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(12) **United States Patent**  
**Espiau et al.**

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(54) **MICROWAVE ENERGIZED PLASMA LAMP  
WITH DIELECTRIC WAVEGUIDE**

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**H01J 7/46** (2006.01)

(52) **U.S. Cl.** ..... **315/39; 315/248**

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See application file for complete search history.

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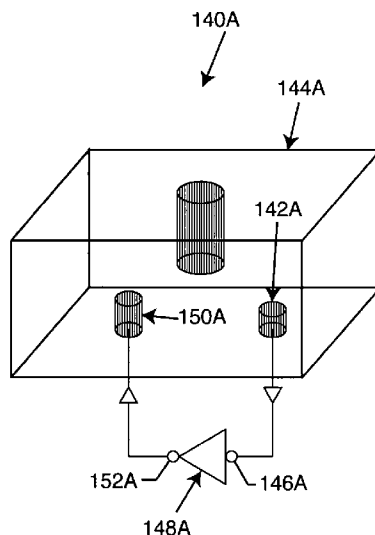
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(57) **ABSTRACT**

A plasma lamp including a waveguide body including at  
least one dielectric material with a dielectric constant greater  
than approximately 2. The body is coupled to a microwave  
source which causes the body to resonate in at least one  
resonant mode. At least one lamp chamber integrated with  
the body contains a bulb with a fill forming a light-emitting  
plasma when the chamber receives power from the resonat-  
ing body. A bulb either is self-enclosed or an envelope sealed  
by a window or lens covering the chamber aperture. Embodiments disclosed include lamps having a drive probe  
and a feedback probe, and lamps having a drive probe,  
feedback probe and start probe, which minimize power  
reflected from the body back to the source both before each  
plasma is formed and after it reaches steady state.

**40 Claims, 25 Drawing Sheets**



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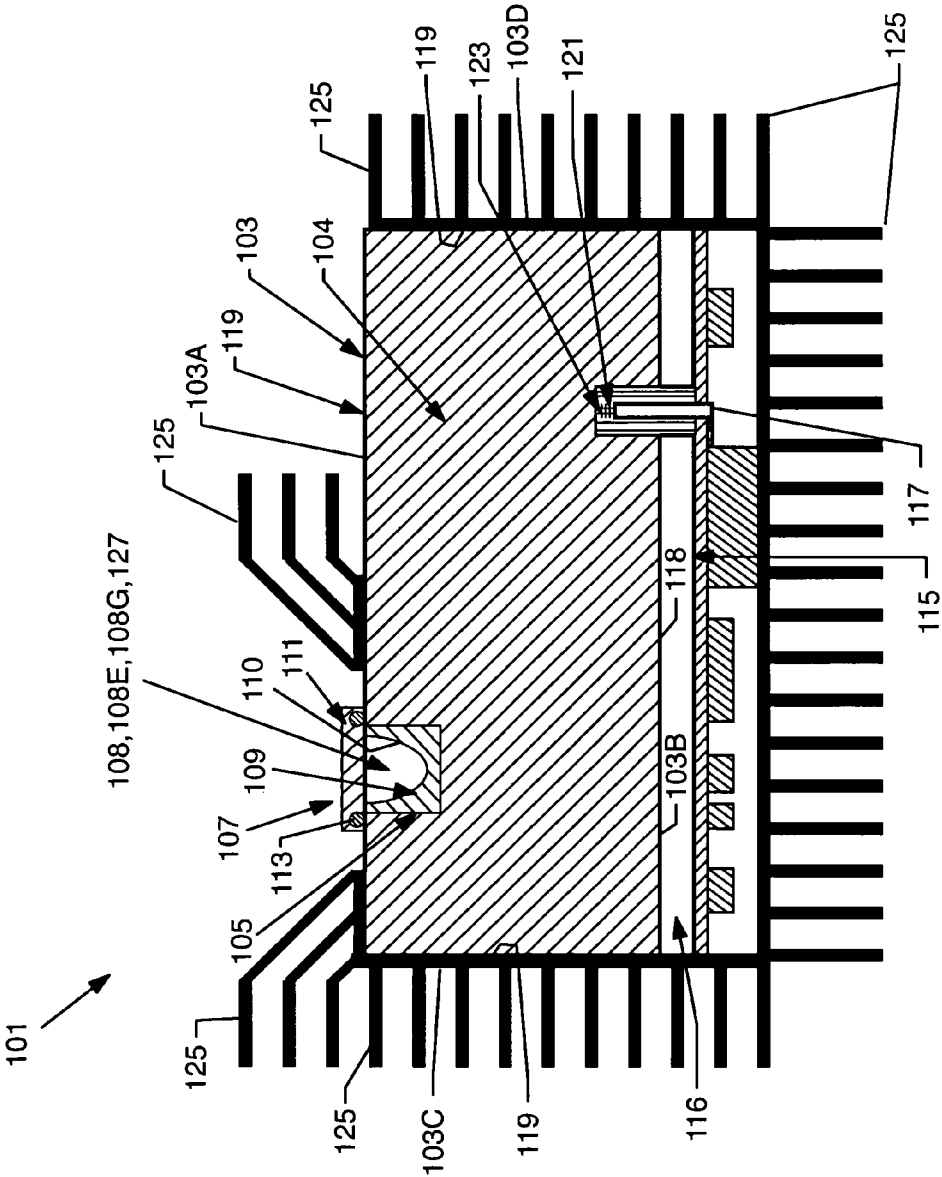


