

(19) World Intellectual Property Organization
International Bureau



(43) International Publication Date
1 February 2007 (01.02.2007)

PCT

(10) International Publication Number
WO 2007/013875 A2

(51) International Patent Classification:
H05H 1/24 (2006.01)

(21) International Application Number:
PCT/US2005/028775

(22) International Filing Date: 11 August 2005 (11.08.2005)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
10/931,223 1 September 2004 (01.09.2004) US
10/931,221 1 September 2004 (01.09.2004) US

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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SM, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

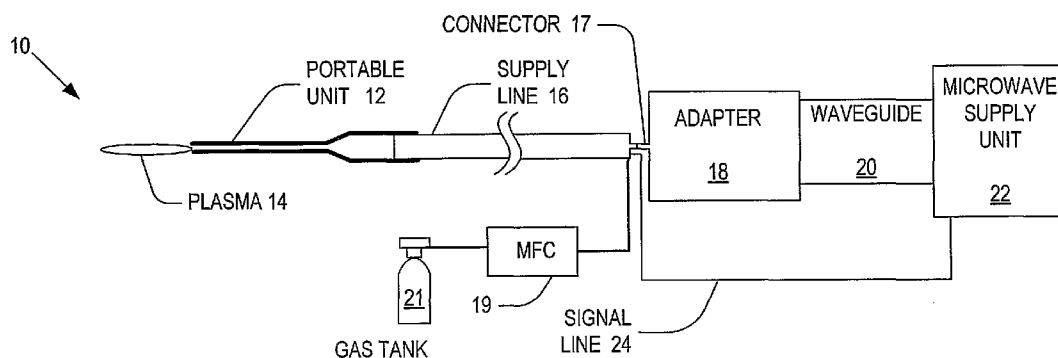
(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— without international search report and to be republished upon receipt of that report

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: A PORTABLE MICROWAVE PLASMA DISCHARGE UNIT



(57) Abstract: A portable microwave plasma discharge unit (12) receives microwaves and a gas flow via a supply line (16). The portable microwave plasma discharge unit (12) generates plasma (14) from the gas flow and the received microwaves. The portable microwave plasma discharge unit (12) includes a gas flow tube (42) made of a conducting and/or dielectric material and a rod-shaped conductor (44) that is axially disposed in the gas flow tube (42). The rod-shaped conductor (44) has an end configured to contact a microwave supply conductor (66) of the supply line (16) to receive microwaves and a tip (46) positioned adjacent the outlet portion of the gas flow tube (42). The tip (46) is configured to focus the microwaves received from the microwave supply conductor (66) to generate plasma (14) from the gas flow.

A PORTABLE MICROWAVE PLASMA DISCHARGE UNIT

BACKGROUND OF THE INVENTION

5 1. Field of the Invention

The present invention relates to plasma generating systems, and more particularly to a portable microwave plasma discharge unit.

2. Discussion of the Related Art

10 In recent years, the progress on producing plasma has been increasing. Typically, plasma consists of positive charged ions, neutral species and electrons. In general, plasmas may be subdivided into two categories: thermal equilibrium and thermal non-equilibrium plasmas. Thermal equilibrium implies that the temperature of all species including positive charged ions, neutral species, and electrons, is the same.

15 Plasmas may also be classified into local thermal equilibrium (LTE) and non-LTE plasmas, where this subdivision is typically related to the pressure of the plasmas. The term "local thermal equilibrium (LTE)" refers to a thermodynamic state where the temperatures of all of the plasma species are the same in the localized areas in the plasma.

20 A high plasma pressure induces a large number of collisions per unit time interval in the plasma, leading to sufficient energy exchange between the species comprising the plasma, and this leads to an equal temperature for the plasma species. A low plasma pressure, on the other hand, may yield one or more temperatures for the plasma species due to insufficient collisions between the species of the plasma.

25 In non-LTE, or simply non-thermal plasmas, the temperature of the ions and the neutral species is usually less than 100°C, while the temperature of the electrons can be up to several tens of thousand degrees in Celsius. Therefore, non-LTE plasma may serve as highly reactive tools for powerful and also gentle applications without consuming a large amount of energy. This "hot coolness" allows a variety of processing possibilities and economic opportunities for various applications. Powerful applications include metal deposition systems and plasma cutters, and gentle applications include plasma surface cleaning systems and plasma displays.

30 One of these applications is plasma sterilization, which uses plasma to destroy microbial life, including highly resistant bacterial endospores. Sterilization is a critical step in ensuring the safety of medical and dental devices, materials, and fabrics for final use. Existing sterilization

methods used in hospitals and industries include autoclaving, ethylene oxide gas (EtO), dry heat, and irradiation by gamma rays or electron beams. These technologies have a number of problems that must be dealt with and overcome and these include issues such as thermal sensitivity and destruction by heat, the formation of toxic byproducts, the high cost of operation, and the inefficiencies in the overall cycle duration. Consequently, healthcare agencies and industries have long needed a sterilizing technique that could function near room temperature and with much shorter times without inducing structural damage to a wide range of medical materials including various heat sensitive electronic components and equipment. Thus, there is a need for devices that can generate atmospheric pressure plasma as an effective and low-cost sterilization source, and more particularly, there is a need for portable atmospheric plasma generating devices that can be quickly applied to sterilize infected areas, such as wounds on human body in medical, military or emergency operations.

Several portable plasma systems have been developed by the industries and by national laboratories. An atmospheric plasma system, as described in a technical paper by Schütze et al., entitled "Atmospheric Pressure Plasma Jet: A review and Comparison to Other Plasma Sources," IEEE Transactions on Plasma Science, Vol. 26, No. 6, Dec. 1998, are 13.56 MHz RF based portable plasma systems. ATMOFLOTM Atmospheric Plasma Products, manufactured by Surfx Technologies, Culver City, CA, are also portable plasma systems based on RF technology. The drawbacks of these conventional Radio Frequency (RF) systems are the component costs and their power efficiency due to an inductive coupling of the RF power. In these systems, low power efficiency requires higher energy to generate plasma and, as a consequence, this requires a cooling system to dissipate wasted energy. Due to this limitation, the RF portable plasma system is somewhat bulky and not suitable for a point-of-use system. Thus, there is the need for portable plasma systems based on a heating mechanism that is more energy efficient than existing RF technologies.

SUMMARY OF THE INVENTION

The present invention provides a portable plasma discharge units that use microwave energy as a heating mechanism. Utilizing microwaves as a heating mechanism is a solution to the limitation of the RF portable systems. Since microwave energy has a higher energy density, a more efficient portable plasma source can be generated using less energy than the RF systems. Also, since less energy is required to generate the plasma, the microwave power may be transmitted through a coaxial cable instead of costly and rigid waveguides. Accordingly, the

usage of the coaxial cable for transmitting power can provide flexible operations for the plasma discharge unit movements.

According to one aspect of the present invention, a portable microwave plasma discharge unit includes a gas flow tube adapted to direct a flow of gas therethrough. The gas flow tube has an inlet portion and an outlet portion. The unit also includes a rod-shaped conductor axially disposed in the gas flow tube. The rod-shaped conductor has an end configured to contact a microwave supply conductor and a tip positioned adjacent the outlet portion of the gas flow tube.

According to another aspect of the present invention, a portable microwave plasma discharge unit includes: a gas flow tube adapted to direct a flow of gas therethrough and having an inlet portion and an outlet portion. The unit also includes a rod-shaped conductor axially disposed in the gas flow tube. The rod-shaped conductor having an end configured to receive microwaves and a tip positioned adjacent the outlet portion and configured to focus microwaves traveling through the rod-shaped conductor. The unit also includes at least one centering disk located within the gas flow tube for securing the rod-shaped conductor to the gas flow tube. Also the centering disk has a structure defining at least one through-pass hole. The unit also includes an interface portion including: a gas flow duct having an outlet portion coupled to the inlet portion of the gas flow tube and an inlet portion coupled to a supply line that comprises a microwave supply conductor; a conductor segment axially disposed within the gas flow duct, the conductor segment being configured to interconnect an end of the rod-shaped conductor with the microwave supply conductor; and a holder located within the gas flow duct for securing the conductor segment to the gas flow duct.

According to still another aspect of the present invention, a portable microwave plasma discharge unit includes a gas flow tube that is adapted to direct a flow of gas therethrough and has an inlet portion and an outlet portion. The unit also includes a rod-shaped conductor that is axially disposed in the gas flow tube. The rod-shaped conductor has an end configured to receive microwaves and a tip positioned adjacent the outlet portion, wherein the tip is configured to focus the microwaves traveling through the rod-shaped conductor. The unit also includes a positioning portion capable of arranging the gas flow tube relative to the rod-shaped conductor.

According to yet another aspect of the present invention, a portable microwave plasma discharge unit includes a gas flow tube that is adapted to direct a flow of gas therethrough and has an inlet portion and an outlet portion. The unit also includes a microwave coaxial cable configured to supply microwaves from a microwave supply unit. The microwave coaxial cable

includes a braid layer and a core conductor, wherein the braid layer is configured to be coupled to the gas flow tube. The rod-shaped conductor has an end configured to receive microwaves and a tip positioned adjacent the outlet portion, wherein the tip is configured to focus the microwaves traveling through the rod-shaped conductor.

5 These and other advantages and features of the invention will become apparent to those persons skilled in the art upon reading the details of the invention as more fully described below.

BRIEF DESCRIPTION OF THE DRAWINGS

10 FIG. 1 is a schematic diagram of a system that has a portable microwave plasma discharge unit in accordance with one embodiment of the present invention.

FIG. 2 is a schematic diagram of the microwave supply unit shown in FIG. 1.

