and second tapered wall **1108***b* surround balun dielectric material **334**, which again surrounds balun center conductor **326**. The portion of the cylindrical tube forms two slots exposing balun dielectric material **334**.

First tapered wall **1108***a* has an exterior surface **1508***a* (shown referring to FIG. **15**C) and an interior surface **1510***a* (shown referring to FIG. **15**C). First tapered wall **1108***a* starts at a first slot end point **1118***a* on a first side and a second slot end point **1118***b* on a second side. A first slot wall **1120***a* of first tapered wall **1108***a* extends from second slot end point **1118***b* to first end point **1110***a*. A second slot wall **1122***a* of first tapered wall **1108***a* extends from first slot end point **1118***a* to second end point **1112***a*.

Second tapered wall **1108***b* has an exterior surface **1508***b* (shown referring to FIG. **15**C) and an interior surface **1510***b* (shown referring to FIG. **15**C). Second tapered wall **1108***b* starts at first slot end point **1118***a* on a first side and second slot end point **1118***b* on a second side. A third slot wall **1120***b* of second tapered wall **1108***b* extends from first slot end point **1118***a* to third end point **1110***b*. A fourth slot wall **1122***b* of second tapered wall **1108***b* extends from second slot end point **1118***b* to fourth end point **1112***b*.

Second dipole arm **1106***a* extends from a first dipole arm wall **1115***a* that is closest to first slot end point **1118***a* to a second dipole arm wall **1522***a* (shown referring to FIG. **15**E). First dipole arm wall **1115***a* is opposite second dipole arm wall **1522***a*. Second dipole arm wall **1522***a* mounts to ring **1104** between a first arm wall **1114***a* and a second arm wall **1116***a*. Second dipole arm **1106***a* forms a semicircular prong.

Third dipole arm **1106***b* extends from a third dipole arm wall **1115***b* that is closest to second slot end point **1118***b* to a third dipole arm wall **1522***b* (shown referring to FIG. **15**E). Third dipole arm wall **1115***b* is opposite third dipole arm wall **1522***b*. Third dipole arm wall **1522***b* mounts to ring **1104** between a third arm wall **1114***b* and a fourth arm wall **1116***b*. Third dipole arm **1106***b* forms a semicircular prong.

Ring **1104** is similar to ring **304**. Ring **1104** is connected to second wall **1520***a* of first tapered wall **1108***a*, to third wall **1520***b* of second tapered wall **1108***b*, to second dipole arm wall **1522***a* of second dipole arm **1106***a*, and to third dipole arm wall **1522***b* of third dipole arm **1106***b*. Ring **1104** forms a short cylindrical tube surrounding balun center conductor **326** and balun dielectric material **334**. Ring **1104** has an inner ring wall **1124** and an outer ring wall **1126**. Second dipole arm **1106***a* and third dipole arm **1106***b* are connected to inner ring wall **328** of ring **1104**, extend towards first wall **1506**, and are located in slots created by first tapered wall **1108***a* and second tapered wall **1108***b*, respectively. Second dipole arm **1106***a* and third dipole arm **1106***b* extend in a direction opposite to first dipole arm **100***a* relative to ring **1104**.

First tapered wall **1108***a*, second tapered wall **1108***b*, and balun center conductor **326** form a balanced parallel-wire line to feed antenna **100** that includes first dipole arm **100***a*, second dipole arm **1106***a*, and third dipole arm **1106***b*. Second dipole arm **1106***a* and third dipole arm **1106***b* are placed in the slots formed by first tapered wall **1108***a* and second tapered wall **1108***b* and are connected to tapered wall **302** through ring **1104** at second dipole arm wall **1522***a* and at third dipole arm wall **1522***b*, respectively. At its operating frequency, second balun **1100** provides balanced currents for antenna **100**. As a result, unbalanced currents flowing back on an outer surface of the conductive shield of coaxial cable **102** are minimized.

Second balun **1100** may be formed by removing a portion of the conductive shield of coaxial cable **102** to form the two slots, second dipole arm **1106***a*, and third dipole arm **1106***b*. For example, a laser may be used to remove the portion of the conductive shield of coaxial cable **102**. As another example, second balun **1100** may be etched from a hollow tube of conductive material such as copper and electrically connected to an inner surface of the conductive shield of coaxial cable **102**.