FIG. 1

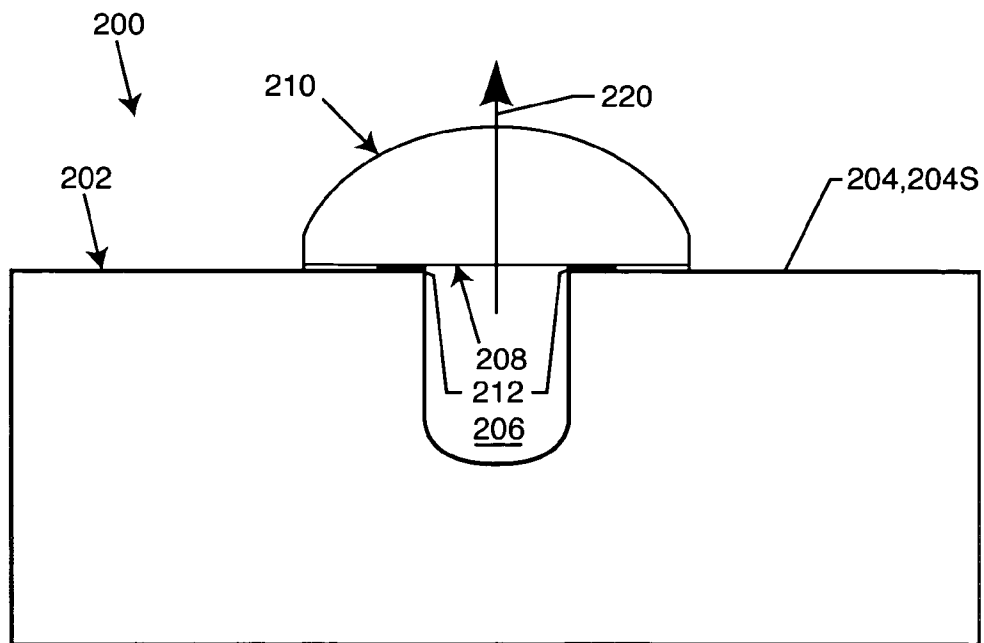


FIG. 2

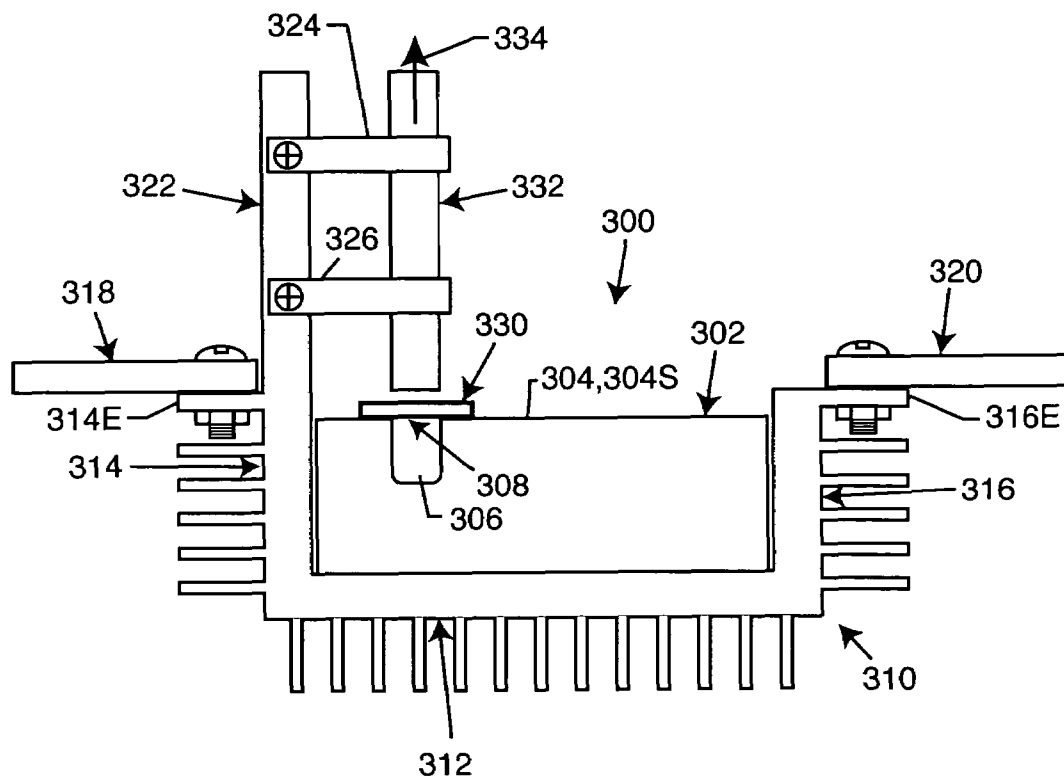


FIG. 3

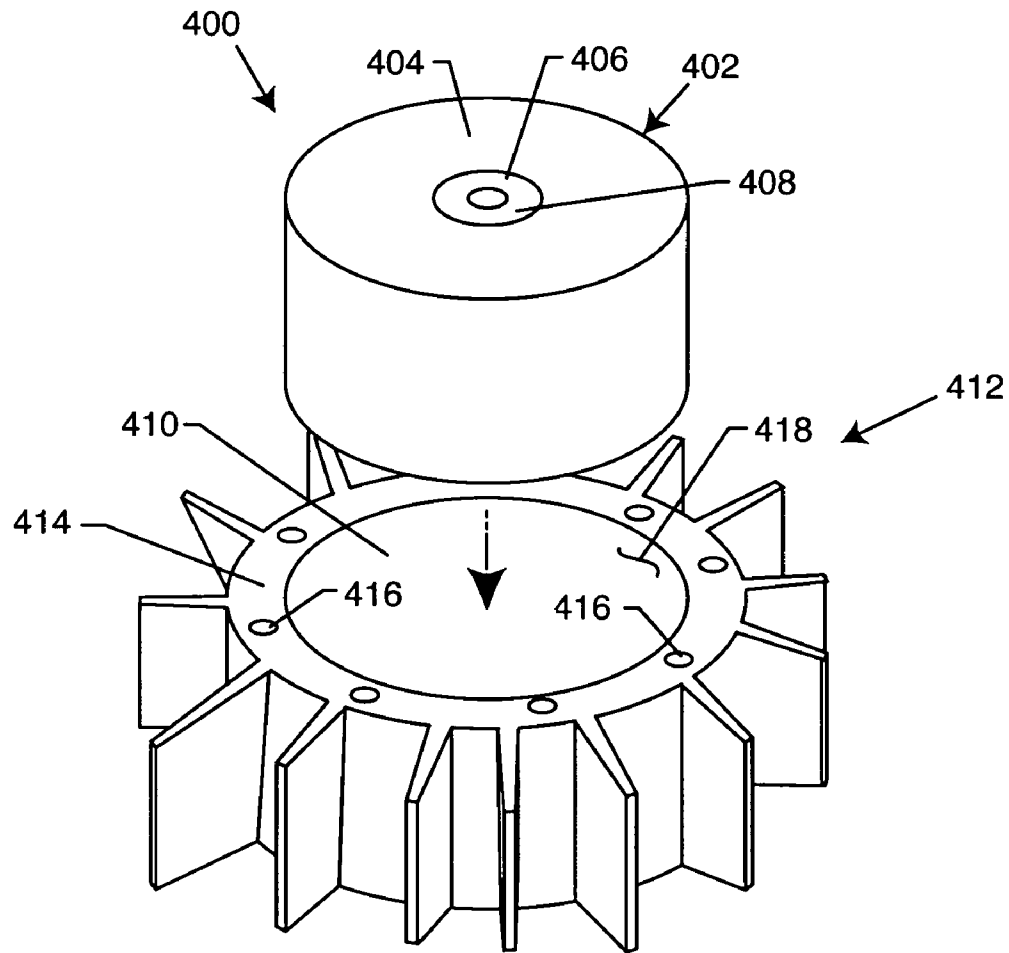


FIG. 4

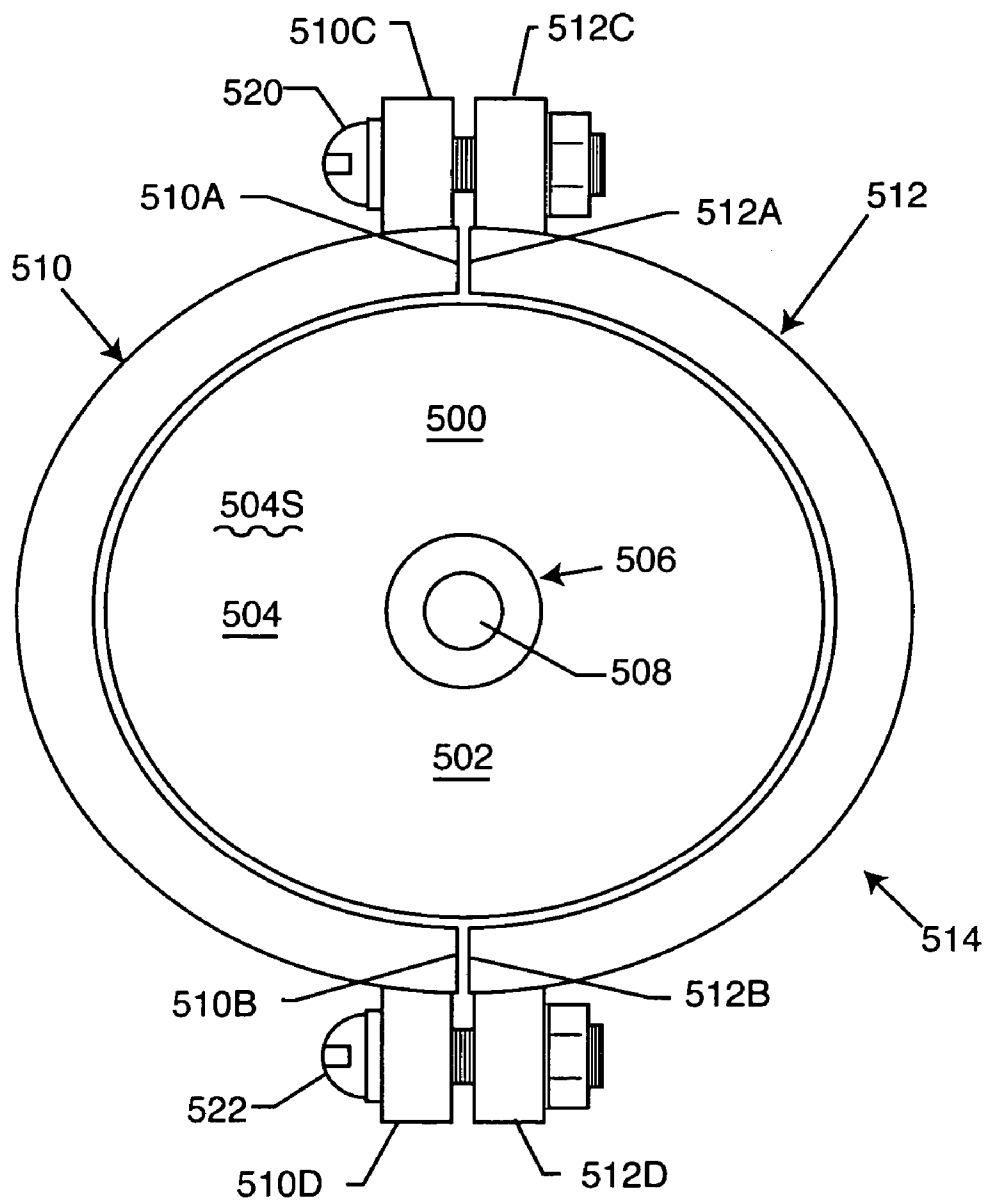


FIG. 5

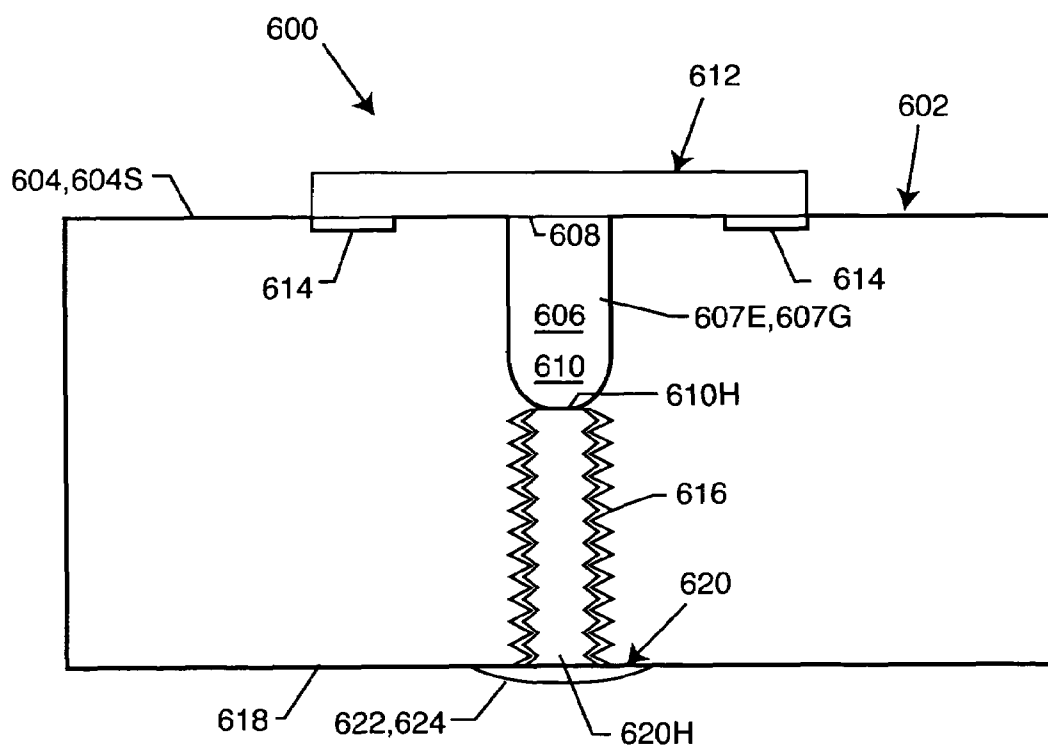


FIG. 6

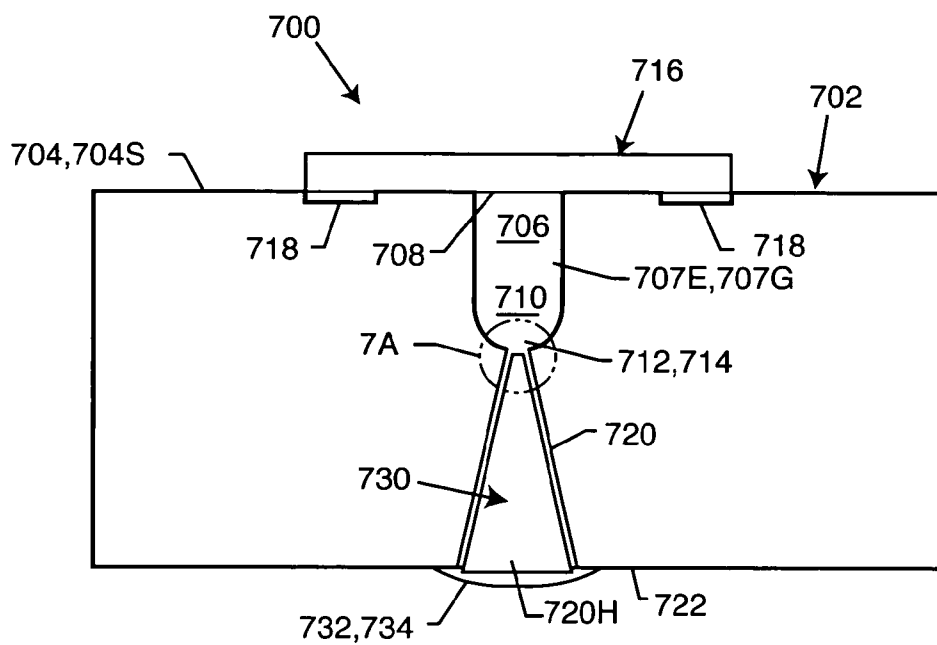


FIG. 7

FIG. 7A

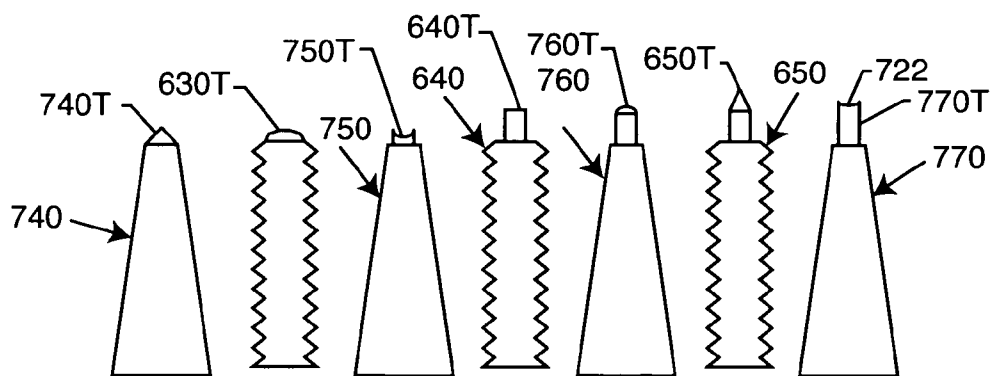
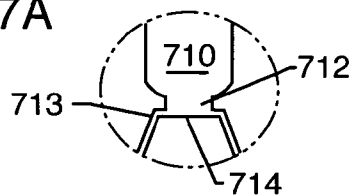