FIG. 3 is a partial cross-sectional view of the portable microwave plasma discharge unit and supply line shown in FIG. 1.

15 FIGS. 4A-4B are cross-sectional views of alternative embodiments of the gas flow tube shown in FIG. 3.

FIGS. 5A-5I are cross-sectional views of alternative embodiments of the rod-shaped conductor shown in FIG. 3.

FIGS. 6A-6C are cross-sectional views of the supply line shown in FIG. 3.

20 FIG. 7 is a cross-sectional view of an alternative embodiment of the portable microwave plasma discharge unit shown in FIG. 3.

FIG. 8A is a cross-sectional view of an alternative embodiment of the supply line shown in FIG. 3.

25 FIG. 8B is a schematic diagram of a centering disk viewed in the longitudinal direction of the supply line shown in FIG. 8A.

FIG. 9 is a cross-sectional view of a typical microwave coaxial cable that may be used in the present invention.

FIG. 10 is a schematic diagram illustrating an interface region where a portable unit is coupled to a supply line in accordance with at least one embodiment of the present invention.

30 FIG. 11 is a schematic diagram of a system having an alternative embodiment of the portable microwave plasma discharge unit and supply line shown in FIG. 1.

FIG. 12 is a partial cross-sectional view of the portable microwave plasma discharge unit shown in FIG. 11.

FIG. 13 is a partial cross-sectional view of an alternative embodiment of the portable microwave plasma discharge unit shown in FIG. 12.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

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Unlike existing RF systems, the present invention provides systems that can generate atmospheric plasma using microwave energy. Due to microwave energy's higher energy density, a more efficient portable plasma source can be generated using less energy than the RF systems. Also, due to the lower amount of energy required to generate the plasma, microwave
10 power may be transmitted through a coaxial cable instead of the expensive and rigid waveguides. The usage of the coaxial cable to transmit power can provide flexible operations for the nozzle movements.

Referring to FIG. 1, FIG. 1 is a schematic diagram of a system 10 that has a portable microwave plasma discharge unit in accordance with one embodiment of the present invention.
15 (It is to be understood that where like numerals are used in different figures, such like numerals refer to the same item.) As illustrated, the system 10 comprises: a microwave supply unit 22 for generating microwaves; a waveguide 20 connected to the microwave supply unit 22; a waveguide-to-coax adapter 18 configured to receive the microwaves within the waveguide 20 and provide the received microwaves through its microwave coaxial connector 17; a portable
20 microwave plasma discharge unit 12 (also called "portable unit") configured to generate a discharge plasma 14; a supply line 16 for supplying a gas flow and microwaves to the portable microwave plasma discharge unit 12, where the supply line 16 is coupled to a gas tank 21 via a Mass Flow Control (MFC) valve 19 and the waveguide-to-coax adapter 18; and a conductor having at least two conductor signal lines 24 that interconnects an adjustable power control unit
25 50 (shown in FIG. 3) with a power level control 40 of a power supply 38 (shown in FIG. 2). The waveguide-to-coax adapter 18 is well known in the art and is preferably, but not limited to, WR284 or WR340 which is used in the system 10.

FIG. 2 is a schematic diagram of the microwave supply unit 22 shown in FIG. 1. The microwave supply unit 22 may comprise: a microwave generator 36 connected to the waveguide
30 20; and the power supply 38 for providing power to the microwave generator 36. The power supply 38 includes the power level control 40 connected to the adjustable power control unit 50 (shown in FIG. 3) via the conductor having at least two signal lines 24.

In an alternative embodiment, the microwave supply unit 22 may comprise: the

microwave generator 36 connected to the waveguide 20; the power supply 38 for the microwave generator 36; an isolator 30 comprising a dummy load 32 configured to dissipate retrogressing microwaves that travel toward a microwave generator 36 and a circulator 34 for directing the retrogressing microwaves to the dummy load 32; a coupler 28 for coupling the microwaves and
5 connected to a power meter 27 for measuring the microwave fluxes; and a tuner 26 to reduce the amount of the retrogressing microwaves.

The components of the microwave supply unit 22 shown in FIG. 2 are well known to those skilled in the art and are provided for exemplary purposes only. Thus, it should also be apparent to one skilled in the art that a system with a capability to provide microwaves to the
10 waveguide 20 may replace the microwave supply unit 22 without deviating from the present invention.

FIG. 3 is a schematic cross-sectional view of the portable unit 12 and the supply line 16 shown in FIG. 1. The portable unit 12 comprises: a gas flow tube 42 configured to receive a gas flow from at least one gas line 62 of the supply line 16; a rod-shaped conductor 44, axially
15 disposed in the gas flow tube 42 and having a tapered tip 46; one or more centering disks 48, each disk having at least one through-pass hole 49; the adjustable power control unit 50 for operating the power level control 40 of the power supply 38; at least two conductor signal lines 24 interconnecting the adjustable power control unit 50 and the power level control 40; and a holder 52 for securing the rod-shaped conductor 44 to the gas flow tube 42, where the holder 52
20 has at least one through-pass hole 54. The centering disks 48 may be made of any microwave-transparent dielectric material, such as ceramic or high temperature plastic, and have at least one through-pass hole 49. The through-pass hole 49 may be configured to generate a helical swirl around the rod-shaped conductor 44 to increase the length and stability of a plasma plume 14. The holder 52 may be made of any microwave-transparent dielectric material, such as ceramic
25 or high temperature plastic, and may have any geometric shape that has at least one through-pass holes for fluid communication between the gas flow tube 42 and the gas lines 62 of the supply line 16.

The gas flow tube 42 provides a mechanical support for the overall portable unit 12 and may be made of any conducting and/or dielectric material. As illustrated in FIG. 3, the gas flow tube 42 may comprise a heating section 56 and an interface section 58. The user of the portable
30 unit 12 may hold the heating section 56 during operation of the system 10 and, for purposes of safety, the gas flow tube 42 may be grounded. In general, a cross-sectional dimension of the heating section 56 taken along a direction normal to the longitudinal axis of the heating section

56 may be different from that of the interface section 58. As will be shown later, the cross-sectional dimension of the interface section 58 may be determined by the dimension of the supply line 16, while the dimension of the heating section 56 may be determined by various operational parameters, such as plasma ignition and stability. As shown in FIG. 3, the gas flow tube 42 is sealed tightly and coupled to the supply line 16. Various coupling mechanisms, such as an o-ring between the inner surface of the gas flow tube 42 and outer surface of the supply line 16, may be used for sealing and providing a secure coupling between the gas flow tube 42 and the supply line 16.

In FIG. 3, the heating section 56 is illustrated as a straight tube. However, one skilled in the art can appreciate that the cross-section of the gas flow tube 42 may change along its longitudinal axis.

FIG. 4A is a cross-sectional view of an alternative embodiment 72 of the gas flow tube 42 shown in FIG. 3, where a heating section 74 includes a frusto-conical section 76. FIG. 4B is a cross-sectional view of another alternative embodiment 78 of the gas flow tube 42, where a heating section 80 includes a bell-shaped section 82.

Referring back to FIG. 3, the rod-shaped conductor 44 may be made of any conducting material and is configured to receive microwaves from a core conductor 66 of a microwave coaxial cable 64 in the supply line 16. The core conductor 66 may be shielded by an outer layer 68 that may have multiple sublayers. (Detailed description of the outer layer 68 will be given in FIG. 9.) As illustrated in the enlarged schematic diagram 53, a plug-mating connection mechanism may be used to provide a secure connection between the rod-shaped conductor 44 and the core conductor 66. The end portion of the microwave coaxial cable 64 may be stripped to expose the core conductor 66 at suitable length, and connected to a mating conductor 45 that may be also connected to the rod-shaped conductor 44. The mating conductor 45 allows the connection between the rod-shaped conductor 44 and core conductor 66 which may have different outer diameters. It should be apparent to those of ordinary skill in the art that other conventional types of connection mechanisms may be used without deviating from the present invention.

The rod-shaped conductor 44 can be made out of copper, aluminum, platinum, gold, silver and other conducting materials. The term rod-shaped conductor is intended to cover conductors having various cross sections such as a circular, oval, elliptical, or an oblong cross section or combinations thereof. It is preferred that the rod-shaped conductor not have a cross section such that two portions thereof meet to form an angle (or sharp point) as the microwaves

will concentrate in this area and decrease the efficiency of the device.

The rod-shaped conductor 44 includes a tip 46 that focuses the received microwaves to generate the plasma 14 using the gas flowing through the gas flow tube 42. Typically, the microwaves travel along the surface of the rod-shaped conductor 44, where the depth of skin responsible for the microwave migration is a function of a microwave frequency and a conductor material, and this depth can be less than a millimeter. Thus, a hollow rod-shaped conductor 84 of FIG. 5A may be considered as an alternative embodiment for the rod-shaped conductor, wherein the hollow rod-shaped conductor 84 has a cavity 85.

It is well known that some precious metals conduct microwaves better than cheap metals, such as copper. To reduce the unit price of the system without compromising performance of a rod-shaped conductor, the skin layer of the rod-shaped conductor may be made of such precious metals while a cheaper conducting material may be used for the inside core. FIG. 5B is a cross sectional view of another alternative embodiment of a rod-shaped conductor 86, wherein the rod-shaped conductor 86 includes a skin layer 90 made of precious metal(s) and a core layer 88 made of a cheaper conducting material.

FIG. 5C is a cross-sectional view of still another alternative embodiment of a rod-shaped conductor 92, wherein the rod-shaped conductor 92 may have a conically-tapered tip 94. Other variations can also be considered. For example, the conically-tapered tip 94 may be eroded faster by plasma than the other portions of the rod-shaped conductor 92, and therefore it may need to be replaced on a regular basis.