A cover (not shown) may enclose first dipole arm **100***a* and second balun **1100**. The cover may be mounted to allow movement relative to first dipole arm **100***a* and second balun **1100** so that first dipole arm **100***a* and second balun **1100** are protected while inserted into a tissue, but can be exposed once inserted into the tissue.

With reference to FIG. **15**A, the top and right side views of FIGS. **11** and **13** are aligned to show cross section locations of second balun **1100** shown with reference to FIGS. **15**B to **15**E. With reference to FIG. **15**B, a cross section of second balun **1100** taken at first slot end point **1118***a* and at second slot end point **1118***b* and indicated as **15**B in FIG. **15**A is shown in accordance with an illustrative embodiment. Balun center conductor **326** has a diameter **1500**. Balun dielectric material **334** has a dielectric width **1502** that surrounds balun center conductor **326**. Tapered wall **1102** has a conductor width **1504** that surrounds balun dielectric material **334**. A cross section of second balun **1100** taken at outer ring wall **1126** of ring **1104** is identical to that taken at first slot end point **1118***a* and at second slot end point **1118***b*. A cross section of second balun **1100** taken at outer ring wall **1126** of ring **1104** is identical to that taken at first slot end point **1118***a* except that first wall **1506** of tapered wall **1102** is replaced with outer ring wall **1126** of ring **1104**.

With reference to FIG. **15**C, a cross section of second balun **1100** taken at a point as indicated by **15**C in FIG. **15**A is shown in accordance with an illustrative embodiment. A first arc length **1512** defines an arc length between first slot wall **1120***a* and second slot wall **1122***a* of first tapered wall **1108***a*. An arc length (not shown) for second tapered wall **1108***b* is identical to first arc length **1512**. Conductor width **1504** is identical between a first exterior surface **1508***a* and a first interior surface **1510***a* of first tapered wall **1108***a* and between a second exterior surface **1508***b* and a second interior surface **1510***b* of second tapered wall **1108***b*.

With reference to FIG. **15**D, a cross section of second balun **1100** taken at first dipole arm wall **1115***a* and at second dipole arm wall **1115***b* as indicated by **15**D in FIG. **15**A is shown in accordance with an illustrative embodiment. A second arc length **1514** defines an arc length between first slot wall **1120***a* and second slot wall **1122***a* of first tapered wall **1108***a* for a cross section taken at first dipole arm wall **1115***a*. An arc length (not shown) for second tapered wall **1108***b* is identical to second arc length **1514** at first dipole arm wall **1115***a*. A prong arc length **1516** defines an arc length between first arm wall **1114***a* and second arm wall **1116***a* of second dipole arm **1106***a* and between third arm wall **1114***b* and fourth arm wall **1116***b* of third dipole arm **1106***b*.

With reference to FIG. **15**E, a cross section of second balun **1100** taken at second wall **1520***a*, third wall **1520***b*, second dipole arm wall **1522***a*, and third dipole arm wall **1522***b* as indicated by **15**E in FIG. **15**A is shown in accordance with an illustrative embodiment. A minimum arc length **1518** defines an arc length between first slot wall **1120***a* and second slot wall **1122***a* of first tapered wall **1108***a*. An arc length (not shown) for second tapered wall **1108***b* is identical to minimum arc length **1518** at first dipole arm wall **1115***a*.