FIG. 8

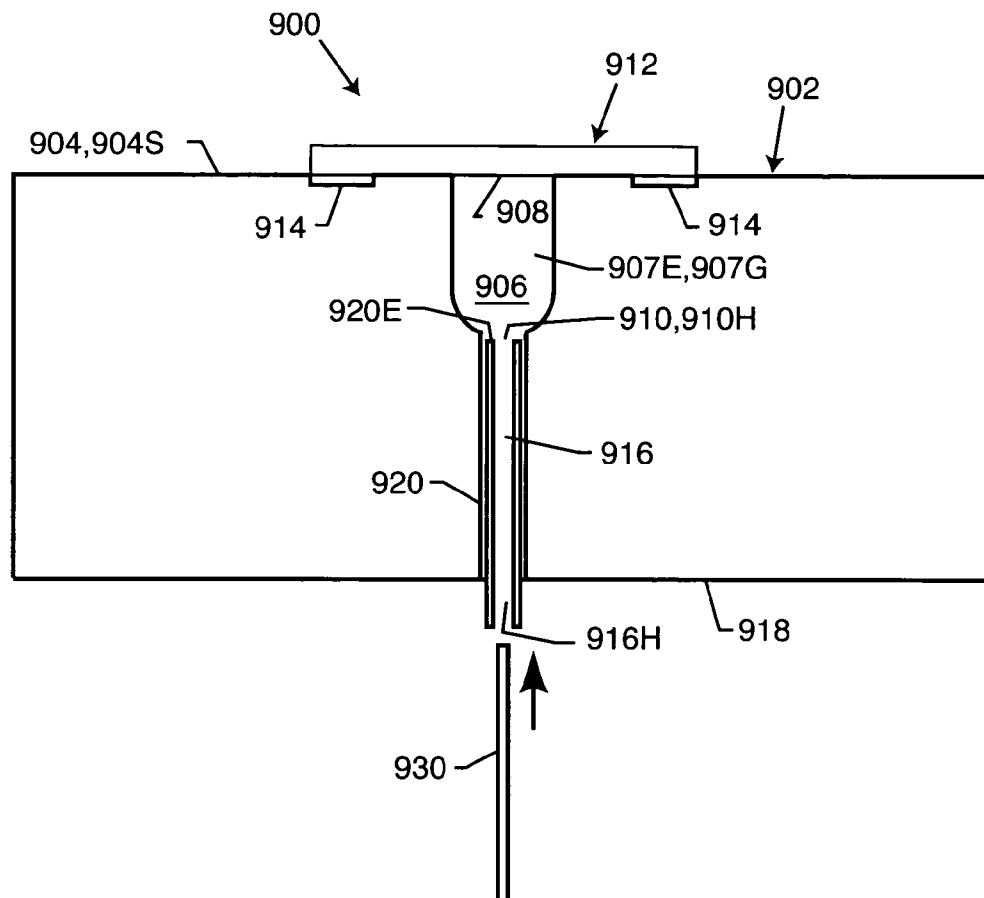


FIG. 9

FIG. 10

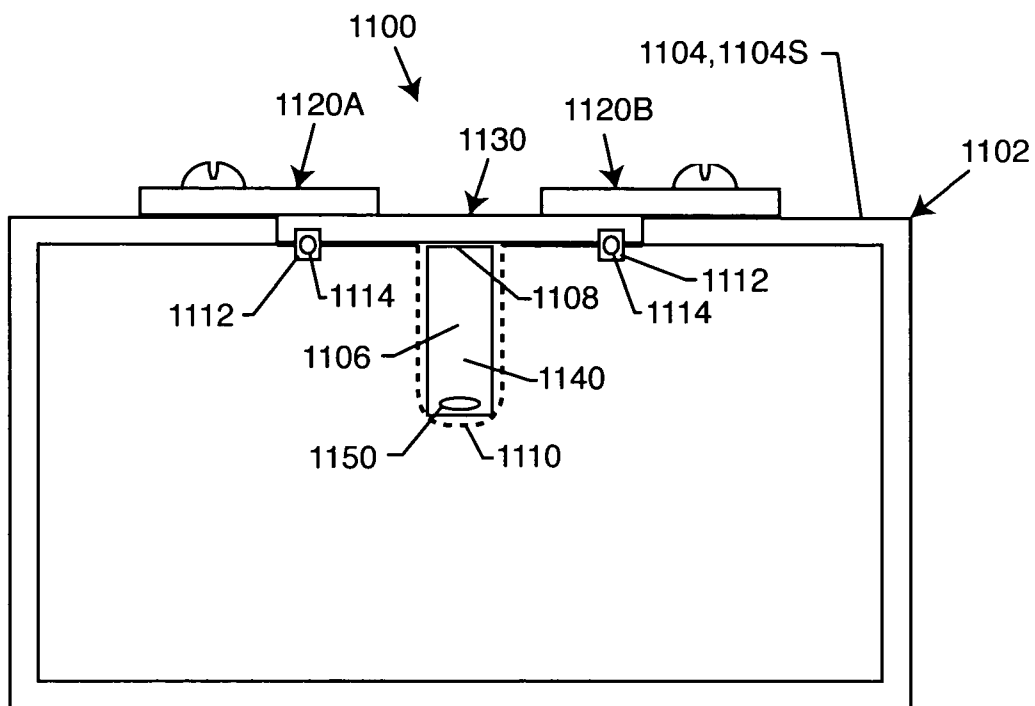


FIG. 11

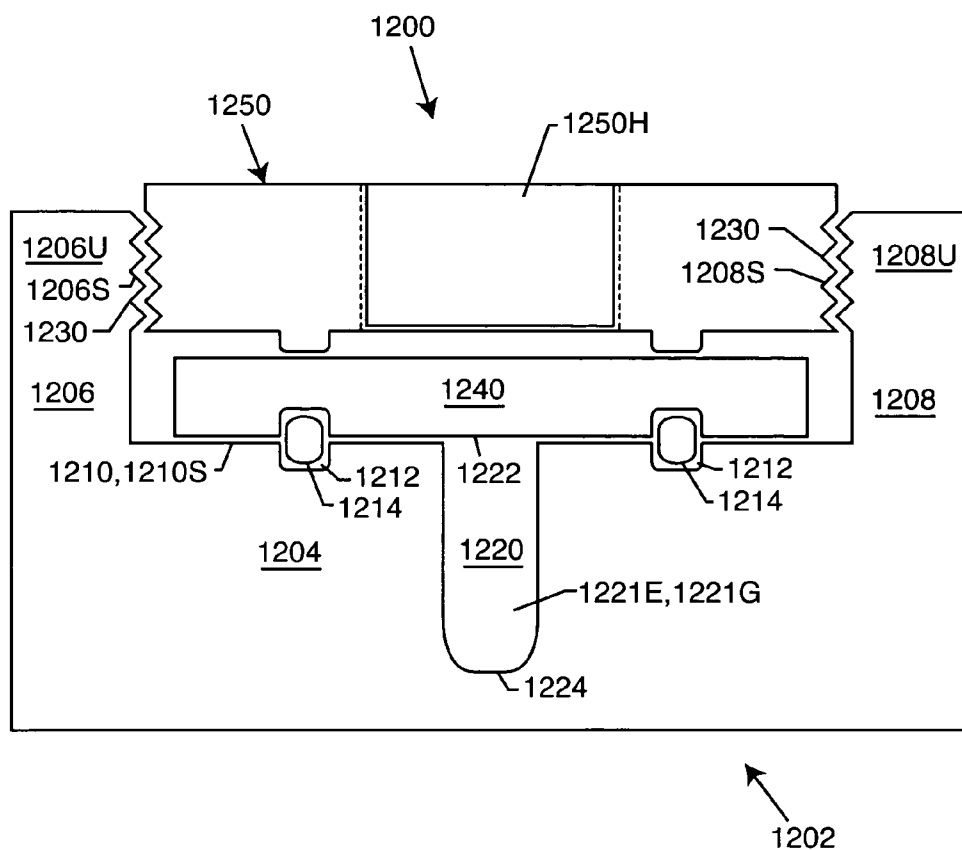


FIG. 12

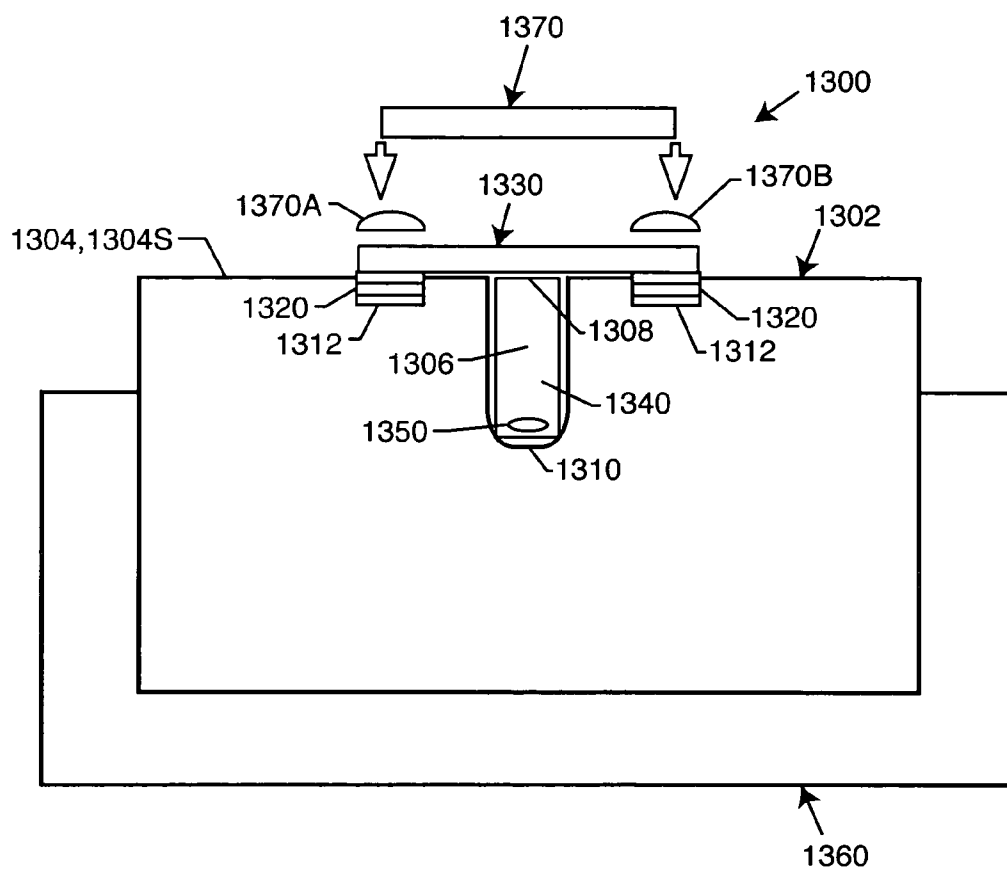


FIG. 13

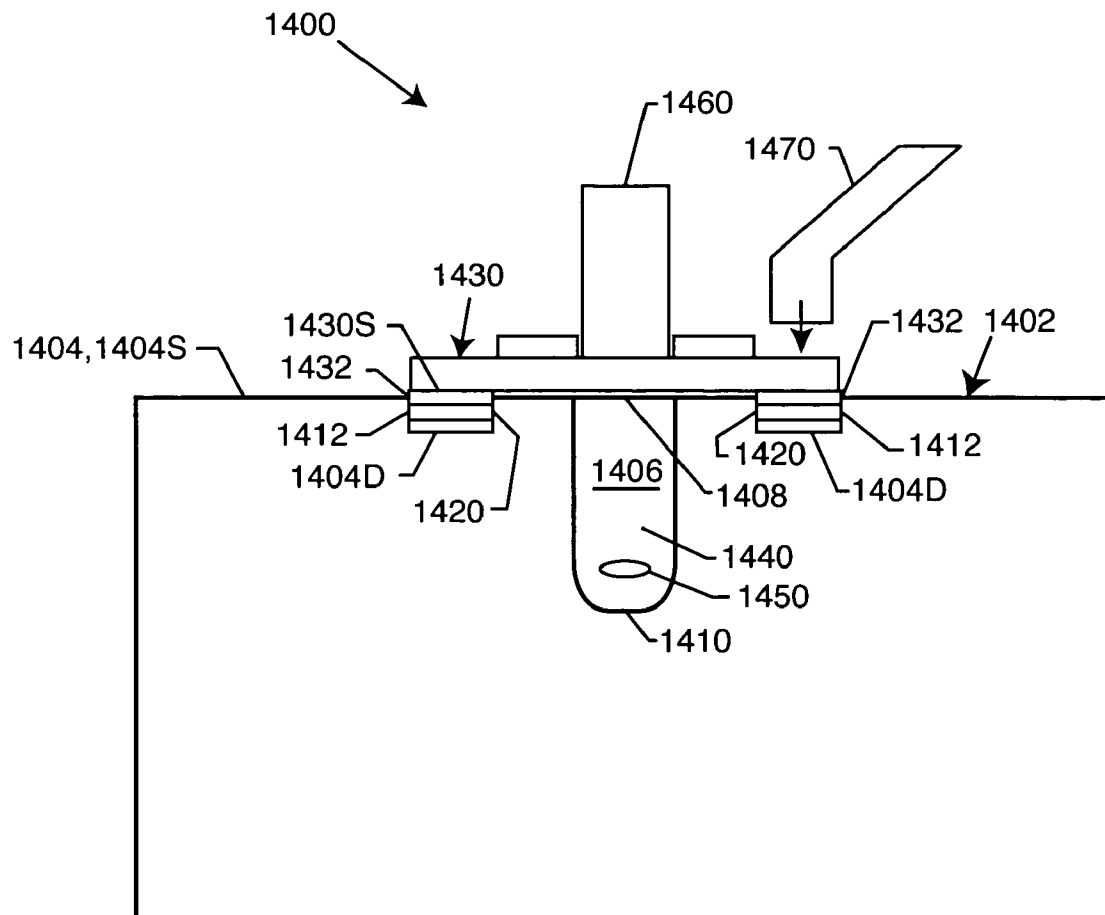


FIG. 14

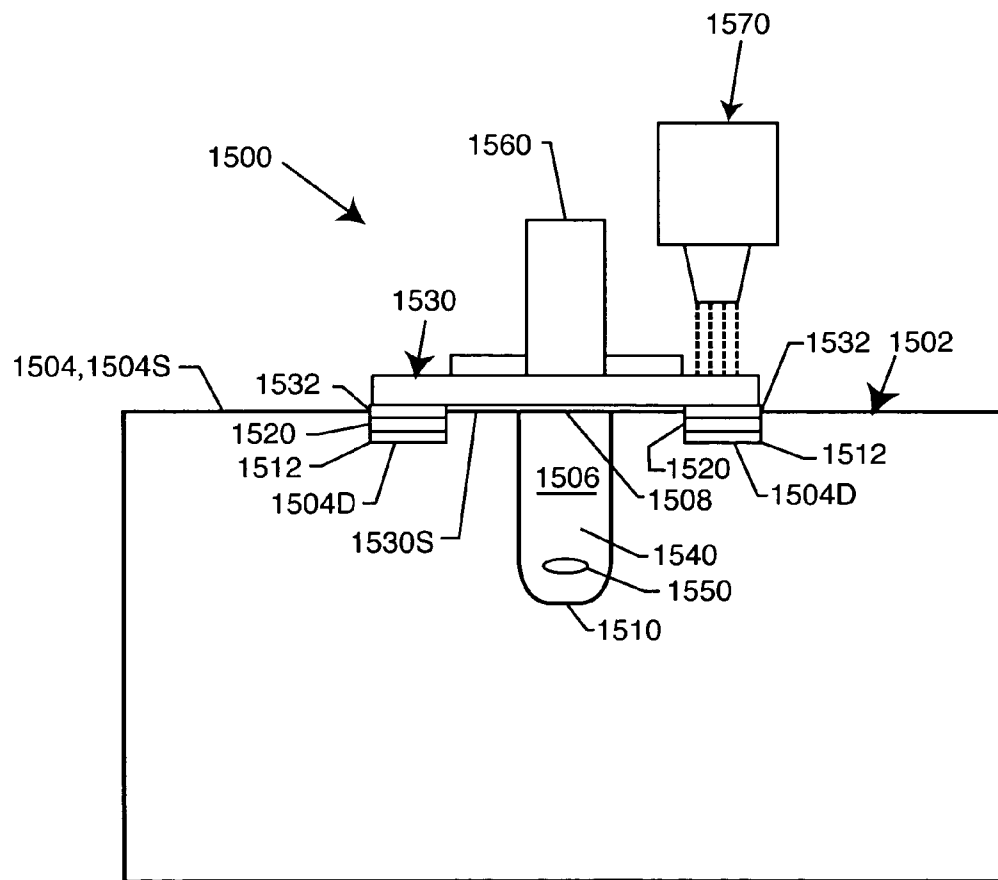


FIG. 15

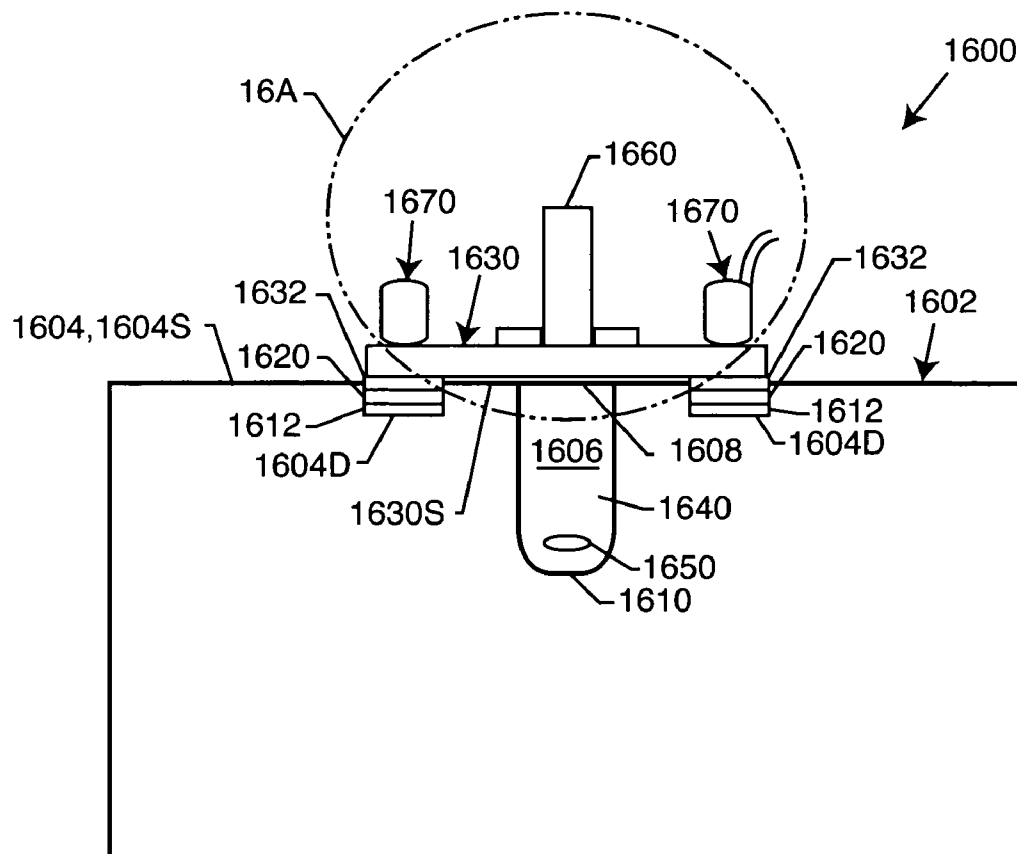


FIG. 16

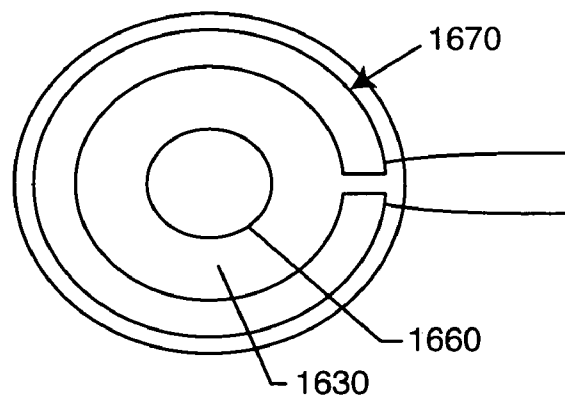


FIG. 16A

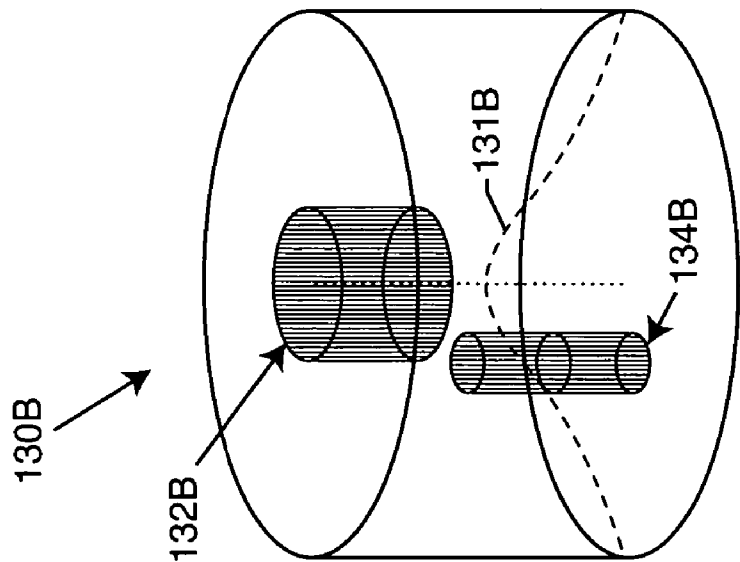


FIG. 17B

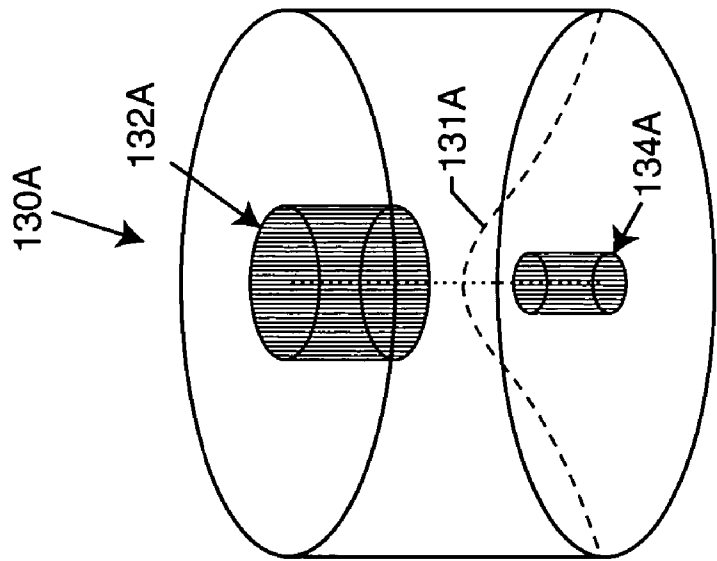


FIG. 17A

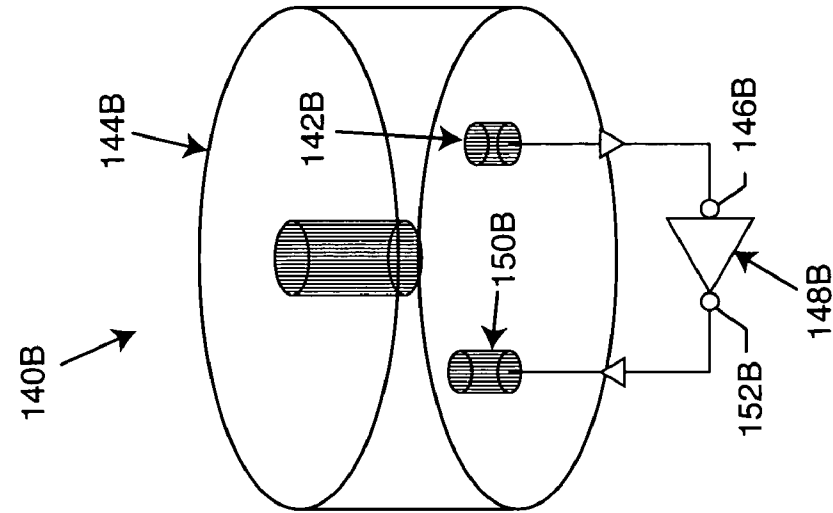


FIG. 18A

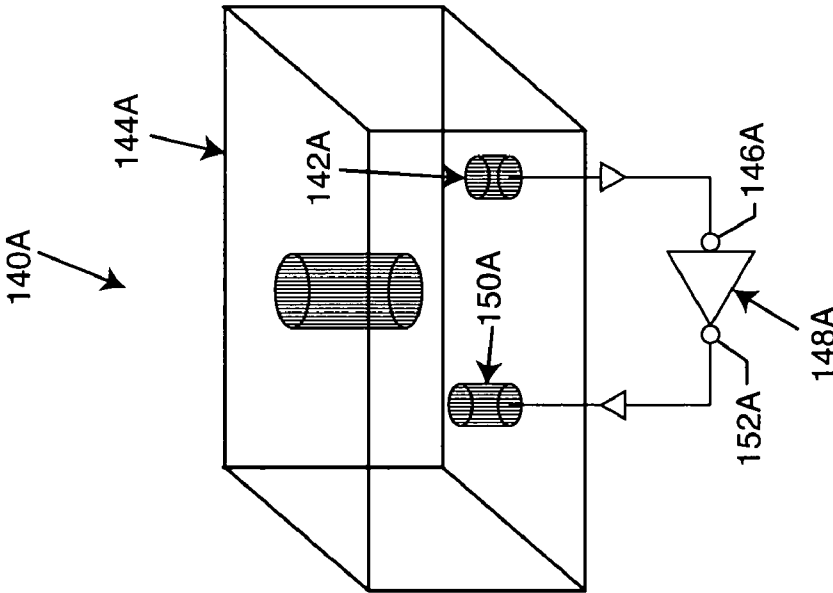