FIG. 5D is a cross sectional view of yet another alternative embodiment of a rod-shaped conductor 96, wherein a rod-shaped conductor 96 has a blunt-tip 98 instead of a pointed tip to increase the lifetime of the rod-shaped conductor 96.

FIG. 5E is a cross sectional view of another alternative embodiment of a rod-shaped conductor 100, wherein the rod-shaped conductor 100 has a tapered section 104 secured to a cylindrical portion 102 by a suitable fastening mechanism 106 (in this case, the tapered section 104 is screwed into the cylindrical portion 102) for easy and quick replacement.

FIGS. 5F-5I show cross-sectional views of further alternative embodiments of the rod-shaped conductors. As illustrated, rod-shaped conductors 200, 202, 206 and 212 are similar to their counterparts 44 (FIG. 3), 84 (FIG. 5A), 86 (FIG. 5B) and 100 (FIG. 5E), respectively, with the difference that they have blunt tips for reducing the erosion rate due to plasma generated at the tips.

Now, referring back to FIG. 3, the supply line 16 comprises: an outer jacket 60 coupled

and sealed tightly to the interface section 58; one or more gas lines 62, connected to the gas tank 21 via the MFC valve 19 (shown in FIG. 1), for providing the gas flow to the portable unit 12; a microwave coaxial cable 64 that comprises a core conductor 66 and an outer layer 68, where one end of the microwave coaxial cable 64 is coupled to the connector 70. The connector 70 is
5 configured to couple to the counterpart connector 17 (FIG. 1) of the waveguide-to-coax adapter 18. The connectors 17 and 70 may be, but are not limited to, BNC, SMA, TMC, N, or UHF type connectors.

FIG. 6A is a schematic cross-sectional view of the supply line 16 taken along the direction A-A in FIG. 3. An outer jacket 60 and the gas lines 62 may be made of any flexible
10 material, where the material is preferably, but not limited to, a conventional dielectric material, such as polyethylene or plastic. Since the outer jacket 60 is coupled to the inner surface of the interface section 58, the interface section 58 may have a similar hexagonal cross-section as the outer jacket 60. In FIG. 6A, each gas line 62 is described as a circular tube. However, it should be apparent those skilled in the art that the number and cross-sectional shape of the gas lines 62
15 can vary without deviating from the present invention. The at least two conductor signal lines 24 (shown in FIG. 3) may be positioned in a space 67 between the gas lines 62. The detailed description of the microwave coaxial cable 64 will be given in connection with FIG. 9.

FIG. 6B is an alternative embodiment of a supply line 108, having components which are similar to their counterparts in FIG. 6A. This embodiment comprises: an outer jacket 110; one
20 or more gas lines 112; a microwave coaxial cable 114 that includes a core conductor 116 and an outer layer 118. In this embodiment, the interface section 58 may have a circular cross-section to receive the supply line 108.

As illustrated in FIGS. 6A-B, one of the functions of the outer jackets 60 and 110 is positioning the gas lines 62 and 112 with respect to the microwave coaxial cables 64 and 114,
25 respectively, such that the gas lines and the coaxial cable may form a supply line unit. As a variation, the supply line may include a gas line(s), microwave coaxial cable and an attachment member that encloses a portion of the gas line(s) and the microwave coaxial cable. In such a configuration, the attachment member may function as a positioning mechanism that detachably fastens the gas line(s) to the microwave coaxial cable. It is also possible to position the gas line
30 relative to the microwave coaxial cable by a clip or tape or other type of attachment without using a specific outer jacket.

FIG. 6C is another alternative embodiment of a supply line 109. This embodiment comprises: a microwave coaxial cable 115 that includes a core conductor 117 and an outer layer

119; a molding member 107 having at least one gas passage 113 and enclosing the microwave coaxial cable 115. In a still alternative embodiment, the supply line 109 may also include an outer jacket.

FIG. 7 is a schematic cross-sectional view of an alternative embodiment 120 of the portable microwave plasma discharge unit 12 shown in FIG. 3. In this embodiment, a portable unit 120 includes two portions; a heating portion 122 and an interface portion 124, where the interface portion 124 may accommodate the heating portion 122 having various dimensions. The heating portion 122 comprises: a gas flow tube 126 made of conducting and/or dielectric material; a rod-shaped conductor 128 axially disposed in the gas flow tube 126 and configured to receive microwaves and focus the received microwaves at its tip 130 to generate a plasma 132; a plurality of centering disks 134 having at least one through-pass hole 135; an adjustable power control unit 136; and a conductor having at least two conductor signal lines 138 that interconnect the adjustable power control unit 136 and the power level control 40 (shown in FIG. 3). The interface portion 124 comprises: a gas flow duct 140 made of a conducting and/or dielectric material and is sealingly coupled to the gas flow tube 126; a conductor segment 142 that interconnects the rod-shaped conductor 128 and the core conductor 66 of the supply line 16; and a holder 144 configured to secure the conductor segment 142 to the gas flow duct 140 in a fixed position and having at least one through-pass hole 146 for fluid communication between the gas lines 62 and the gas flow tube 126. A typical plug-mating connection between the rod-shaped conductor 128 and the conductor segment 142 may be used to provide a secure connection. For purposes of operational safety, the gas flow tube 126 and gas flow duct 140 may be grounded.

A plug-mating connection 131 between the rod-shaped conductor 128 and the conductor segment 142 may be used to provide a secure connection. Likewise, a plug-mating connection 133 may be used to provide a secure connection between the conductor segment 142 and the core conductor 66. It should be apparent to those of ordinary skill in the art that other types of connections may be used to connect the conductor segment 142 with the rod-shaped conductor 128 and the core conductor 66 without deviating from the present invention.

It is well known that microwaves travel along the surface of a conductor. The depth of skin responsible for microwave migration is a function of microwave frequency and conductor material, and can be less than a millimeter. Thus, the diameters of the rod-shaped conductor 128 and the conductor segment 142 may vary without deviating from the present invention as long as they are large enough to accommodate the microwave migration.

FIG. 8A is a schematic cross-sectional view of an alternative embodiment 148 of the supply line 16. As illustrated in FIG. 8A, the supply line 148 comprises: an outer jacket 152 connected to the gas tank 21 via the MFC 19 (shown in FIG. 1); a plurality of centering disks 150; and a microwave coaxial cable 154 that comprises a core conductor 156 and an outer layer 158; where one end of the microwave coaxial cable 154 is coupled to the connector 160. The outer layer 158 may have sublayers that are similar to those of the layer 68. The connector 160 is configured to be coupled to the counterpart connector 17 of the adapter 18. A plug-mating connection 157 between the rod-shaped conductor 44 and the core conductor 156 may be used to provide a secure connection.

FIG. 8B is a schematic diagram of the centering disk 150 viewed in the longitudinal direction of the outer jacket 152. As illustrated in FIG. 8B, the outer rim 161 and the inner rim 163 are connected by four spokes 162 forming spaces 164. The outer jacket 152 and the microwave coaxial cable 154 engage an outer perimeter of the outer rim 161 and an inner perimeter of the inner rim 163, respectively. It should be apparent to those skilled in the art that the number and shape of the spokes 162 can vary without deviating from the present invention.

FIG. 9 is a schematic cross-sectional view of the microwave coaxial cable 64, which may be a conventional type known in the art. As illustrated in FIG. 9, the microwave coaxial cable 64 comprises: the core conductor 66 that transmits microwaves and an outer layer 68 that shields the core conductor 66. The outer layer 68 may comprise: a dielectric layer 166; a metal tape layer 168 comprising a conducting material which is configured to shield a dielectric layer 166; a braid layer 170 for providing additional shielding; and an outer jacket layer 172. The dielectric layer 166 may be comprised of a cellular dielectric material that has a high dielectric constant. The metal tape layer 168 may be made of any metal, and preferably is aluminum or copper, but is not limited thereto.

FIG. 10 is a schematic diagram illustrating an interface region 178 where a portable unit 12 is coupled to a supply line 16 in accordance with at least one embodiment of the present invention. The supply line 16 may include: a microwave coaxial cable 64 and gas lines 62, where the microwave coaxial cable 64 may include core conductor 66; dielectric layer 166; metal tape layer 168; braid layer 170 and outer jacket layer 172. The rod-shaped conductor 44 may be connected to the core conductor 66 by a mating conductor 184. Grounded cable holder 180 made of a conducting material may connect the gas flow tube 42 with the braid layer 170 so that the gas flow tube 42 is grounded via the braid layer 170. The mating conductor 184 may be insulated from the grounded cable holder 180 by a dielectric layer 182. The dielectric layer 182

may be comprised of a dielectric material, preferably polyethylene.

FIG. 11 is a schematic diagram of a system shown at 300 and having an alternative embodiment of the portable microwave plasma discharge unit and supply line shown in FIG. 1. As illustrated, the system 300 comprises: a microwave supply unit 22 for generating
5 microwaves; a waveguide 20 connected to the microwave supply unit 22; a waveguide-to-coax adapter 18 configured to receive the microwaves within the waveguide 20 and provide the received microwaves through its microwave coaxial connector 17; a portable microwave plasma discharge unit (or shortly, portable unit) 312 configured to generate a discharge plasma 310; a microwave coaxial cable 64 coupled to a waveguide-to-coax adapter 18 and to supply
10 microwaves to the portable microwave plasma discharge unit 312; a gas line 335 for providing gas flow for the portable unit 312, where the gas line 335 is coupled to a gas tank 21 via a Mass Flow Control (MFC) valve; and a conductor having at least two conductor signal lines 328 that interconnects an adjustable power control unit 326 (shown in FIG. 12) with a power level control 40 of a power supply 38 (shown in FIG. 2). The waveguide-to-coax adapter 18 is well
15 known in the art and is preferably, but not limited to, WR284 or WR340 which is used in the system 300.