With reference to FIG. **16**, a top view of second balun **1100** unrolled and placed on a flat surface is shown in accordance with an illustrative embodiment. A total length **1600** of second balun **1100** is measured between first wall **1506** and outer ring wall **1126** of ring **1104**. A tapered wall length **1602** of first tapered wall **1108***a* and of second tapered wall **1108***b* is measured between first wall **1506** and second wall **1520***a* of first tapered wall **1108***a* and between first wall **1506** and fourth wall **1520***b* of second tapered wall **1108***b*, respectively. A tapered wall circumference **1604** defines a circumference of tapered wall **1102** at first slot end point **1115***a*. A tapered wall height **1606** is measured between first end point **1110***a* and second end point **1112***a* and defines a length of second wall **1520***a* of first tapered wall **1108***a* that mounts to inner ring wall **1124** of ring **1104**. Tapered wall height **1606** also defines a length of third wall **1520***b* of second tapered wall **1108***b* that mounts to inner ring wall **1124** of ring **1104**. A ring circumference **1608** defines a circumference of inner ring wall **1124** and outer ring wall **1126** of ring **1104**. A ring width **1610** defines a width of ring **1104** measured between inner ring wall **1124** and outer ring wall **1126**. A prong length **1612** is measured between first dipole arm wall **1115***a* and outer ring wall **330** of ring **1104** and includes ring width **1610**. Prong length **1612** also defined a length between second dipole arm wall **1115***b* and outer ring wall **330** of ring **1104** and includes ring width **1610**. A prong width **1614** defines a width of second dipole arm **1106***a* measured between first arm wall **1114***a* and second arm wall **1116***a*. A prong width **1614** defines a width of third dipole arm **1106***b* measured between third arm wall **1114***b* and fourth arm wall **1116***b*.

In the illustrative embodiment, when flattened, first slot wall **1120***a*, second slot wall **1122***a*, third slot wall **1120***b*, and fourth slot wall **1122***b* have a linear slope. In alternative embodiments, when flattened, first slot wall **1120***a*, second slot wall **1122***a*, third slot wall **1120***b*, and fourth slot wall **1122***b* may have different slopes that may be non-linear. For example, when flattened, first slot wall **1120***a*, second slot wall **1122***a*, third slot wall **1120***b*, and fourth slot wall **1122***b* may form a concave or convex curve between the slot wall end points. First slot wall **1120***a* and third slot wall **1120***b* have a same flattened shape. Second slot wall **1122***a* and fourth slot wall **1122***b* have a same flattened shape that is complementary to that of first slot wall **1120***a* and third slot wall **1120***b*.

Total length **1600** may be selected from a range defined by

$$\frac{\lambda_0}{4} \text{ and } \frac{3\lambda_0}{2},$$

where λ_0 is the wavelength at the operating frequency of the signal carried by balun center conductor **326**. Tapered wall height **1606**, ring width **1610**, and prong width **1614** may each be selected from a range defined by

$$\frac{d}{2} \text{ and } 2\times d,$$

where d is diameter **1500** of balun center conductor **326**. Tapered wall height **1606**, ring width **1610**, and/or prong width **1614** may be equal. Prong length **1612** and dipole arm length **338** are selected from a range defined by

$$\frac{\lambda_1}{4} \text{ and } \frac{\lambda_1}{2},$$

where λ_1 is an effective wavelength of an operating frequency of a signal carried by balun center conductor **326** in a medium defined by a tissue into which second balun **1100** and first dipole arm **100***a* are at least partially inserted. Tapered wall circumference **1604** and ring circumference **1608** may be equal to $2\pi r$, where

$$r = \frac{d}{2} + d_d + d_c,$$

where d_d equals dielectric width **1502**, and d_c equals conductor width **1504**.

For illustration, the parameters of second balun **1100** and first dipole arm **100***a* to achieve localized specific absorption rate (SAR) and heating patterns and a good impedance match between antenna **100** and coaxial cable **102** at 6 GHz were again determined. The dimensions were determined as prong length **1612** equal to 8 mm, dipole arm length **1128** equal to 7 mm, total length **1600** equal to 18 mm, prong width **1614** equal to 0.7 mm, tapered wall height **1606** and ring width **1610** each equal to 0.5 mm, and tapered wall circumference **1604** and ring circumference **1608** each equal to π×2.2 mm, the outer circumference of coaxial cable **102**. Coaxial cable **102** was selected as 50-Ω UT-085C semi-rigid cable. Copper tubing was used for second balun **1100**. Polytetrafluoroethylene was used for balun dielectric material **334**. Second balun **1100** and first dipole arm **100***a* were embedded in a polytetrafluoroethylene coating with a diameter of 2.6 mm.