FIG. 18B

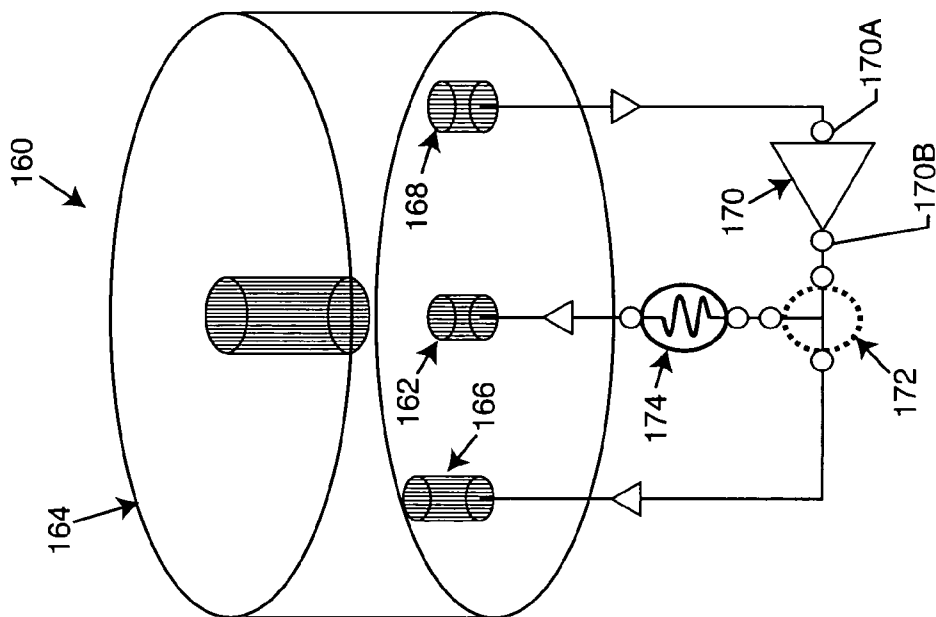


FIG. 19

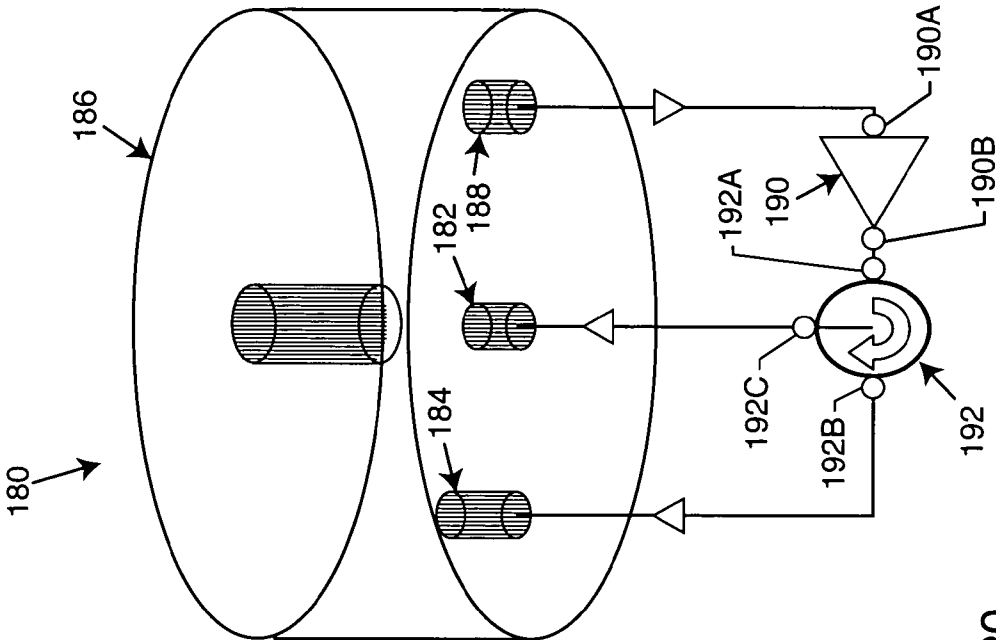


FIG. 20

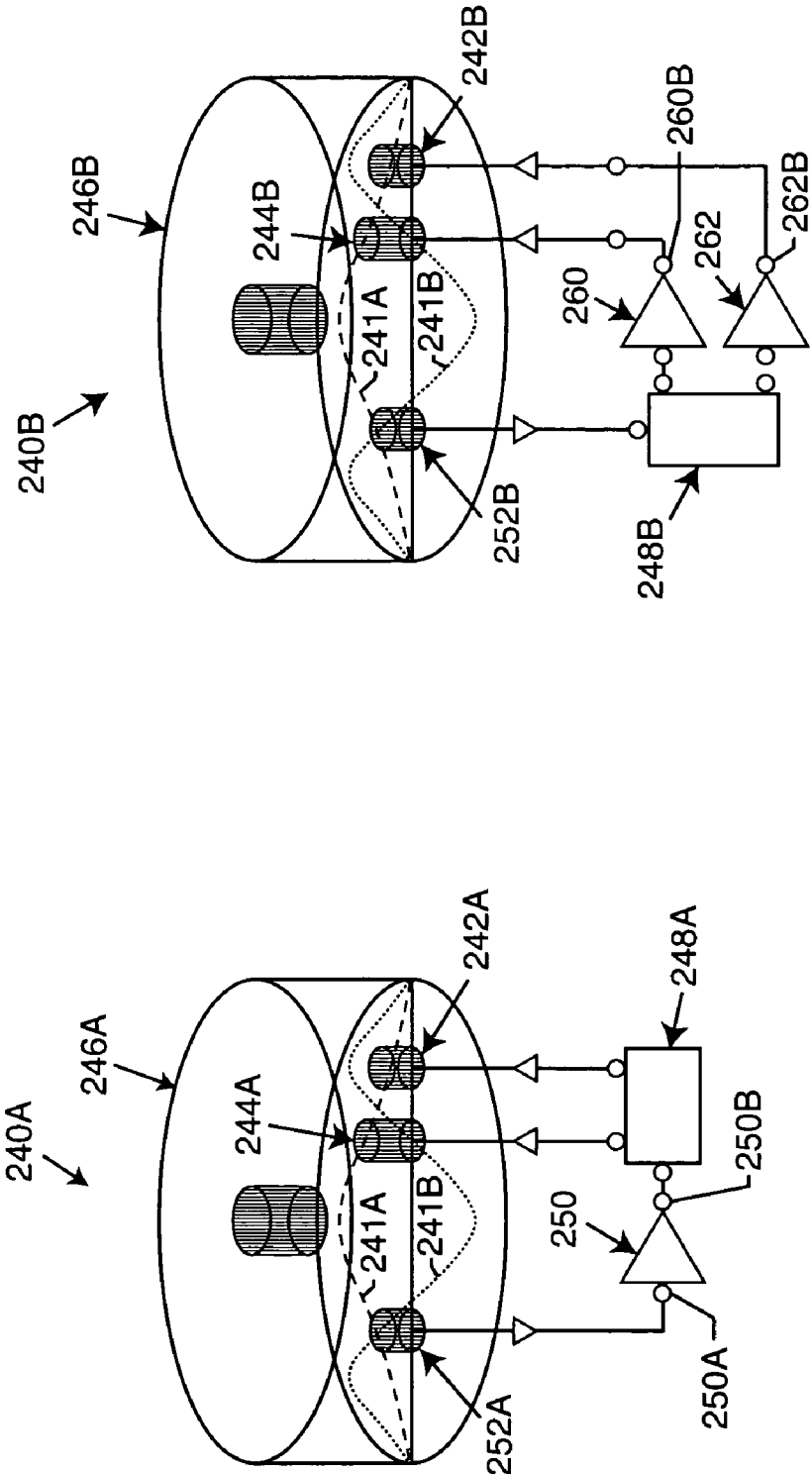


FIG. 21A

FIG. 21B

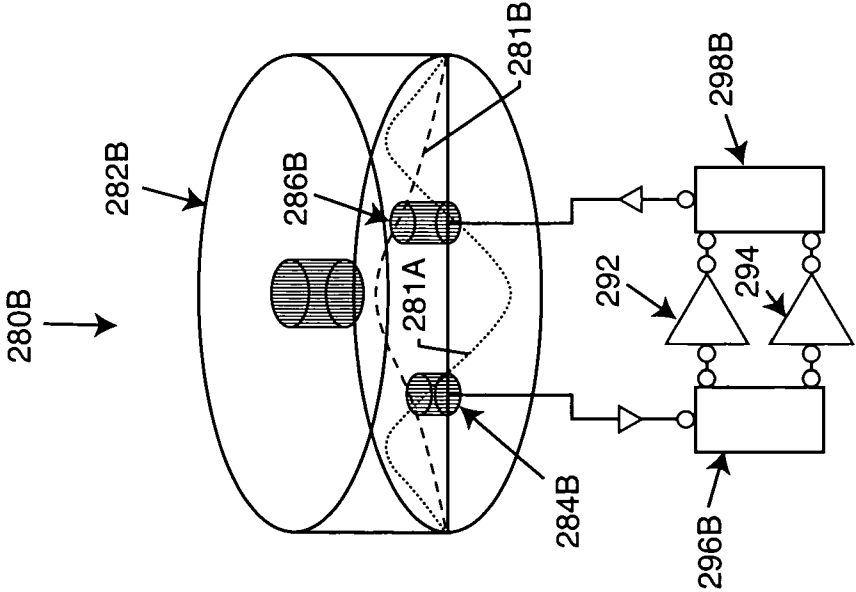


FIG. 22A

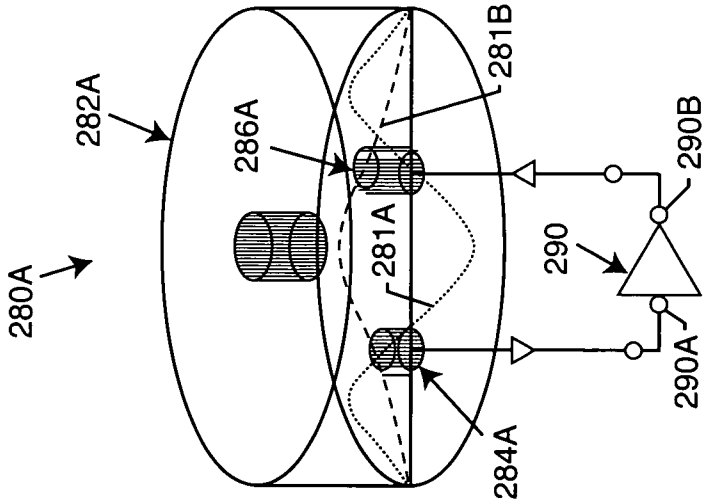


FIG. 22B

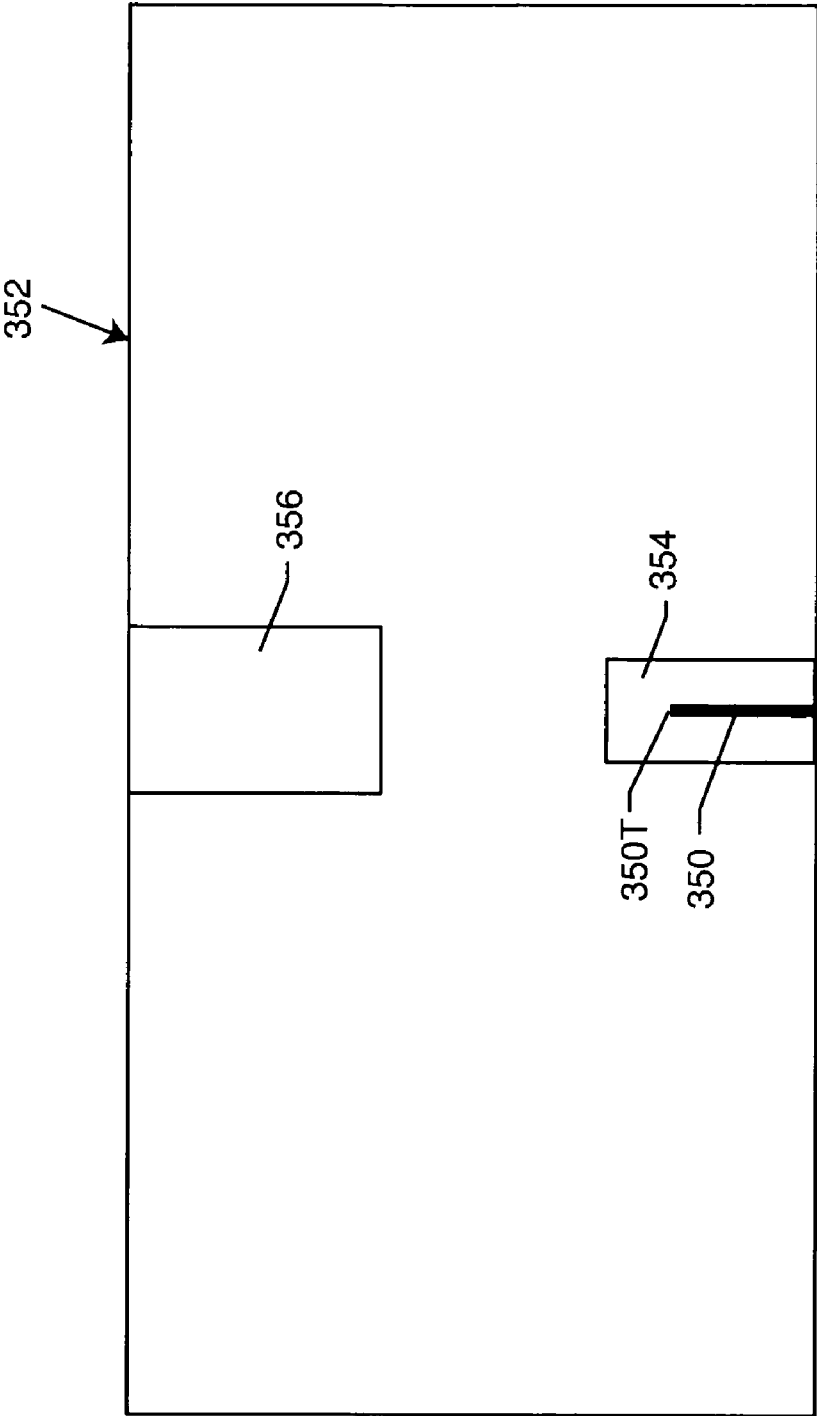


FIG. 23

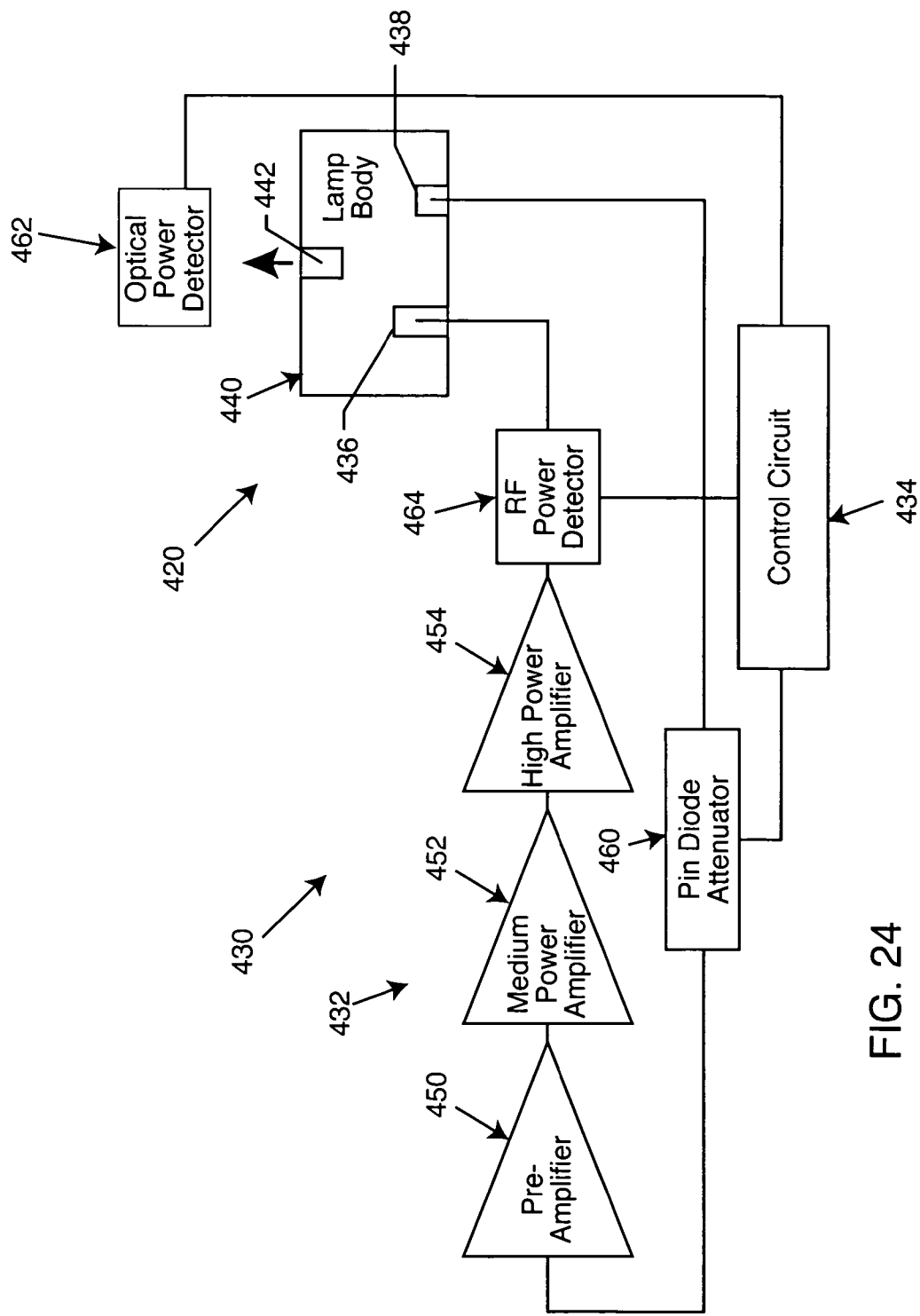


FIG. 24

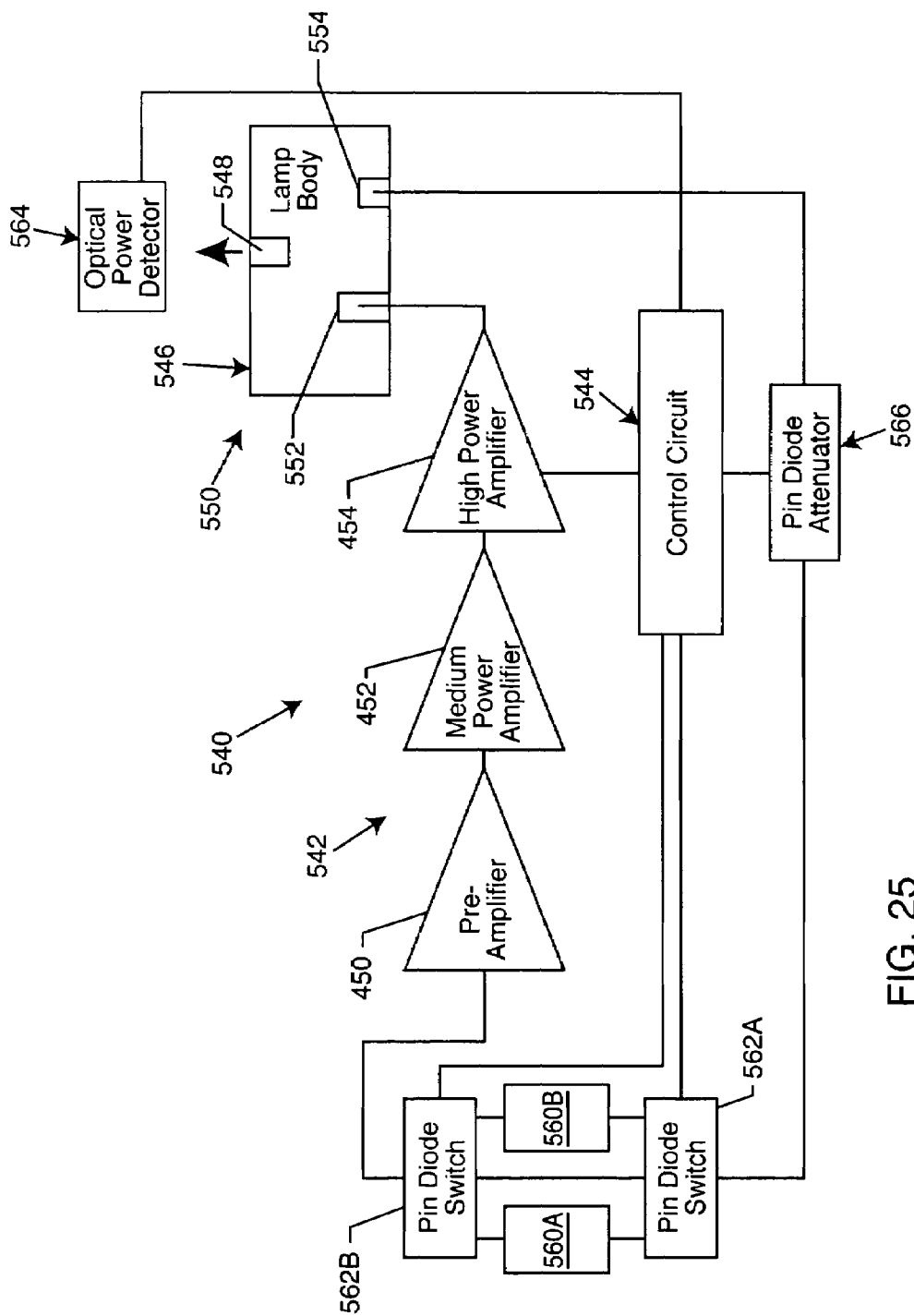


FIG. 25

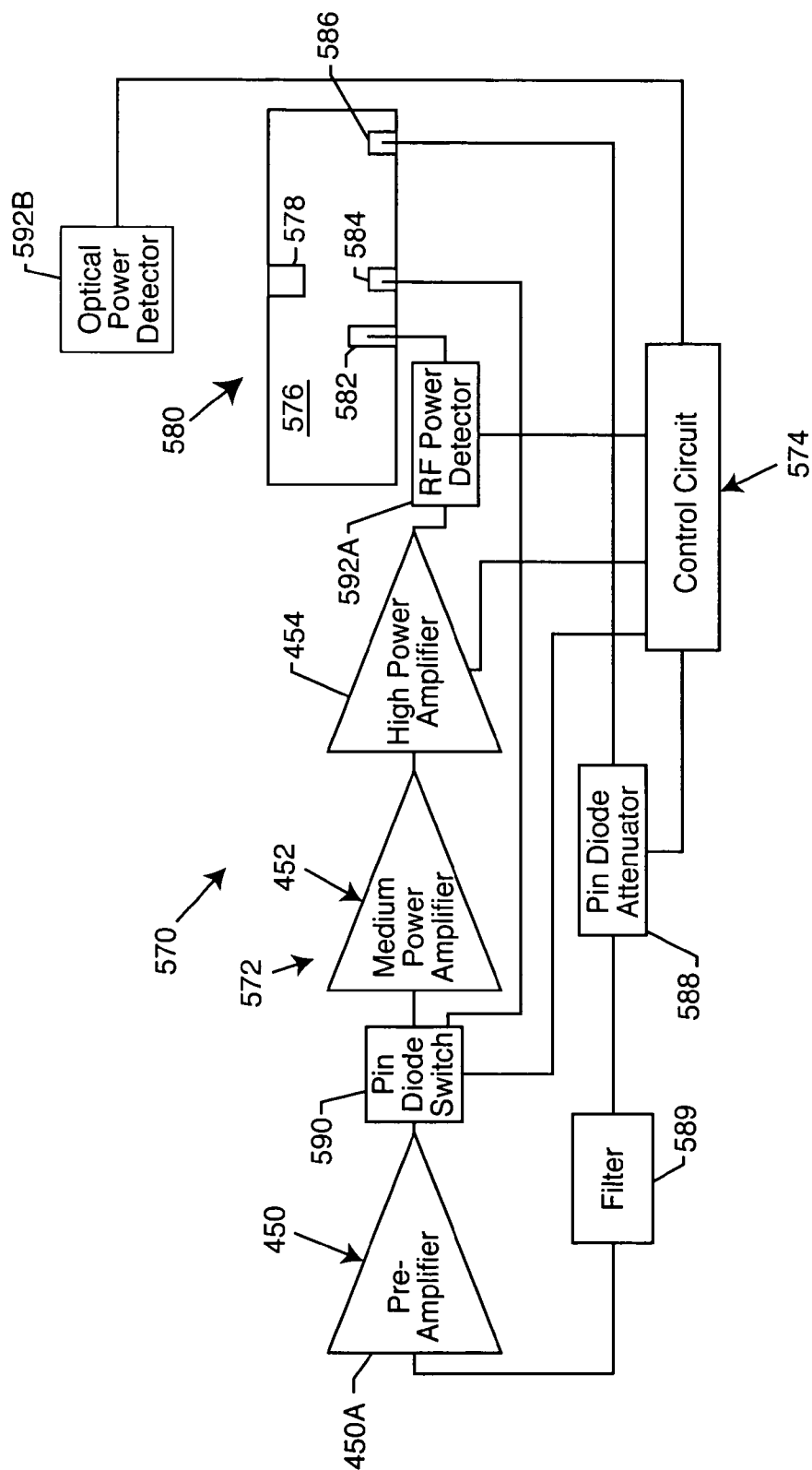


FIG. 26

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# MICROWAVE ENERGIZED PLASMA LAMP WITH DIELECTRIC WAVEGUIDE

## CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of application Ser. No. 10/356,340 filed on Jan. 31, 2003 now U.S. Pat. No. 6,922,021 and entitled "Microwave Energized Plasma Lamp With Dielectric Waveguide," which is a continuation-in-part of application Ser. No. 09/809,718 ("718"), filed on Mar. 15, 2001 and issued as U.S. Pat. No. 6,737,809 B2 and entitled "Plasma Lamp With Dielectric Waveguide", which claimed benefit of priority of provisional patent application Ser. No. 60/222,028, filed on Jul. 31, 2000 and entitled "Plasma Lamp". Application Ser. Nos. 09/809,718 and 60/222,028 are incorporated herein in their entirety by this reference.