FIG. 12 is a partial cross-sectional view of the portable microwave plasma discharge unit 312 shown in FIG. 11. The portable unit 312 comprises: a gas flow tube 318 configured to receive a gas flow from a gas line 335; a rod-shaped conductor 316, axially disposed in the gas
20 flow tube 318 and having a tapered tip 320; one or more centering disks 322, each disk having at least one through-pass hole 324; the adjustable power control unit 326 for operating the power level control 40 of the power supply 38 (shown in FIG. 2); at least two conductor signal lines 328 interconnecting the adjustable power control unit 326 and the power level control 40; and a holder 330 for securing the rod-shaped conductor 316 to the gas flow tube 318. The centering
25 disks 322 may be made of any microwave-transparent dielectric material, such as ceramic or high temperature plastic, and have at least one through-pass hole 324. The through-pass hole 324 may be configured to generate a helical swirl around the rod-shaped conductor 316 to increase the length and stability of a plasma plume 310. The holder 330 may be made of any microwave-transparent dielectric material, such as ceramic or high temperature plastic. In
30 contrast to the holder 52 in FIG. 3, the holder 330 does not include any gas passage.

The gas flow tube 318 provides a mechanical support for the overall portable unit 312 and may be made of any conducting and/or dielectric material. As illustrated in FIG. 12, the gas flow tube 318 may comprise a heating section 336 and an interface section 338. The user of the

portable unit 312 may hold the heating section 336 during operation of the system 300 and, for purposes of safety, the gas flow tube 318 may be grounded. In general, a cross-sectional dimension of the heating section 336 taken along a direction normal to the longitudinal axis of the heating section 336 may be different from that of the interface section 338. The cross-sectional dimension of the interface section 338 may be determined by the dimension of the microwave coaxial cable 64, while the dimension of the heating section 336 may be determined by various operational parameters, such as plasma ignition and stability.

As shown in FIG. 12, the gas flow tube 318 is sealed tightly and coupled to the microwave coaxial cable 64. Various coupling mechanisms, such as an o-ring between the inner surface of the gas flow tube 318 and outer surface of the microwave coaxial cable 64, may be used for sealing and providing a secure coupling between the gas flow tube 318 and the microwave coaxial cable 64.

In FIG. 12, the heating section 336 is illustrated as a straight tube. However, one skilled in the art can appreciate that the cross-section of the gas flow tube 318 may change along its longitudinal axis.

One of the major differences between the portable unit 12 in FIG. 1 and portable unit 312 in FIG. 12 is that the portable unit 312 may not use the supply line 16 as shown in FIG. 1. Instead, the gas flow tube 318 of the portable unit 312 may have a gas line interface or port 332 that is configured to receive gas from the gas line 335. As depicted in FIG. 12, the gas line interface 332 may have an opening to accommodate the gas line 335. Various coupling mechanisms, such as an o-ring between the inner surface of the opening and outer surface of the gas line 335 may be used for sealing and providing a secure coupling between the gas line 335 and gas line interface 332. It should be apparent to those of ordinary skill that other suitable types of coupling mechanism may be used to connect the gas line interface 332 to the gas line 335.

The gas line interface 332 may have variations in shape. For example, FIG. 13 is a partial cross-sectional view of an alternative embodiment of the portable microwave plasma discharge unit 312 shown in FIG. 12, wherein a gas line interface 382 defines an opening aligned in a direction substantially normal to the longitudinal axis of the gas flow tube 368. In this embodiment, the gas line interface or port 382 may be connected to the gas line 385 via a gas line adapter 384.

The gas line adapter 384 may have a shape for connecting the gas line interface 382 to the gas line 385, wherein the diameters of the gas line interface 382 and gas line 385 may be

different. In an alternative embodiment, the gas line adapter 384 may be formed at the end of and a part of the gas line 385. In another alternative embodiment, the branch angle of the gas line interface 382 with respect to the gas flow tube 368 may be more or less than 90 degrees.

In FIG. 12, the portable unit 312 includes the heating and interface portions 336, 338 that
5 are formed in one body. In an alternative embodiment, these two portions may be formed of two separate bodies and coupled to each other to form a portable unit as in the case of the portable unit 120 depicted in FIG. 7. Likewise, in another alternative embodiment, the portable unit 362 in FIG. 13 may have a pair of heating and interface portions that are formed of two separate bodies.

10 While the present invention has been described with a reference to the specific embodiments thereof, it should be understood, of course, that the foregoing relates to preferred embodiments of the invention and that modifications may be made without departing from the spirit and the scope of the invention as set forth in the following claims.

15

What is claimed is:

1. A microwave plasma discharge unit, comprising:
a gas flow tube adapted to direct a flow of gas therethrough and said gas flow tube
5 having an inlet portion and an outlet portion; and
a rod-shaped conductor axially disposed in said gas flow tube, said rod-shaped conductor
having an end configured to contact a microwave supply conductor and a tip positioned adjacent
the outlet portion of said gas flow tube.
- 10 2. A microwave plasma discharge unit as defined in claim 1, further comprising:
at least one centering disk located within said gas flow tube for securing said rod-shaped
conductor to said gas flow tube, said at least one centering disk having at least one through-pass
hole.
- 15 3. A microwave plasma discharge unit as defined in claim 2, wherein said at least one
centering disk comprises a dielectric material.
4. A microwave plasma discharge unit as defined in claim 2, wherein said at least one
through-pass hole of said at least one centering disk is configured and disposed for imparting a
20 helical shaped flow direction around said rod-shaped conductor to a gas passing along said at
least one through-pass hole to generate a helical flow swirl around said rod-shaped conductor.
5. A microwave plasma discharge unit as defined in claim 1, further comprising:
a holder located within said gas flow tube adjacent to said inlet portion for securing said
25 rod-shaped conductor relative to said gas flow tube, said holder having at least one through-pass
hole therein.
6. A microwave plasma discharge unit as defined in claim 5, wherein said holder is
comprised of a dielectric material.
- 30 7. A microwave plasma discharge unit as defined in claim 1, wherein the inlet portion of
said gas flow tube is coupled to a supply line comprising a microwave supply conductor and at
least one gas line capable of providing a flow of gas for said gas flow tube.

8. A microwave plasma discharge unit as defined in claim 1, further comprising:
a holder located within said gas flow tube adjacent to said inlet portion for securing said
rod-shaped conductor relative to said gas flow tube, wherein said gas flow tube includes a gas
line interface configured to couple to a gas line capable of providing a flow of gas for said gas
flow tube and wherein the inlet portion of said gas flow tube is configured to couple to a
microwave coaxial cable comprising the microwave supply conductor.

9. A microwave plasma discharge unit as defined in claim 8, wherein said gas line
interface is coupled to the gas line via a gas line adapter.

10. A microwave plasma discharge unit as defined in claim 1, wherein said gas flow
tube comprises at least one of a dielectric material and a conducting material.

11. A microwave plasma discharge unit as defined in claim 1, wherein said gas flow
tube is electrically grounded.

12. A microwave plasma discharge unit as defined in claim 1, further comprising:
an adjustable power control unit mounted on said gas flow tube for controlling
transmission of microwaves through said microwave supply conductor.

13. A microwave plasma discharge unit as defined in claim 12, further comprising:
at least two conductor signal lines interconnecting said adjustable power control unit
with a power level control of a microwave supply unit, wherein said microwave supply unit
transmits microwaves via the microwave supply conductor.

14. A microwave plasma discharge unit as defined in claim 1, wherein the outlet portion
of said gas flow tube has a frusto-conical shape.

15. A microwave plasma discharge unit as defined in claim 1, wherein the outlet portion
of said gas flow tube has a bell shape.

16. A microwave plasma discharge unit as defined in claim 1, wherein said rod-shaped
conductor includes a cavity having a generally tubular shape.

17. A microwave plasma discharge unit as defined in claim 16, wherein another conducting material is disposed in the cavity.

18. A microwave plasma discharge unit as defined in claim 1, wherein said tip is removable from another portion of said rod-shaped conductor.

19. A microwave plasma discharge unit as defined in claim 1, wherein said tip includes a pointed tip.

20. A microwave plasma discharge unit as defined in claim 1, wherein said tip includes a blunt tip.

21. A microwave plasma discharge unit as defined in claim 1, wherein said tip is tapered.

22. A device comprising:
a gas flow tube adapted to direct a flow of gas therethrough and having an inlet portion and an outlet portion;
a rod-shaped conductor axially disposed in said gas flow tube, said rod-shaped conductor having an end configured to receive microwaves and a tip positioned adjacent the outlet portion and configured to focus microwaves traveling through said rod-shaped conductor;
at least one centering disk located within said gas flow tube for securing said rod-shaped conductor to said gas flow tube, said at least one centering disk having structure defining at least one through-pass hole; and

an interface portion including:
a gas flow duct having an outlet portion coupled to the inlet portion of said gas flow tube and an inlet portion coupled to a supply line that includes a microwave supply conductor;
a conductor segment axially disposed within said gas flow duct, said conductor segment being configured to interconnect an end of said rod-shaped conductor with said microwave supply conductor, and
a holder located within said gas flow duct for securing said conductor segment to said gas flow duct.