Referring to FIG. **17**, a measured VSWR curve **1700** and a simulated VSWR curve **1702** are shown. Referring to FIG. **18**, a measured $|S_{11}|$ curve **1800** and a simulated $|S_{11}|$ curve **1802** are shown. The measured and simulated curves are in good agreement and show a good impedance match between antenna **100** and coaxial cable **102** over a wide frequency range (from 5 GHz to over 8 GHz). At the operating frequency of 6 GHz, the measured VSWR is 1.19 ($|S_{11}|$ of −22 dB), which is slightly better than the simulated values (VSWR=1.21, $|S_{11}|$=−20 dB). Additionally, the measured input impedance of antenna **100** was unchanged as the insertion depth of antenna **100** was varied as long as the entire second balun **1100** was immersed in liver with first dipole arm **100***a*. This confirmed that the outer surface currents were effectively suppressed along coaxial cable **102** up to a starting point of second balun **1100**.

First dipole arm **100***a* with second balun **1100** achieved a slightly better impedance matching (VSWR=1.21, $|S_{11}|$=−20 dB) than first dipole arm **100***a* with first balun **300** (VSWR=1.38, $|S_{11}|$=−16 dB) at the operating frequency of 6 GHz. While increasing tapered wall length **1602** of first tapered wall **1108***a* and of second tapered wall **1108***b* may help reduce the reflection coefficient, the frequency of best impedance match is most sensitive to the dimensions of first dipole arm **100***a*, second dipole arm **1106***a*, and third dipole arm **1106***b* of the dipole and a thickness of the outermost coating, which in this case was 2.6 mm of polytetrafluoroethylene.

Referring to FIGS. **19** and **20**, a normalized SAR pattern of antenna **100** with second balun **1100** is shown in the x-z and y-z planes, respectively, where z is along an axis of balun center conductor **326**. The x-y planes define the cross sections of second balun **1100** with the x-axis and the y-axis as indicated in FIG. **5**D. Referring to FIG. **19**, a −10 dB curve **1900** shows a SAR level reduced by 10 dB compared to the maximum SAR level. A −20 dB curve **1902** shows a SAR level reduced by 20 dB compared to the maximum SAR level. A −30 dB curve **1904** shows a SAR level reduced by 30 dB compared to the maximum SAR level. A region **1906** indicates a location of second balun **1100** for reference.

Referring to FIG. **20**, a −10 dB curve **2000** shows a SAR level reduced by 10 dB compared to the maximum SAR level. A −20 dB curve **2002** shows a SAR level reduced by 20 dB compared to the maximum SAR level. A −30 dB curve **2004** shows a SAR level reduced by 30 dB compared to the maximum SAR level. A region **2006** indicates a location of second balun **1100** for reference. The results indicate that the outer surface currents are effectively suppressed using second balun **1100**, resulting in a compact SAR pattern with minimal tails along the shaft of coaxial cable **102**. SAR values are reduced by 30 dB near first slot end point **1115***a* and second slot end point **1115***b*. First dipole arm **100***a* with second balun **1100** produced a highly compact volume enclosed by −30 dB curve **2004**, of which the lateral diameter (about 26 mm) is even larger than the axial diameter (about 20 mm). Due to the lack of an axial symmetry, the SAR pattern in the x-z plane is slightly different from that in the y-z plane.

Referring to FIG. **21**, a simulated 50° C. contour, used to predict a boundary of an ablation zone, is shown in the x-z and the y-z planes at the end of a five minute ablation using an input power of 20 Watts (W). An x-z ablation zone **2100** and a y-z ablation zone **2102** are symmetrical. Despite a slight difference of the SAR pattern in the x-z (**2100**) and y-z (**2102**) planes, the ablation zone appears to be identical in these two cut planes, which demonstrates that first dipole arm **100***a* with second balun **1100** is capable of producing a rotationally symmetric ablation zone.