## BACKGROUND OF THE INVENTION

### 1. Field of the Invention

This invention relates to devices and methods for generating light, and more particularly to electrodeless plasma lamps energized by microwave radiation. Rather than using a waveguide with an air-filled resonant cavity, embodiments of the invention use a waveguide having a body including at least one dielectric material with a dielectric constant greater than approximately 2. Such dielectric materials include solid materials such as ceramics, and liquid materials such as silicone oil. The body is integrated with at least one lamp chamber containing a bulb.

### 2. Description of the Related Art

Electrodeless plasma lamps provide point-like, bright, white light sources. Because electrodes are not used, they often have longer useful lifetimes than other lamps. Electrodeless lamps wherein microwave energy is directed into an air-filled waveguide enclosing or otherwise coupled to a bulb containing a mixture of substances that when ignited form a light-emitting plasma include: European Pat. App. EP 0 035 898 to Yoshizawa et al.; and U.S. Pat. No. 4,954,755 to Lynch et al., U.S. Pat. No. 4,975,625 to Lynch et al., U.S. Pat. No. 4,978,891 to Ury et al., U.S. Pat. No. 5,021,704 to Walter et al., U.S. Pat. No. 5,448,135 to Simpson, U.S. Pat. No. 5,594,303 to Simpson, U.S. Pat. No. 5,841,242 to Simpson et al., U.S. Pat. No. 5,910,710 to Simpson, and U.S. Pat. No. 6,031,333 to Simpson. U.S. Pat. No. 6,617,806 B2 to Kirkpatrick et al. discloses a plasma lamp having a cylindrical, metallic resonant cavity containing solid dielectric material allowing a reduction in cavity size.

## SUMMARY OF THE INVENTION

In a first aspect the present invention provides a lamp including a waveguide having a body including at least one dielectric material with a dielectric constant greater than approximately 2. A first microwave probe positioned within the body and connected to the source output couples power into the body from a microwave source operating at a frequency such that the body resonates in at least one resonant mode having at least one electric field maximum. The body has at least one lamp chamber depending from a waveguide outer surface and having an aperture at that surface. The body and lamp chamber(s) form an integrated structure. Each chamber contains a fill mixture including a starting gas and a light emitter, which when receiving power provided by the resonating body forms a light-emitting

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plasma. Using a second probe or second and third probes positioned within the body, the invention provides means for minimizing power reflected back to the source when: (a) the source operates at a frequency such that the body resonates in a single resonant mode; or (b) the source operates at one frequency such that the body resonates in a relatively higher order resonant mode before a plasma is formed in each chamber, and at another frequency such that the body resonates in a relatively lower resonant mode after the plasma reaches steady state. The invention further provides alternative means for depositing the starting gas and light emitter within lamp chambers, and alternative means for sealing chamber apertures to the environment while allowing light transmission.

In a second aspect the invention provides a lamp including a waveguide having a body including at least one dielectric material with a dielectric constant greater than approximately 2. A first microwave probe positioned within the body is connected to an output of a source of microwave power operable at at least one frequency such that the body resonates in at least one resonant mode having at least one electric field maximum. A second microwave probe, positioned within the body, is connected to a source input. At least one lamp chamber, integrated with the body, contains a fill mixture which when receiving power provided by the resonating body forms a light-emitting plasma. The lamp further includes means for minimizing power reflected from the body back to the source.

In a third aspect the invention provides a lamp including a waveguide having a body including at least one dielectric material with a dielectric constant greater than approximately 2. A first microwave probe positioned within the body is connected to an output of a source of microwave power operable at at least one frequency such that the body resonates in at least one resonant mode having at least one electric field maximum. A second microwave probe, positioned within the body, is connected to a source input. A third microwave probe is connected to the source output. At least one lamp chamber, integrated with the body, contains a fill mixture which when receiving power provided by the resonating body forms a light-emitting plasma. The lamp further includes means for minimizing power reflected from the body back to the source.

A more complete understanding of the present invention and other aspects and advantages thereof will be gained from a consideration of the following description of the preferred embodiments read in conjunction with the accompanying drawing figures provided herein. In the figures and description, numerals indicate the various features of the invention, like numerals referring to like features throughout both the drawings and description.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1, which is FIG. 1 of the '718 application, shows a sectional view of a DWIPL including a waveguide having a body consisting essentially of a solid dielectric material, integrated with a bulb containing a light-emitting plasma.

FIG. 2 schematically depicts a DWIPL having a body with a lamp chamber enclosed and sealed by a ball lens.

FIG. 3 schematically depicts a DWIPL having a body with a lamp chamber enclosed and sealed by a window or lens aligned with an optical element attached to brackets attached to a flange extending from a heatsink surrounding the body.

FIG. 4 schematically depicts a DWIPL having a cylindrical body attached to a cylindrical heatsink with a bore which closely receives the body.

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FIG. 5 schematically depicts a DWIPL having a cylindrical body enclosed within a “clamshell”-type heatsink.

FIG. 6 schematically depicts a DWIPL having a body with a tapped bore extending between a body side opposed to a side having a lamp chamber aperture, and the chamber bottom. A fill, including a starting gas and light emitter, in the chamber is sealed by a window over the aperture and a plug screwed into the bore.

FIG. 7 schematically depicts the FIG. 6 DWIPL wherein the bore is tapered and a tapered plug is press-fitted into the bore.

FIG. 7A is a detail view of the circled region “7A” in FIG. 7, showing the plug tip and chamber bottom.

FIG. 8 shows first, second and third plug configurations for the FIG. 6 DWIPL, and first, second, third and fourth plug configurations for the FIG. 7 DWIPL.

FIG. 9 schematically depicts a DWIPL having a body with a narrow cylindrical bore with a glass or quartz tube inserted therein, extending between a body side opposed to a side having a lamp chamber aperture, and the chamber bottom. Fill in the chamber is sealed by a window over the aperture and a glass or quartz rod inserted into the tube.

FIG. 10 schematically depicts a DWIPL having a body with a side having a lamp chamber aperture covered by a window. Fill in the chamber is sealed by a glass or quartz rod inserted into a glass or quartz tube inserted into a hole in the side in communication with a hole in a chamber wall.

FIG. 11 schematically depicts a DWIPL having a body with a side having a lamp chamber aperture circumscribed by a groove in which is disposed an O-ring. Fill in the chamber is sealed by a window maintained in pressing contact with the O-ring by a clamping mechanism.

FIG. 12 schematically depicts a DWIPL having a “U”-shaped body with a surface having a lamp chamber aperture circumscribed by a groove in which is disposed an O-ring. Fill in the chamber is sealed by a window maintained in pressing contact with the O-ring by a screw cap.

FIG. 13 schematically depicts a DWIPL having a body with a side having a lamp chamber aperture circumscribed by a preformed seal. Fill in the chamber is sealed by a heated window which melts the seal when the window is brought into pressing contact with the seal by a hot mandrel.

FIG. 14 schematically depicts a DWIPL having a body with a side having a lamp chamber aperture circumscribed by an attached first metallization ring and a preformed seal. Fill in the chamber is sealed when a second metallization ring attached to a window is brought into pressing contact the first ring by a clamp and heat is applied to melt the preformed seal.

FIG. 15 schematically depicts the FIG. 14 DWIPL wherein a laser is used to melt the preformed seal.

FIG. 16 schematically depicts the FIG. 14 DWIPL wherein the melting of the preformed seal results from inductive heating by an RF coil.

FIG. 16A is a top plan view of the FIG. 16 DWIPL.

FIG. 17A schematically depicts a DWIPL having a cylindrical body wherein a bulb and a drive probe are located at the electric field maximum of a resonant mode.

FIG. 17B schematically depicts the FIG. 17A DWIPL wherein the bulb is located at the electric field maximum of the FIG. 17A resonant mode, and a drive probe is offset from the maximum. The FIG. 17B probe is longer than the FIG. 17A probe to compensate for coupling loss due to the offset.

FIG. 18A schematically depicts a DWIPL having a rectangular prism-shaped body wherein are disposed a bulb, and a drive probe and a feedback probe connected by a combined amplifier and control circuit.

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FIG. 18B schematically depicts a DWIPL having a cylindrical body wherein are disposed a bulb, and a drive probe and a feedback probe connected by a combined amplifier and control circuit.

FIG. 19 schematically depicts a first embodiment of a DWIPL utilizing a start probe. The DWIPL has a cylindrical body wherein are disposed a bulb, a drive probe, a feedback probe, and the start probe. The feedback probe is connected to the drive probe by a combined amplifier and control circuit, and a splitter, and is connected to the start probe by the amplifier and control circuit, the splitter, and a phase shifter.

FIG. 20 schematically depicts a second embodiment of a DWIPL utilizing a start probe. The DWIPL has a cylindrical body wherein are disposed a bulb, a drive probe, a feedback probe, and the start probe. The feedback probe is connected to the drive probe and the start probe by a combined amplifier and control circuit, and a circulator.

FIG. 21A schematically depicts a third embodiment of a DWIPL utilizing a start probe. The DWIPL has a cylindrical body wherein are disposed a bulb, a drive probe, a feedback probe, and the start probe. The feedback probe is connected to the drive probe and the start probe by a combined amplifier and control circuit, and a diplexer.

FIG. 21B schematically depicts an alternative configuration of the FIG. 21A embodiment wherein the feedback probe is connected to the drive probe by a diplexer and a first combined amplifier and control circuit, and to the start probe by the diplexer and a second combined amplifier and control circuit.

FIG. 22A schematically depicts a DWIPL wherein a start resonant mode is used before plasma formation and a drive resonant mode is used to power the plasma to steady state. The DWIPL has a cylindrical body wherein are disposed a bulb, a drive probe, and a feedback probe. A combined amplifier and control circuit connects the drive and feedback probes.

FIG. 22B schematically depicts an alternative configuration of the FIG. 22A embodiment wherein the feedback probe is connected to the drive probe by first and second diplexers and first and second combined amplifiers and control circuits.

FIG. 23 schematically depicts a DWIPL having a body with a high dielectric constant. A drive probe extending into the body is surrounded by a dielectric material having a high breakdown voltage.

FIG. 24 is a block diagram of a first configuration of the FIGS. 18A, 18B, 22A and 22B combined amplifier and control circuit.

FIG. 25 is a block diagram of a second configuration of the FIGS. 18A, 18B, 22A and 22B combined amplifier and control circuit.

FIG. 26 is a block diagram of a configuration of the FIGS. 19, 20, 21A and 21B combined amplifier and control circuit.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

While the present invention is open to various modifications and alternative constructions, the preferred embodiments shown in the drawings will be described herein in detail. It is to be understood, however, there is no intention to limit the invention to the particular forms disclosed. On the contrary, it is intended that the invention cover all modifications, equivalences and alternative constructions falling within the spirit and scope of the invention as expressed in the appended claims.

As used herein, the terms “dielectric waveguide integrated plasma lamp”, “DWIPL”, “microwave energized plasma lamp with solid dielectric waveguide”, and “lamp” are synonymous, and the term “lamp body” is synonymous with “waveguide body”. The term “probe” herein is synonymous with “feed” in the '718 application. The term “power”, i.e., energy per unit time, is used herein rather than “energy” as in the '718 application. The terms “lamp chamber” and “hole” herein are synonymous with “cavity” in the '718 application, and are used in describing construction details, such as seals and materials, of the several DWIPL embodiments disclosed. A “lamp chamber” is defined herein as a receptacle, i.e., hole, in a waveguide body having an aperture in a body surface which typically is coplanar with a waveguide surface exposed to the environment. The term “bulb” denotes (A) a self-enclosed, discrete structure containing a fill mixture and positioned within a lamp chamber; or (B) a “bulb envelope,” viz., a chamber containing a fill mixture and sealed from the environment by a window or lens. As used here, the term “fill” is synonymous with “fill mixture.” The term “self-enclosed bulb” is specific to meaning (A). The term “cavity” is used herein when describing microwave technology-related details such as probe design, coupling and resonant modes. This change in terminology was made because from an electromagnetic point of view a DWIPL body is a resonant cavity.

FIG. 1, copied from the '718 application, shows a “baseline” embodiment of a dielectric waveguide integrated plasma lamp to which the embodiments disclosed herein may be compared. DWIPL 101 includes a source 115 of microwave radiation, a waveguide 103 having a body 104 consisting essentially of a solid dielectric material, and a drive probe 117 coupling the source 115 to the waveguide, which is in the shape of a rectangular prism determined by opposed sides 103A, 103B, and opposed sides 103C, 103D generally transverse to sides 103A, 103B. DWIPL 101 further includes a bulb 107 of the (B) variety, disposed proximate to side 103A and preferably generally opposed to probe 117, containing a fill 108 including a “starting” gas 108G, such as a noble gas, and a light emitter 108E, which when receiving microwave power at a predetermined operating frequency and intensity forms a plasma and emits light. Source 115 provides microwave power to waveguide 103 via probe 117. The waveguide contains and guides the energy flow to an enclosed lamp chamber 105, depending from side 103A into body 104, in which bulb 107 is disposed. This energy flow frees electrons from the starting gas atoms, thereby creating a plasma. In many cases the light emitter is solid at room temperature. It may contain any one of a number of elements or compounds known in the art, such as sulfur, selenium, a compound containing sulfur or selenium, or a metal halide such as indium bromide. The starting plasma vaporizes the light emitter, and the microwave powered free electrons excite the light emitter electrons to higher energy levels. De-excitation of the light emitter electrons results in light emission. Use of a starting gas in combination with a solid light emitter is not a necessity; a gas fill alone, such as xenon, can be used to start the plasma and to emit light. The preferred operating frequency range for source 115 is from about 0.5 GHz to about 10 GHz. However, operating frequencies as low as about 0.25 GHz and as high as about 30 GHz are feasible. Source 115 may be thermally isolated from bulb 107 which during operation typically reaches temperatures between about 700° C. and about 1000° C., thus avoiding degradation of the source due to heating. Preferably, the waveguide body provides a substantial thermal mass which aids efficient

distribution and dissipation of heat and provides thermal isolation between the lamp and source. Additional thermal isolation of the source may be accomplished by using an insulating material or vacuum gap occupying an optional space 116 between source 115 and waveguide 103. When the space 116 is included, appropriate microwave probes are used to couple the source to the waveguide.