23. A device as defined in claim 22, wherein said supply line further includes at least one gas line and wherein said holder includes at least one through-pass hole to provide fluid communication between said gas line and said gas flow tube

5 24. A device as defined in claim 22, wherein said supply line is a microwave coaxial cable and wherein said gas flow tube further includes a gas line interface configured to couple to a gas line capable of providing a flow of gas for said gas flow tube.

10 25. A device as defined in claim 22, wherein said at least one through-pass hole of said at least one centering disk is configured and disposed for imparting a helical shaped flow direction around said rod-shaped conductor to a gas passing along said at least one through-pass hole.

15 26. A device as defined in claim 22, wherein said at least one centering disk comprises a dielectric material.

27. A device as defined in claim 26, wherein the dielectric material is one selected from the group consisting of ceramic and high temperature plastic.

20 28. A device as defined in claim 22, wherein said holder comprises a dielectric material.

29. A device as defined in claim 28, wherein said dielectric material is one selected from the group consisting of ceramic and high temperature plastic.

25 30. A device as defined in claim 22, wherein said gas flow tube comprises at least one of a dielectric material and a conducting material.

31. A device as defined in claim 22, wherein said gas flow tube is electrically grounded.

30 32. A device as defined in claim 22, wherein said gas flow duct comprises at least one of a dielectric material and a conducting material.

33. A device as defined in claim 22, wherein said gas flow duct is electrically grounded.

34. A device as defined in claim 22, further comprising:

an adjustable power control unit operatively connected to said gas flow tube for

5 controlling transmission of microwaves through the microwave supply conductor.

35. A device as defined in claim 34, further comprising:

at least two conductor signal lines interconnecting said adjustable power control unit

with a power level control of a microwave supply unit, wherein said microwave supply unit

10 transmits microwaves through the microwave supply conductor.

36. A device as defined in claim 22, wherein the outlet portion of said gas flow tube has a frusto-conical shape.

15 37. A device as defined in claim 22, wherein the outlet portion of said gas flow tube has a bell shape.

38. A device as defined in claim 22, wherein said rod-shaped conductor includes a cavity having a generally tubular shape.

20

39. A device as defined in claim 38, wherein another conducting material is disposed in the cavity.

40. A device as defined in claim 22, wherein said tip is removable from another portion

25

of said rod-shaped conductor.

41. A device as defined in claim 22, wherein said tip includes a pointed tip.

42. A device as defined in claim 22, wherein said tip includes a blunt tip.

30

43. A device as defined in claim 22, wherein said tip is tapered.

44. A microwave plasma discharge unit, comprising:

a gas flow tube adapted to direct a flow of gas therethrough and said gas flow tube having an inlet portion and an outlet portion;

5 a microwave supply conductor configured for supplying microwaves from a microwave supply unit; and

a rod-shaped conductor axially disposed in said gas flow tube, said rod-shaped conductor having an end configured to contact said microwave supply conductor and a tip positioned adjacent to the outlet portion of said gas flow tube.

10 45. A device comprising:

a gas flow tube adapted to direct a flow of gas therethrough and having an inlet portion and an outlet portion;

15 a rod-shaped conductor axially disposed in said gas flow tube, said rod-shaped conductor having an end configured to receive microwaves and a tip positioned adjacent the outlet portion and configured to focus the microwaves traveling through said rod-shaped conductor; and

a positioning portion capable of arranging said gas flow tube relative to said rod-shaped conductor.

46. A device as defined in claim 45, further comprising:

20 at least one centering disk located within said gas flow tube for securing said rod-shaped conductor to said gas flow tube, said at least one centering disk having structure defining at least one through-pass hole.

47. A device as defined in claim 45, further comprising an interface portion that includes

25 a gas flow duct having an outlet portion coupled to the inlet portion of said gas flow tube and an inlet portion coupled to a supply line that includes a microwave supply conductor.

48. A device as defined in claim 47, wherein said positioning portion includes a

30 conductor segment axially disposed within said gas flow duct, said conductor segment being configured to interconnect an end of said rod-shaped conductor with said microwave supply conductor.

49. A device as defined in claim 48, wherein said supply line further includes at least one gas line, wherein said positioning portion further includes a holder located within said gas flow duct for securing said conductor segment to said gas flow duct, and wherein said holder includes at least one through-pass hole allowing fluid communication between said at least one
5 gas line and said gas flow tube.

50. A device as defined in claim 48, wherein said supply line is a microwave coaxial cable.

10 51. A device as defined in claim 50, wherein said positioning portion includes a holder located within said gas flow duct for securing said conductor segment to said gas flow duct and wherein said gas flow tube includes a gas line interface configured to couple to a gas line capable of providing a flow of gas for said gas flow tube.

15 52. A microwave plasma discharge unit, comprising:
a gas flow tube adapted to direct a flow of gas therethrough and said gas flow tube having an inlet portion and an outlet portion;
a microwave coaxial cable configured to supply microwaves from a microwave supply unit, said microwave coaxial cable including a braid layer and a core conductor, said braid layer
20 configured to be coupled to said gas flow tube; and
a rod-shaped conductor axially disposed in said gas flow tube, said rod-shaped conductor having an end configured to couple to said core conductor and a tip positioned adjacent to the outlet portion of said gas flow tube.

25 53. A microwave plasma discharge unit as defined in claim 52, further comprising:
a cable holder interposed between said gas flow tube and said microwave coaxial cable and configured to couple said braid layer to said gas flow tube and be insulated from said core conductor and said rod-shaped conductor.