Compared to the antenna using the single-slot balun, SAR values less than −30 dB fall off faster along the shaft of second balun **1100**. This is evident in the slightly longer tails of the −30 dB contours shown in −30 dB curve **804** and −30 dB curve 904 in comparison with −30 dB curve **1904** and −30 dB curve **2004**. Moreover, first dipole arm **100***a* with second balun **1100** produced a symmetric SAR pattern in the y-z plane, as opposed to the asymmetric one in this cut plane of first dipole arm **100***a* with first balun **300**. While thermal simulation results show that both provide ablation zones with similar dimensions, the one provided by first dipole arm **100***a* with second balun **1100** is more rotationally symmetric. Overall, the better impedance matching and more symmetric heating pattern make first dipole arm **100***a* with second balun **1100** a more desirable design for ablation applications where directional heating is not needed.

Referring to FIG. **22**, a block diagram of a MWA system **2200** is shown in accordance with an illustrative embodiment. MWA system **2200** may include a signal generator **2202**, an amplifier **2204**, a connector **2206**, coaxial cable **102**, first balun **300** or second balun **1100**, and antenna **100**. For illustration, antenna **100** may include first dipole arm **100***a* and second dipole arm **1106***a* and third dipole arm **1106***b*. Signal generator **2202** generates an analog signal at the operating frequency selected for antenna **100**. A duty cycle of the analog signal may be controlled by signal generator **2202** based, for example, on an ablation zone size and heating rate. The analog signal may be amplified by amplifier **2204**. Connector **2206** connects a second end of coaxial cable **102** opposite first dipole arm **100***a*. The loss through coaxial cable **102** is considered when adjusting the output power level of amplifier **2204** for a desired input power level to first dipole arm **100***a* and second dipole arm **1106***a* and third dipole arm **1106***b*. Connector **2206** may be a coaxial connector designed to maintain the coaxial form across the connection and having the same impedance as coaxial cable **102**.

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

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

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

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

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

What is claimed is:

1. A balun comprising:

a center conductor extending a length of the balun;

a dielectric material surrounding the center conductor along the length of the balun;

a tapered wall forming a portion of a tube between a first wall and a second wall, wherein the first wall is opposite the second wall, wherein the tapered wall is formed of a conductive material, wherein the portion of the tube forms a slot exposing the dielectric material;

a ring connected to the second wall of the tapered wall, wherein the ring is formed of the conductive material, wherein the ring forms a tube surrounding the center conductor and the dielectric material; and

a prong connected to the ring to extend toward the first wall, wherein the prong is formed of the conductive material, wherein the prong extends over a portion of the dielectric material exposed by the slot.

2. The balun of claim **1**, wherein a length between the first wall and an outer wall of the ring is selected from a range defined by

$$\frac{\lambda_1}{4} \text{ and } \frac{3\lambda_1}{2},$$

where λ_1 is a wavelength at an operating frequency of a signal carried by the center conductor, wherein the outer wall is opposite the second wall.

3. The balun of claim **2**, wherein a width of the second wall is selected from a range defined by

$$\frac{d}{2} \text{ and } 2 \times d,$$

where d is a diameter of the center conductor, wherein the width of the second wall is in a direction perpendicular to the length.

4. The balun of claim **1**, wherein a length between a wall of the prong closest to the first wall and an outer wall of the ring is selected from a range defined by $\lambda_{1/}4$ and $\lambda_{1/}2$, where λ_1 is a wavelength at an operating frequency of a signal carried by the center conductor, wherein the outer wall is opposite the second wall.

5. The balun of claim **4**, wherein a width of the prong is selected from a range defined by

$$\frac{d}{2} \text{ and } 2 \times d,$$

where d is a diameter of the center conductor, wherein the width of the prong is in a direction perpendicular to the length.

6. The balun of claim **1**, wherein a length between the second wall and an outer wall of the ring is selected from a range defined by

$$\frac{d}{2} \text{ and } 2 \times d,$$

where d is a diameter of the center conductor, wherein the outer wall is opposite the second wall.

7. The balun of claim **1**, wherein a circumference of the ring is equal to a length of the first wall.

8. The balun of claim **1**, further comprising:

a second tapered wall forming a second portion of the tube between a third wall and a fourth wall, wherein the second tapered wall is formed of the conductive material, wherein the second portion of the tube forms a second slot exposing the dielectric material, wherein the ring is connected to the fourth wall of the second tapered wall, wherein the third wall is opposite the fourth wall; and a second prong connected to the ring to extend toward the third wall, wherein the second prong is formed of the conductive material, wherein the second prong extends over a second portion of the dielectric material exposed by the second slot.