Due to mechanical and other considerations such as heat, vibration, aging and shock, contact between the probe 117 and waveguide 103 preferably is maintained using a positive contact mechanism 121, shown in FIG. 1 as a spring loaded device. The mechanism provides a constant pressure by the probe on the waveguide to minimize the possibility that microwave power will be reflected back through the probe rather than entering the waveguide. In providing constant pressure, the mechanism compensates for small dimensional changes in the probe and waveguide that may occur due to thermal heating or mechanical shock. Preferably, contact is made by depositing a metallic material 123 directly on the waveguide at its point of contact with probe 117 so as to eliminate gaps that may disturb the coupling.

Sides 103A, 103B, 103C, 103D of waveguide 103, with the exception of those surfaces depending from side 103A into body 104 which form lamp chamber 105, are coated with a thin metallic coating 119 which reflects microwaves in the operating frequency range. The overall reflectivity of the coating determines the level of energy within the waveguide. The more energy that can be stored within the waveguide, the greater the lamp efficiency. Preferably, coating 119 also suppresses evanescent radiation leakage and significantly attenuates any stray microwave field(s). Bulb 107 includes an outer wall 109 having an inner surface 110, and a window 111. Alternatively, the lamp chamber wall acts as the bulb outer wall. The components of bulb 107 preferably include at least one dielectric material, such as a ceramic or sapphire. The ceramic in the bulb may be the same as the material used in body 104. Dielectric materials are preferred for bulb 107 because the bulb preferably is surrounded by the body 104, and the dielectric materials facilitate efficient coupling of microwave power with the fill 108 in the bulb. Outer wall 109 is coupled to window 111 using a seal 113, thereby determining a bulb envelope 127 which contains the fill. To confine the fill within the bulb, seal 113 preferably is a hermetic seal. Outer wall 109 preferably includes alumina because of its white color, temperature stability, low porosity, and low coefficient of thermal expansion. Preferably, inner surface 110 of outer wall 109 is contoured to maximize the amount of light reflected out of cavity 105 through window 111. Preferably, window 111 includes sapphire which has high light transmissivity and a coefficient of thermal expansion which matches well with that of alumina. Window 111 may include a lens to collect and focus the emitted light. During operation when bulb 107 may reach temperatures of up to about 1000° C., body 104 acts as a heatsink for the bulb. Effective heat dissipation is achieved by attaching a plurality of heat-sinking fins 125 to sides 103A, 103C and 103D.

When the waveguide body 104 consists essentially of a dielectric material which generally is unstable at high temperature, such as a titanate, waveguide 103 may be shielded from the heat generated in bulb 107 by interposing a thermal barrier between the body and bulb. Alternatively, outer wall 109 includes a material with low thermal conductivity, such as an NZP ( $\text{NaZr}_2(\text{PO}_4)_3$ ) ceramic which acts as a thermal barrier.

Although FIG. 1 shows waveguide 103 in the shape of a rectangular prism, a waveguide according to the invention

disclosed in the '718 application may be in the shape of a cylindrical prism, a sphere, or in any other shape that can efficiently guide microwave power from a drive probe to a bulb integrated with the waveguide body, including a complex, irregular shape whose resonant frequencies preferably are determined using electromagnetic theory simulation tools. The waveguide dimensions will vary depending upon the microwave operating frequency and the dielectric constant of the waveguide body. Regardless of its shape and size, a waveguide body preferably consists essentially of at least one dielectric material having the following properties: (1) a dielectric constant greater than approximately 2.0; (2) a loss tangent less than approximately 0.01; (3) a thermal shock resistance quantified by a failure temperature greater than approximately 200° C.; (4) a DC breakdown threshold greater than approximately 200 kilovolts/inch; (5) a coefficient of thermal expansion less than approximately  $10^{-5}/^{\circ}\text{C}$ .; (6) a zero or slightly negative temperature coefficient of the dielectric constant; (7) stoichiometric stability over a temperature range of about -80° C. to about 1000° C.; and (8) a thermal conductivity of approximately 2 W/mK (watts per milliKelvin). Ceramics having these properties as well as satisfactory electrical and thermo-mechanical properties include alumina, zirconia, certain titanates, and variations or combinations of these materials. However, as disclosed in the '718 application, one or more liquid materials having a dielectric constant greater than approximately 2, such as silicone oil, may also be used.

High resonant energy within waveguide **103**, corresponding to a high Q-value in the waveguide (where Q is the ratio of the operating frequency to the frequency bandwidth of the resonance), results in high evanescent leakage of microwave energy into lamp chamber **105**. Such leakage leads to quasi-static breakdown of the starting gas within envelope **127**, thereby generating initial free electrons. The oscillating energy of the free electrons scales as  $I\lambda^2$ , where I is the circulating intensity of the microwave energy and  $\lambda$  is the wavelength. Thus, the higher the microwave energy, the greater is the oscillating energy of the free electrons. By making the oscillating energy greater than the ionization potential of the gas, electron-neutral collisions result in efficient build-up of plasma density. Once a plasma is formed and the incoming power is absorbed, the waveguide's Q-value drops due to the conductivity and absorption properties of the plasma. The drop in Q-value is generally due to a change in waveguide impedance. After plasma formation, the presence of the plasma in the lamp chamber makes the chamber absorptive to the resonant energy, thus changing the impedance. The change in impedance is effectively a reduction in the overall reflectivity of the waveguide. By matching the reflectivity of the drive probe to be close to the reduced reflectivity of the waveguide, a relatively low net reflection back into the energy source is realized. Much of the energy absorbed by the plasma eventually appears as heat. When the waveguide is used as a heatsink, the dimensions of the waveguide may change due to thermal expansion. If the waveguide expands, the microwave frequency that will resonate within the waveguide changes and resonance is lost. In order for resonance to be maintained, the waveguide must have at least one dimension equal to an integer multiple of the half-wavelength of the microwaves being generated by source **115**. Such dimensional changes can be compensated for by choosing a dielectric material for body **104** having a temperature coefficient for its refractive index that is approximately equal and opposite in sign to its coefficient of

thermal expansion, so that expansion due to heating is at least partially offset by a change in refractive index.

A lamp chamber in a DWIPL is a shaped hole in the solid dielectric lamp body. The hole is covered with a transparent window or lens to keep the fill mixture inside, which typically is a noble gas or a mixture of a noble gas such as argon and a salt or halide such as indium bromide or indium iodide. The cross-section of the hole at the lamp body surface from which the hole depends is termed the "aperture." An aperture can be circular, rectangular, or an arbitrary shape. The three-dimensional shape of the chamber hole can be: a regular prism whose cross-section has the same shape as the aperture, e.g., a cylindrical prism and a circular aperture; a regular prism whose cross-section is shaped differently than the aperture, so that there is a transition region proximate to the aperture; or an arbitrary shape. A lamp chamber bottom can be shaped to serve as a light reflector, so that light striking the bottom is reflected toward the aperture. Specifically, a bottom can be shaped as a paraboloid, an ellipsoid, a chiseled prism, or with one or more curvatures tailored for a specific application.

A lamp chamber can be shaped to provide desired characteristics of the emitted light. For example, the chamber can be a cylinder with a diameter optimally chosen to match the dimensions of a light collecting apparatus connected to the lamp. The diameter is constrained at a lower limit by the requirement that the mean free path of an energized electron be long enough that sufficient electron-ion collisions occur before the electron strikes the chamber wall. Otherwise, the resulting efficiency will be too low. The diameter is constrained at an upper limit dependent on the lamp operating frequency. Otherwise, microwave energy will be emitted through the aperture.

A typical requirement for a lamp used in an application such as a projection television set is to make the chamber have an "optical extent" (or "etendue" E) which depends on the aperture area A and an f-number ("f#"), characterizing the cone angle of the emitted light, which depends on the ratio of the diameter to the chamber depth. Specifically,  $E = \pi A / (f\#)^2$ . Typically, the depth is selected to achieve a desired f#, with a greater depth resulting in a smaller f# and a smaller etendue. For a very deep chamber, light emitted toward the chamber middle or bottom may tend to hit the chamber wall and be absorbed, reducing the net efficiency of the lamp. For a very shallow chamber, light may be emitted in too broad a cone angle.

A lamp chamber may include a discontinuity in shape to provide an electric field concentration point (see FIGS. 7A and 8) which tends to facilitate breakdown of the fill mixture when the lamp is off, resulting in easier starting. Such a discontinuity can be a cone-or cup-shape projecting from the chamber bottom or side. Alternatively, a discontinuity can be formed by a deliberately added object, such as a fill tube end extending into the chamber.

There can be several lamp chambers in the same lamp body. The chambers are located at electric field maxima which exist for the selected waveguide operating mode. Preferably, a mode is selected which allows the chambers to be disposed in a configuration useful for providing light to each of several different optical paths. Each chamber can contain the same fill mixture, or the mixtures can be different. Thus, the spectrum of light emitted from each chamber can be the same, or the spectra can be different. For example, a lamp having three chambers, each with a unique fill mixture, could emit from each chamber, respectively, primarily red, blue and green light, so that the light from each chamber could be used for a separate channel of a red-blue-

green optical engine. Alternatively, each chamber could contain the same fill mixture so that multiple independent sources would be available for related but separate uses.

A lamp body can essentially consist of more than one solid dielectric material. For example, a lamp body can have a small volume around the lamp chamber made of alumina, to take advantage of its good mechanical, thermal and chemical properties, with the rest of the body made of a material with a higher dielectric constant than that of alumina but which does not have thermal, mechanical and/or electrical properties adequate to contain a plasma. Such a lamp would be a smaller than a lamp having an all-alumina body, likely would operate at a lower frequency than an all-alumina lamp of the same size, and would be less expensive to manufacture since it would require less high dielectric constant material.

The electromagnetic design of a lamp body having more than one solid dielectric material is performed in iterative steps. Firstly, a rough lamp shape is selected and an electromagnetic analysis and simulation performed for a lamp body consisting of the material occupying the greatest amount of body volume. Secondly, the simulation results are assessed to determine how close the lamp is to the desired operating frequency. Thirdly, the simulation is repeated with the several dielectric materials included in the simulated structure. Using the analysis results, the dimensions are adjusted and the simulation repeated until the body has the desired combination of operating frequency, size and proportions of materials.

A lamp body with several dielectric materials can be designed to include a layer, such as an evacuated space, inert gas, or a solid material, between two materials to serve as a thermal barrier. An evacuated space contributes to thermal management by increasing the temperature of the chamber wall(s), and providing a region in which the net lamp thermal flow rate results in a greater temperature differential than without the evacuated space (see FIGS. 3A and 3B of the '718 application).

One or more mechanical elements are required to enclose and seal a lamp chamber against the high thermomechanical stresses and pressures created by a plasma. Referring to FIG. 2, a DWIPL 200 includes a body 202 having a side 204 with a surface 204S from which depends a lamp chamber 206 having an aperture 208. A ball lens 210 is attached to surface 204S by a seal 212. Preferably, lens 210 is made of sapphire. Indicum 220 shows the direction of light emitted from chamber 206.

A window or lens enclosing and sealing a chamber can be coupled to other optical elements which collect, process and direct lamp light output. Examples include a tube lined with a reflective material or coating, and a light pipe. Such optical elements can be mounted to brackets integrally attached to a heatsink around a lamp body, providing a low cost, high integrity way to mount and attach optical components to the lamp. Referring to FIG. 3, a DWIPL 300 includes a body 302 having a side 304 with a surface 304S from which depends a lamp chamber 306 having an aperture 308. Body 302 is enclosed by a "U"-shaped heatsink 310 having a central portion 312 attached and generally orthogonal to opposed, generally parallel first and second portions 314, 316, respectively, having, respectively, ears 314E, 316E generally orthogonal to portions 314, 316 and attached to opposed first and second lamp mounting panels 318, 320, respectively. Portion 314 extends in a flange 322 to which are rigidly attached generally opposed first and second brackets 324, 326 generally orthogonal to the flange 322. A window/lens 330 attached to surface 304S and covering

aperture 308 encloses and seals the chamber 306. An optical element 332, such as a light pipe, is rigidly attached to the brackets 324, 326 and aligned with window/lens 330. Indicum 334 shows the direction of light output from element 332.

A DWIPL can consist of a single integrated assembly including: a lamp body with a sealed lamp chamber; a driver circuit and driver circuit board; a thermal barrier separating the body and driver circuit; and an outer heatsink. Alternatively, separate packages are used for: (a) the lamp body and heatsink; and (b) the driver circuit and its heatsink. For a DWIPL utilizing two probes (see FIGS. 15A and 15B, and FIG. 6 of the '718 application), the body and driver circuit are connected by two RF power cables, one connecting the output of the driver circuit to the body, and the other providing feedback from the body to the driver circuit. The use of two separate packages allows greater flexibility in the distribution of lamp heat and lamp driver heat. This may enable a projection television or other device to be built without including a fan for the lamp. Such two-package configurations may also enable design of television sets having smaller depth in the critical dimension from viewing screen to back panel than has heretofore been achieved.

A DWIPL offers substantial advantages for heat removal because the solid dielectric material(s) used for the lamp body can be chosen for characteristics which result in heat flow along desired paths. A heatsink can have an arbitrary shape, optimized for thermal and end-use considerations. The heatsink for a cylindrical-shaped lamp body might also be cylindrical with fins and mounting details standardized for attachment to a projection television chassis, and with features for mounting optics to the lamp assembly. For a cylindrical lamp and cylindrical heatsink, a useful construction technique is to heat the heatsink until it expands, then place it around the lamp body, and let it cool and contract to form intimate mechanical contact with the body. A metallic heatsink can be used to provide a conductive outer coating of the lamp body. This technique ensures a durable and intimate connection, and satisfies both thermal and electrical requirements of the lamp, reducing its total cost.