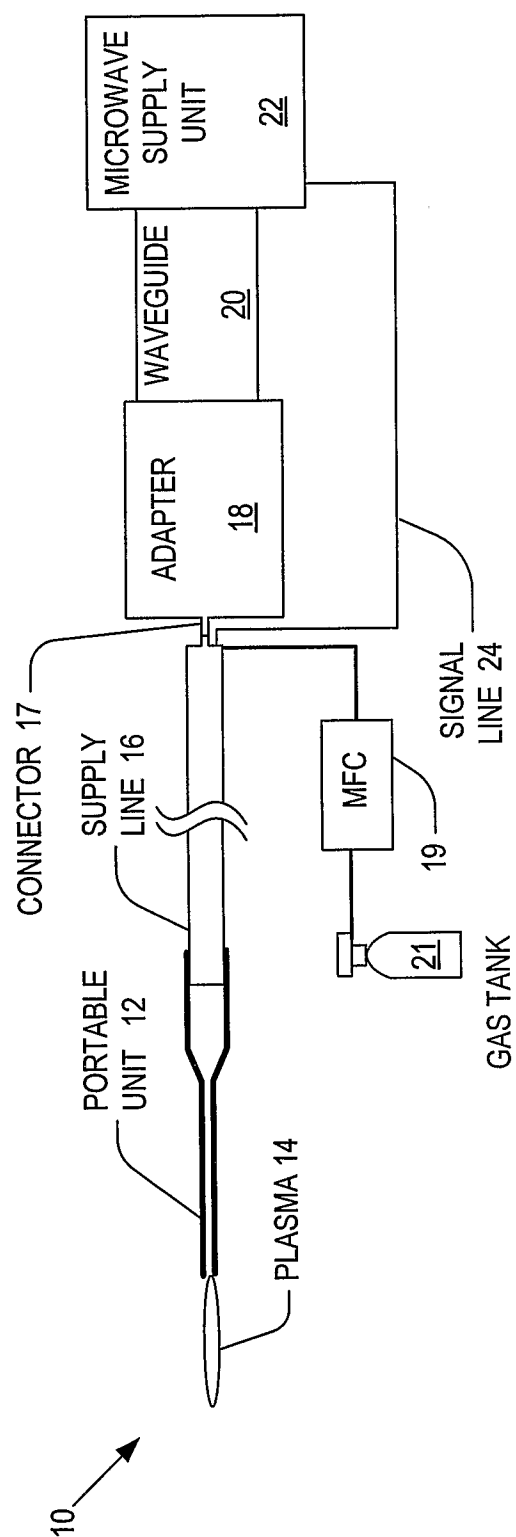


FIG. 1

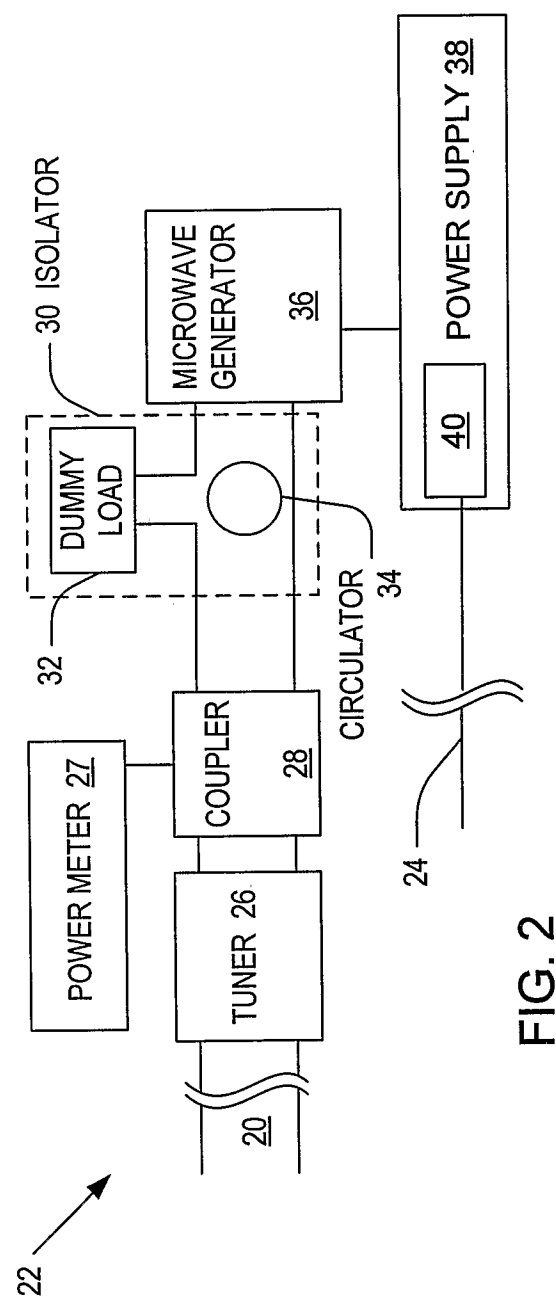


FIG. 2

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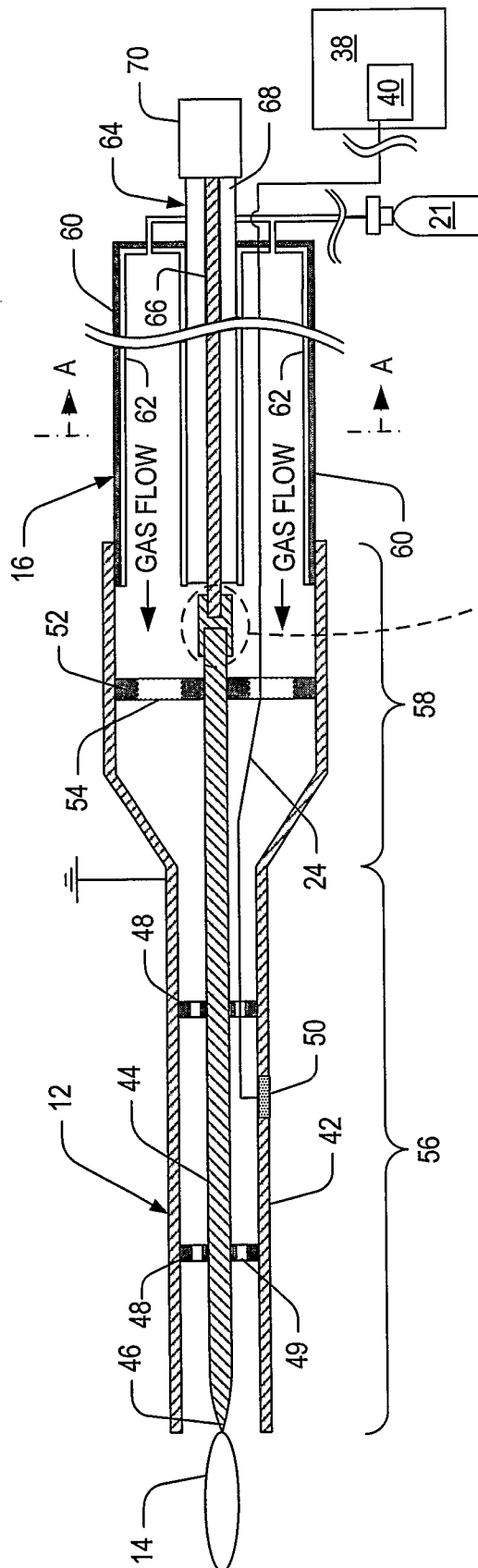


FIG. 3

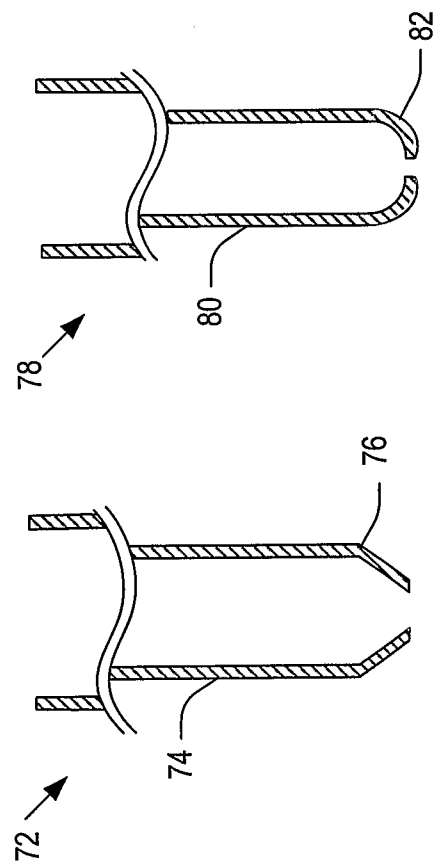
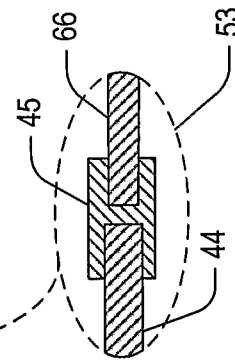


FIG. 4A

FIG. 4B

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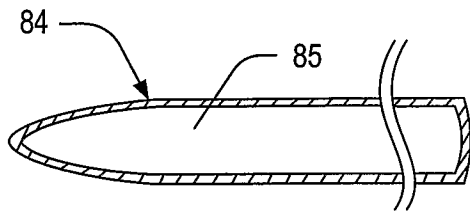