9. The balun of claim **8**, wherein a length between the first wall and an outer wall of the ring is selected from a range defined by

$$\frac{\lambda_1}{4} \text{ and } \frac{3\lambda_1}{2},$$

where λ_1 is a wavelength at an operating frequency of a signal carried by the center conductor, wherein the outer wall is opposite the second wall, wherein a second length between the third wall and the outer wall of the ring is equal to the length.

10. The balun of claim **9**, wherein a width of the second wall is selected from a range defined by

$$\frac{d}{2} \text{ and } 2 \times d,$$

where d is a diameter of the center conductor, wherein the width of the second wall is in a direction perpendicular to the length, wherein a width of the fourth wall is equal to the width of the second wall.

11. The balun of claim **8**, wherein a length between a wall of the prong closest to the first wall and an outer wall of the ring is selected from a range defined by $\lambda_1/4$ and $\lambda_1/2$, where λ_1 is a wavelength at an operating frequency of a signal carried by the center conductor, wherein the outer wall is opposite the second wall, wherein a second length between a wall of the second prong closest to the third wall and the outer wall of the ring is equal to the length.

12. The balun of claim **11**, wherein a width of the prong is selected from a range defined by

$$\frac{d}{2} \text{ and } 2 \times d,$$

where d is a diameter of the center conductor, wherein the width of the prong is in a direction perpendicular to the length, wherein a width of the second prong is equal to the width of the prong.

13. The balun of claim **8**, wherein a length between the second wall and an outer wall of the ring is selected from a range defined by

$$\frac{d}{2} \text{ and } 2 \times d,$$

where d is a diameter of the center conductor, wherein the outer wall is opposite the second wall.

14. The balun of claim **8**, wherein a circumference of the ring is equal to a length of the first wall plus the third wall.

15. 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;

a first dipole arm connected to the center conductor; and

a balun connected between an end of the coaxial cable and the first dipole arm, the balun comprising

a second center conductor extending a length of the balun, the second center conductor connected to and extending from the center conductor between the center conductor and the first dipole arm;

a second dielectric material surrounding the second center conductor along the length of the balun;

a tapered wall forming a portion of a tube between a first wall and a second wall, wherein the first wall is opposite the second wall, wherein the first wall is connected to the conductive shield, wherein the tapered wall is formed of a conductive material, wherein the portion of the tube forms a slot exposing the second dielectric material;

a ring connected to the second wall of the tapered wall, wherein the ring is formed of the conductive material, wherein the ring forms a tube surrounding the second center conductor and the second dielectric material; and

a prong connected to the ring to extend toward the first wall, wherein the prong is formed of the conductive material, wherein the prong extends over a portion of the second dielectric material exposed by the slot and forms a second dipole arm.

16. The antenna system of claim **15**, wherein the second center conductor is formed as an extension of the center conductor.

17. The antenna system of claim **16**, wherein the first dipole arm is formed as an extension of the second center conductor.

18. The antenna system of claim **15**, wherein a length between the first wall and an outer wall of the ring is selected from a range defined by

$$\frac{\lambda_1}{4} \text{ and } \frac{3\lambda_1}{2},$$

where λ_1 is a wavelength at an operating frequency of a signal carried by the center conductor, wherein the outer wall is opposite the second wall.

19. The antenna system of claim **15**, wherein a length between a wall of the prong closest to the first wall and an outer wall of the ring is selected from a range defined by $\lambda_1/4$ and $\lambda_1/2$, where λ_1 is a wavelength at an operating frequency of a signal carried by the center conductor, wherein the outer wall is opposite the second wall.

20. The antenna system of claim **15**, wherein a length of the first dipole arm is selected from a range defined by $\lambda_1/4$ and $\lambda_1/2$, where λ_1 is a wavelength at an operating frequency of a signal carried by the center conductor.

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