FIG. 5A

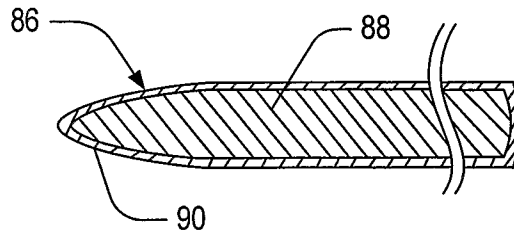


FIG. 5B

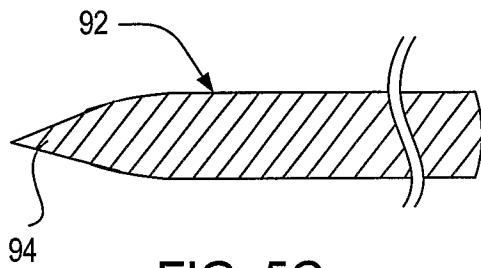


FIG. 5C

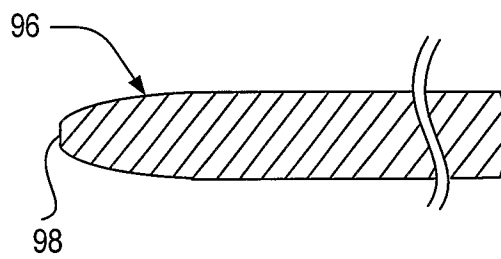


FIG. 5D

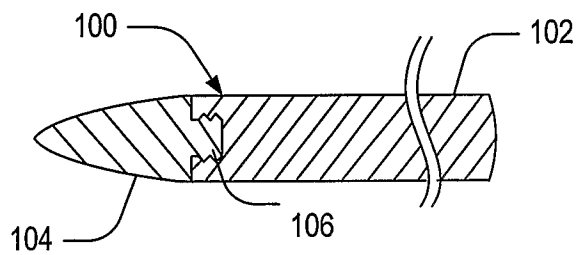


FIG. 5E

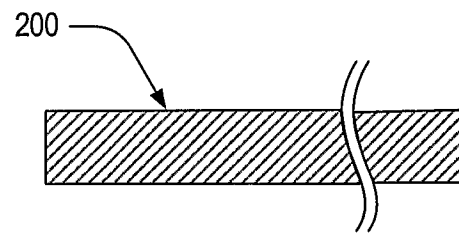


FIG. 5F

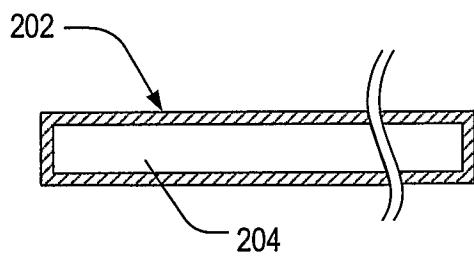


FIG. 5G

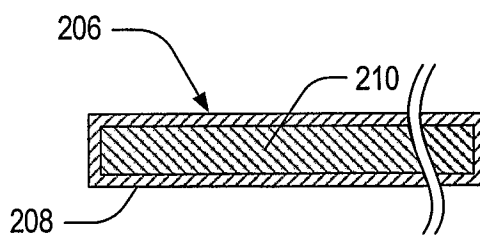


FIG. 5H

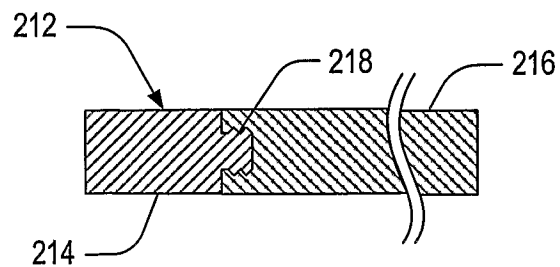


FIG. 5I

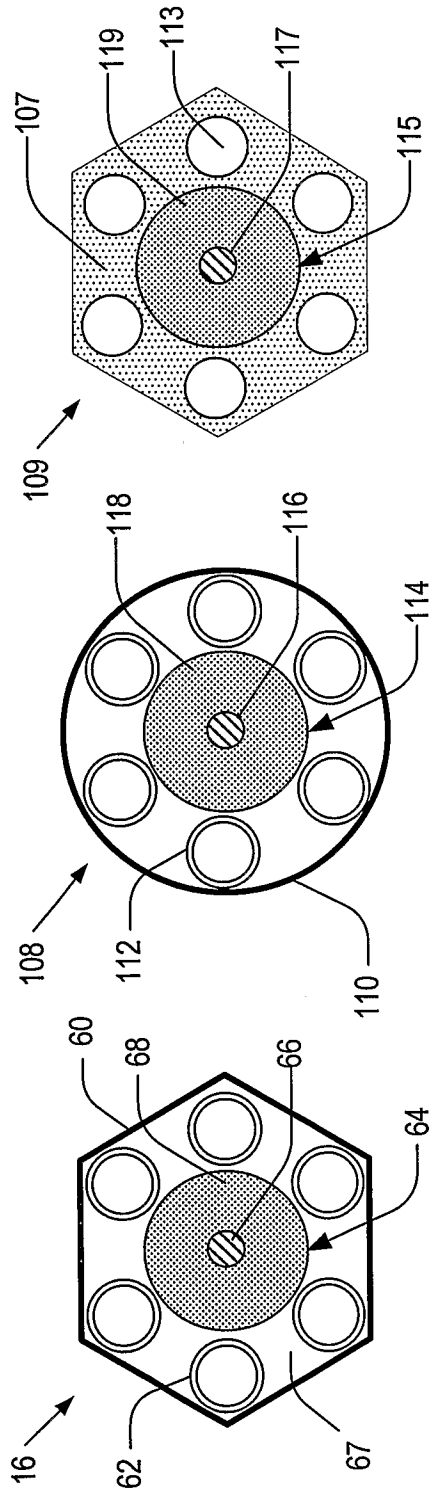


FIG. 6A

FIG. 6B

FIG. 6C

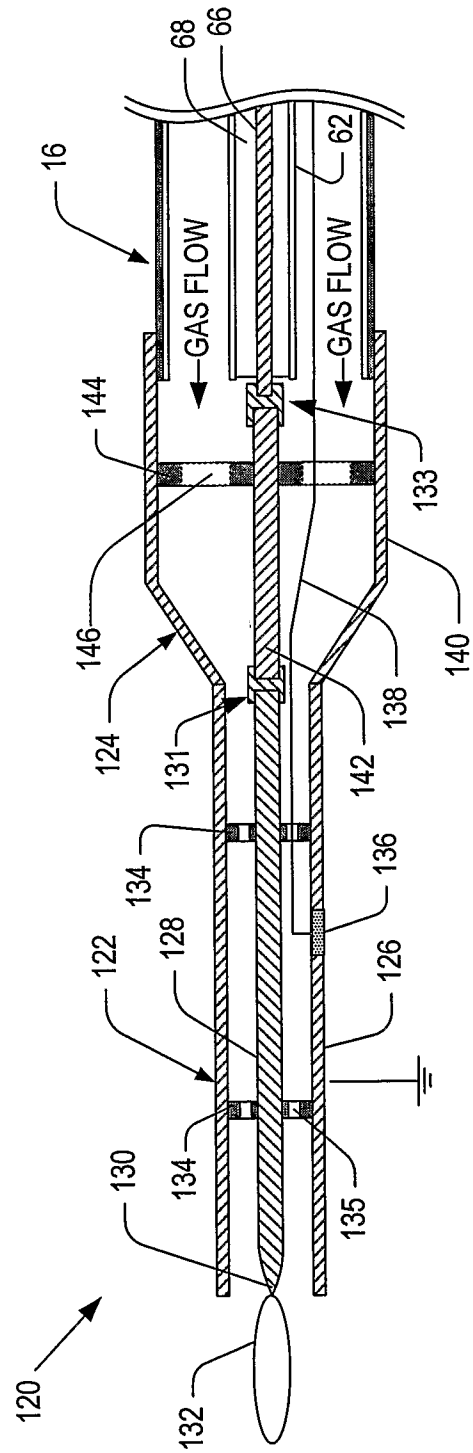


FIG. 7

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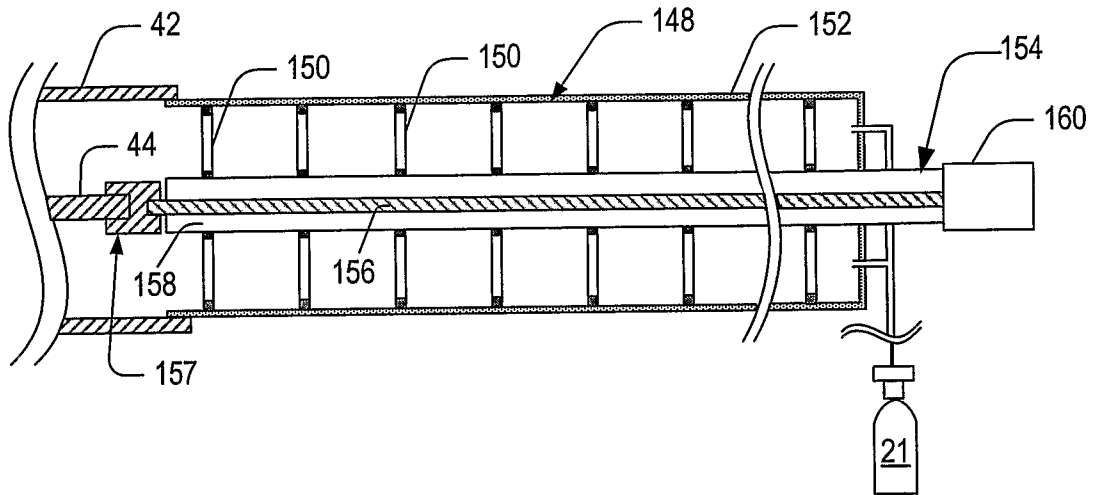


FIG. 8A

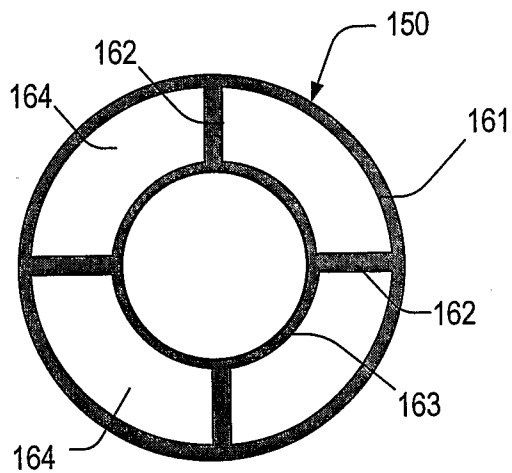


FIG. 8B

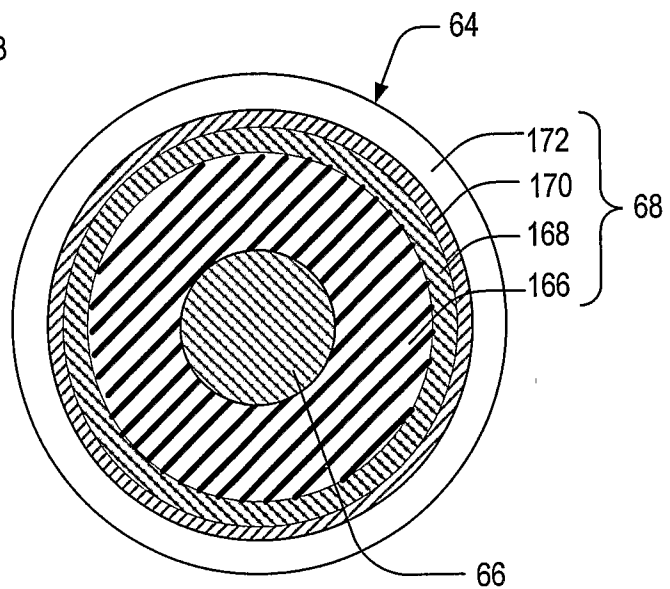


FIG. 9 (PRIOR ART)

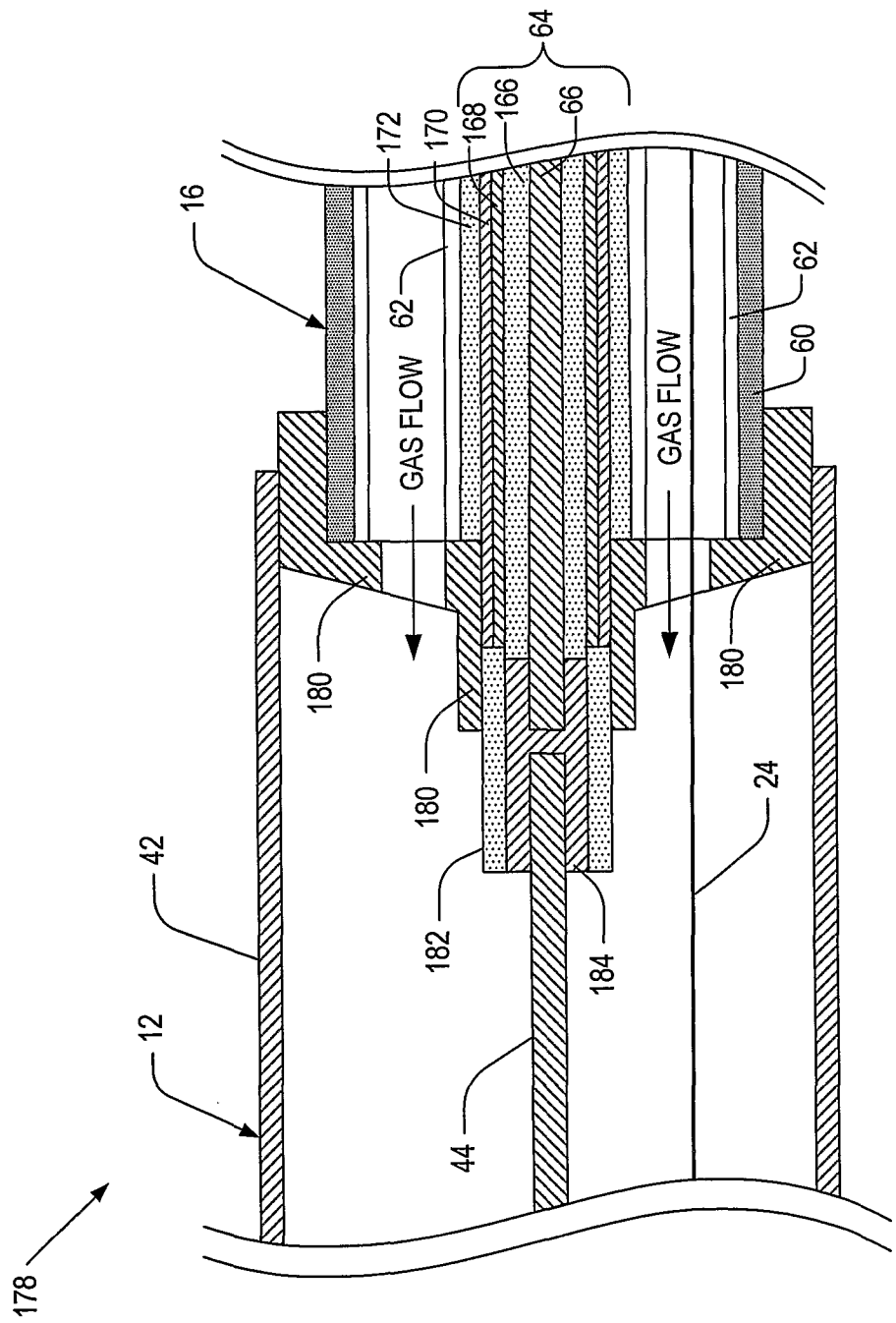


FIG. 10

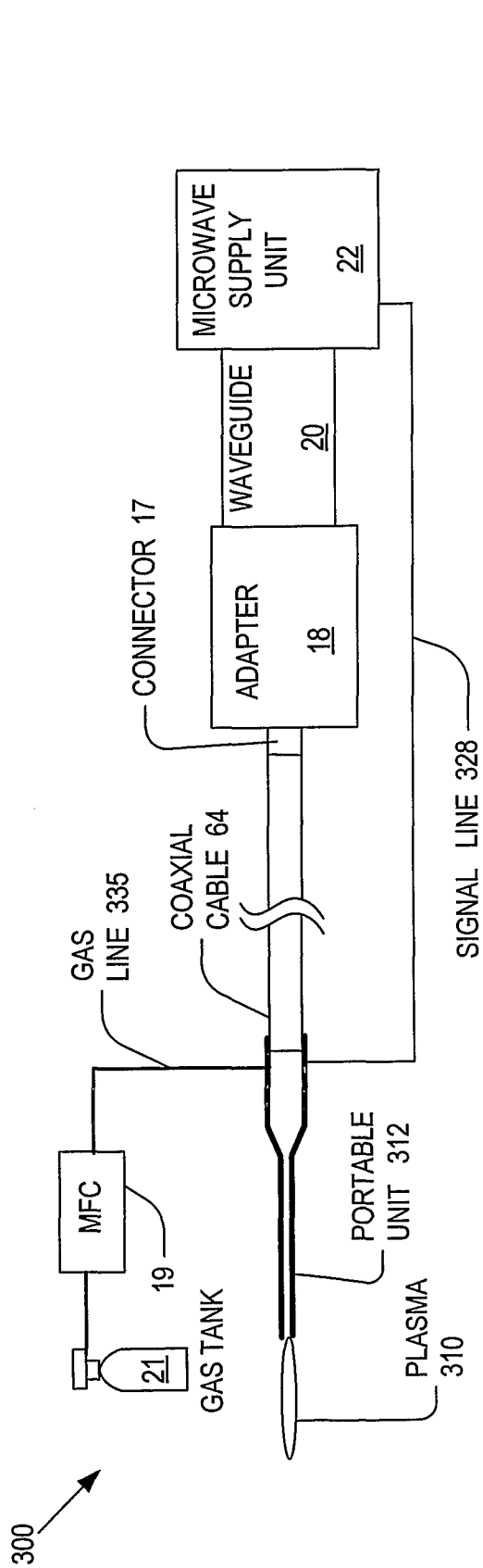


FIG. 11

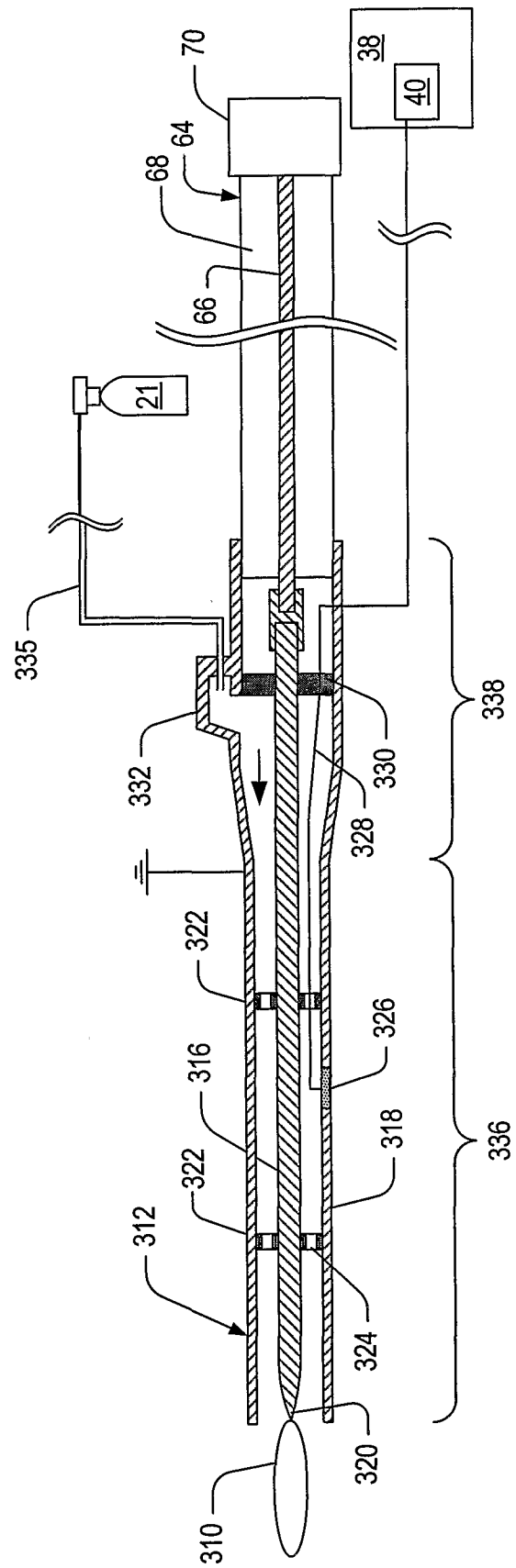


FIG. 12

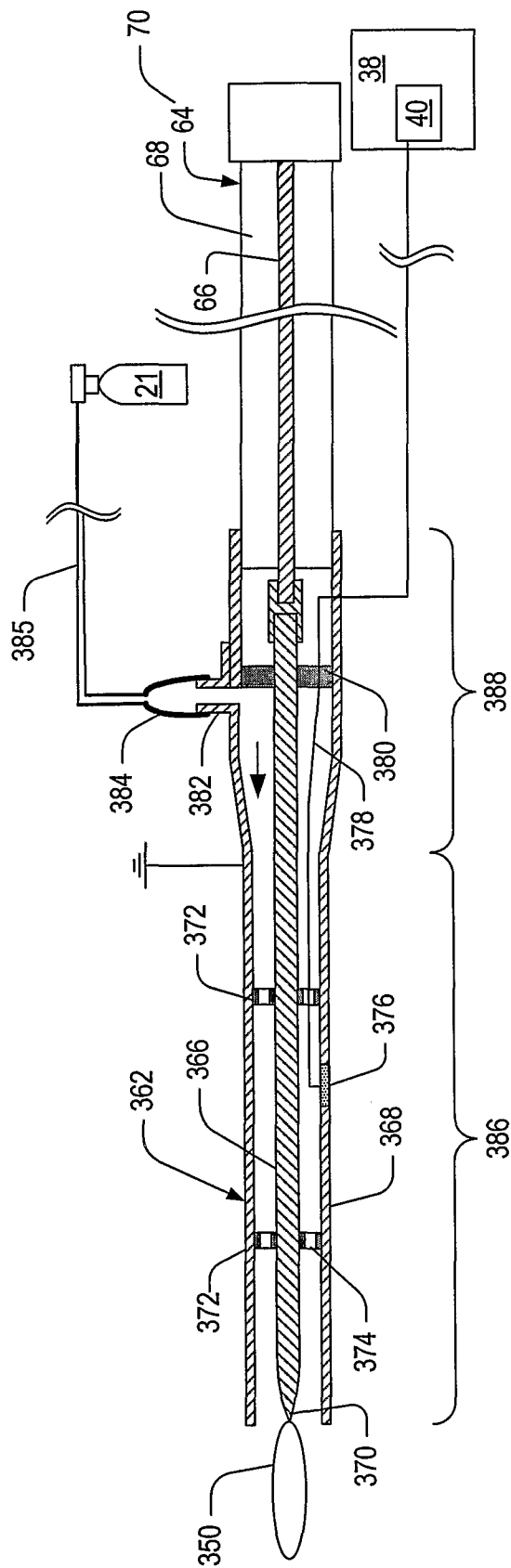


FIG. 13