Referring to FIG. 4, a DWIPL 400 includes a generally cylindrical lamp body 402 having a top face 404 with a surface 404S to which is attached a window 406 covering a lamp chamber aperture 408. Body 402 is closely received within a generally cylindrical bore 410 of a generally cylindrical metallic heatsink 412 having an annular upper face 414 with a plurality of mounting holes 416. Preferably, a compliant, high temperature thermal interface material 418, e.g., grease or a silicone pad, is inserted between body 402 and heatsink 412.

Another practical heatsink arrangement is a two-piece "clamshell" in which two similar or identical pieces make intimate contact with a lamp body over a large area. The pieces are held together by fasteners in compression. Referring to FIG. 5, a DWIPL 500 has a generally cylindrical body 502, a top face 504 with a surface 504S, and a window 506 attached to surface 504S and covering a lamp chamber aperture 508. Body 502 is enclosed by semi-cylindrical portions 510, 512 of a clamshell-type heatsink 514. Portions 510 and 512 each are determined by ends 510A, 510B and 512A, 512B, respectively, attached to flanges 510C, 510D and 512C, 512D, respectively. First and second fasteners 520, 522 are used to connect the aligned flanges, compressing portions 510, 512 about the body 502.

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Still another heatsink arrangement is to plate a lamp body with a thermally and electrically conductive material, such as silver or nickel, and then solder or braze heatsink pieces to the plating.

When microwave power is applied from the driver circuit to the lamp body, it heats the fill mixture, melting and then vaporizing the salt or halide, causing a large increase in the lamp chamber pressure. Depending on the salt or halide used, this pressure can become as high as 400 atmospheres, and the bulb temperature can be as high as 1000° C. Consequently, a seal attaching a window or lens to a lamp body must be extremely robust.

Referring to FIG. 6, a DWIPL 600 includes a body 602 having a side 604 with a surface 604S from which depends a lamp chamber 606 having an aperture 608 and a bottom 610 with a hole 610H. A window 612, preferably made of sapphire, is attached to surface 604S by a seal 614. Lamp body 602 further includes a tapped bore 616 extending between a hole 620H in a body side 618 generally opposed to side 604, and chamber bottom 610, so that the bore is in communication with hole 610H. The window 612 is sealed to surface 604S in an inert atmosphere, using a ceramic sealing technique known in the art, such as brazing, frit, or metal sealing. Lamp body 602 and a screw-type plug 620 having a head 622 are then brought into an atmospheric chamber containing the starting gas 607G to be used in the lamp chamber, which is at or near the desired non-operating pressure for the lamp. The light emitter 607E is then deposited in lamp chamber 606 through bore 616 and hole 610H. Plug 620, which provides a mechanical and gas barrier to contain the fill mixture, is then screwed into bore 616 through hole 620H, and a metallic or glass material 624 deposited over head 622 to effect a final seal.

Referring to FIGS. 7 and 7A, a DWIPL 700 includes a body 702 having a side 704 with a surface 704S from which depends a lamp chamber 706 having a first aperture 708 and a lower portion 710 tapering in a neck 712 terminating in a second aperture 714. A window 716, preferably made of sapphire, is attached to surface 704S by a seal 718. Lamp body 702 further includes a tapered bore 720 extending between a hole 720H in a body side 722 generally opposed to side 704, and aperture 714, so that the bore is in communication with the neck 712, forming a lip 713. Window 716 is sealed to surface 704S in an inert atmosphere. Lamp body 702 and a plug 730, tapered to match the taper of bore 720 and having a head 732, are then brought into an atmospheric chamber containing the starting gas 707G to be used in the lamp chamber, which is at or near the desired non-operating pressure for the lamp. The light emitter 707E is then deposited in lamp chamber 706 through bore 720 and aperture 714. Plug 730 is then force-fitted through hole 720H into bore 720 so that the plug contacts lip 713, effecting a mechanical seal, and a metallic or glass material 734 deposited over head 732 to effect a final seal.

FIG. 8 shows three configurations 630, 640, 650 of the screw-type plug 620, and four configurations 740, 750, 760, 770 of the tapered plug 730. Plugs 630, 640 and 650 have, respectively, a dome-shaped tip 630T, a rod-shaped tip 640T, and a chisel-shaped tip 650T. Plugs 740, 750, 760 and 770 have, respectively, a conical tip 740T, a cup-shaped tip 750T, a chisel-shaped tip 760T, and a rod-shaped tip 770T having a concave end 722. If a plug having an extended tip such as plug 650 or plug 760 is used, the tip extends well into chamber 706 creating a discontinuity which provides an electric field concentration point.

Referring to FIG. 9, a DWIPL 900 includes a body 902 having a side 904 with a surface 904S from which depends

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a lamp chamber 906 having an aperture 908 and a bottom 910 with a hole 910H. A window 912, preferably made of sapphire, is attached to surface 904S by a seal 914. Lamp body 902 further includes a cylindrical bore 916 extending between a body side 918 generally opposed to side 904, and chamber bottom 910, so that the bore is in communication with hole 910H. After window 912 is sealed to surface 904S in an inert atmosphere, a glass or quartz tube 920 having an end 920E is inserted into bore 916 through a hole 916H so that end 920E extends through hole 910H into chamber 906. The chamber is then evacuated by a vacuum pump connected to tube 920. A fill mixture of starting gas 907G and light emitter 907E is then deposited into the chamber via the tube. When the fill is complete, a glass or quartz rod 930 having an outer diameter a little smaller than the inner diameter of the tube is inserted into the tube, and the tube and rod heated and pinched off. Thus, tube 920 is filled with a dielectric material which provides a reliable seal. The chamber filling and sealing process can be done without resort to a vacuum chamber, i.e., with the lamp at atmospheric pressure. Alternatively, the lamp body 902 with tube 920 inserted into bore 916 is brought into an atmospheric chamber containing the starting gas to be used in the lamp chamber, which is at or near the desired non-operating pressure for the lamp. The light emitter is then introduced into the chamber via the tube. When the fill is complete, the rod 930 is inserted into the tube, and the tube and rod heated and pinched off.

Referring to FIG. 10, a DWIPL 1000 includes a body 1002 having a side 1004 with a surface 1004S from which depends a lamp chamber 1006 having an aperture 1008 and a bottom 1010. Side 1004 has a hole 1004H in communication with a hole 1006H in chamber 1006. A glass or quartz tube 1020 having an end 1020E is inserted through holes 1004H and 1006H so that the end penetrates the chamber. A window 1030 covering aperture 1008, preferably made of sapphire, is then attached to surface 1004S by a frit or sealing material 1032 which melts at a temperature which will not melt the tube. After the window is sealed to surface 1004S with the tube 1020 in place and hole 1004H plugged by the sealing material, the chamber is evacuated by a vacuum pump connected to the tube. A fill mixture of starting gas 1007G and light emitter 1007E is then deposited into the chamber via the tube. When the fill is complete, a glass or quartz rod 1040 with an outer diameter a little smaller than the inner diameter of tube 1020 is inserted into the tube, and the tube 1020 and rod 1040 heated and pinched off.

Referring to FIG. 11, a DWIPL 1100 includes a body 1102 having a side 1104 with a surface 1104S from which depends a lamp chamber 1106 having an aperture 1108 and a bottom 1110. Side 1104 has an O-ring groove 1112 circumscribing the aperture 1108. DWIPL 1100 further includes first and second clamps 1120A, 1120B, respectively, which can apply mechanical compression to a window 1130 covering the aperture. The lamp body 1102, window 1130, an O-ring 1114, and a fill mixture of starting gas 1140 and light emitter 1150 are brought into an atmospheric chamber containing the gas 1140 at a pressure at or near the desired non-operating pressure for the lamp. The light emitter is then deposited in the chamber 1106, the O-ring 1114 is placed into groove 1112, the window 1130 is placed on top of the O-ring, and the clamps 1120A, 1120B tightened, thus forming a temporary or permanent seal.

Referring to FIG. 12, a DWIPL 1200 includes a "U"-shaped body 1202 having a central body portion 1204 attached to generally opposed first and second body portions

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1206, 1208, respectively, which are generally orthogonal to body portion 1204 and extend in upper portions 1206U, 1208U, respectively. Body portion 1204 has a side 1210 with a surface 1210S from which depends a lamp chamber 1220 having an aperture 1222 and a bottom 1224. Side 1210 has an O-ring groove 1212 which circumscribes aperture 1222. Upper portions 1206U, 1208U have, respectively, an interior surface 1206S, 1208S, having a thread 1230. The thread may be a metallic attachment to the interior surfaces or cut into the surfaces. As for the FIG. 11 embodiment, the lamp body 1202 and a window 1240, an O-ring 1214, and a fill mixture of starting gas 1221G and light emitter 1221E are brought into an atmospheric chamber containing the gas at a pressure at or near the desired non-operating pressure for the lamp. The light emitter is deposited in the chamber 1220, the O-ring 1214 is placed into groove 1212, the window 1240 is placed on top of the O-ring, and a screw-type metallic cap 1250 is engaged with the thread 1230. Cap 1250 has therethrough a central hole 1250H which serves as a light tunnel. Screwing down the cap applies pressure to the window, thereby compressing the O-ring to form a temporary or permanent seal.

Referring to FIG. 13, a DWIPL 1300 includes a body 1302 having a side 1304 with a surface 1304S from which depends a lamp chamber 1306 having an aperture 1308 and a bottom 1310. Side 1304 has therein a detail 1312 circumscribing the aperture 1308 and adapted to closely receive a seal preform 1320, such as a platinum or glass ring. The lamp body 1302, a window 1330, the seal 1320, and a fill mixture of starting gas 1340 and light emitter 1350 are brought into an atmospheric chamber containing the gas 1340 at a pressure at or near the desired non-operating pressure for the lamp. The light emitter is deposited in the chamber 1306, the seal 1320 placed in the detail 1312, and the window 1330 placed on top of the seal preform. The lamp body 1302 is then placed on or clamped to a cold surface 1360, so that the body and fill mixture remain sufficiently cool that no materials vaporize during heating of the seal preform. A hot mandrel 1370 is then applied in pressing contact to window 1330, heating the window and melting the seal preform. Indicia 1370A and 1370B denote melt-through heat transfer. The seal preform material is chosen to melt and flow at a temperature below the thermal limit for the window and lamp body. When the seal preform melts and then is cooled, it forms a seal between the window and side 1304. During the sealing operation, the gas pressure in the lamp chamber must be selected to compensate for expansion during heating.

Referring to FIG. 14, a DWIPL 1400 includes a body 1402 having a side 1404 with a surface 1404S from which depends a lamp chamber 1406 having an aperture 1408 and a bottom 1410. Attached to side 1404 by brazing, vacuum deposition or screening, and disposed within a detail 1404D in side 1404 is a first metallization ring 1412 circumscribing the aperture 1408. Within detail 1404D is a seal preform 1420, such as a platinum ring, superposed on ring 1412. A window 1430 has a lower surface 1430S to which, proximate to its periphery, is attached by brazing, vacuum deposition or screening a second metallization ring 1432. The lamp body 1402, the window 1430, the seal preform 1420, and a fill mixture of starting gas 1440 and light emitter 1450 are brought into an atmospheric chamber containing the gas 1440 at a pressure at or near the desired non-operating pressure for the lamp. The light emitter is deposited in the chamber 1406, and the window 1430 placed on top of the seal preform 1420 so that the preform is sandwiched between rings 1412 and 1432. Preferably, a clamp 1460

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holds the window in place while a brazing flame 1470 or other heat source is applied to melt the preform and form a seal.

Referring to FIG. 15, a DWIPL 1500 includes a body 1502 having a side 1504 with a surface 1504S from which depends a lamp chamber 1506 having an aperture 1508 and a bottom 1510. Attached to side 1504 by brazing, vacuum deposition or screening, and disposed within a detail 1504D in side 1504 is a first metallization ring 1512 circumscribing the aperture 1508. Within detail 1504D is a seal preform 1520, such as a platinum or glass ring, superposed on ring 1512. A window 1530 has a lower surface 1530S to which, proximate to its periphery, is attached by brazing, vacuum deposition or screening a second metallization ring 1532. The lamp body 1502, the window 1530, the seal preform 1520, and a fill mixture of starting gas 1540 and light emitter 1550 are brought into an atmospheric chamber containing the gas 1540 at a pressure at or near the desired non-operating pressure for the lamp. The mixture is deposited in the chamber 1506, and the window 1530 placed on top of the seal preform 1520 so that the preform is sandwiched between rings 1512 and 1532. Preferably, a clamp 1560 holds the window in place while a laser 1570 is focused and moved in a controlled pattern to melt and then permit cooling of the seal preform material. Laser sealing can be done at atmospheric or partial pressure.

Referring to FIGS. 16 and 16A, a DWIPL 1600 includes a body 1602 having a side 1604 with a surface 1604S from which depends a lamp chamber 1606 having an aperture 1608 and a bottom 1610. Attached to side 1604 by brazing, vacuum deposition or screening, and disposed within a detail 1604D of side 1604 is a first metallization ring 1612 circumscribing the aperture 1608. Within detail 1604D is a seal preform 1620, such as a platinum or other conductive material, superposed on ring 1612. A window 1630 has a lower surface 1630S to which, proximate to its periphery, is attached by brazing, vacuum deposition or screening a second metallization ring 1632. The lamp body 1602, the window 1630, the seal preform 1620, and a fill mixture of starting gas 1640 and light emitter 1650 are brought into an atmospheric chamber containing the gas 1640 at a pressure at or near the desired non-operating pressure for the lamp. The light emitter 1650 is deposited in the chamber 1606, and the window 1630 placed on top of the seal preform 1620 so that the preform is sandwiched between rings 1612 and 1632. Preferably, a clamp 1660 holds the window in place while a radio frequency (RF) coil 1670 is moved close to the seal preform. The coil heats and melts the preform which, after cooling, forms a seal between the window and side 1604. RF sealing can be done at atmospheric or partial pressure.

Electromagnetically, a DWIPL is a resonant cavity having at least one drive probe supplying microwave power for energizing a plasma contained in at least one bulb. In the following portion of the detailed description "cavity" denotes a DWIPL body. As disclosed in the '718 application, a "bulb" may be a separate enclosure containing a fill mixture disposed within a lamp chamber, or the chamber itself may be the bulb. To provide optimal efficiency, a bulb preferably is located at an electric field maximum of the resonant cavity mode being used. However the bulb can be moved away from a field maximum at the cost of additional power dissipated by the wall and cavity. The location of the drive probe is not critical, as long as it is not at a field minimum, because the desired coupling efficiency can be achieved by varying probe design parameters, particularly length and shape. FIGS. 17A and 17B schematically show

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two cylindrical lamp configurations **130A**, **130B**, respectively, both operating at the fundamental cylindrical cavity mode, commonly known as  $TM_{0,1,0}$ , and having a bulb **132A**, **132B**, respectively, located at the single electric field maximum. Dashed curves **131A**, **131B** show, respectively, the electric field distribution in the cavity. In FIG. **17A**, a drive probe **134A** is located at the field maximum. In FIG. **17B**, drive probe **134B** is not located at the field maximum; however, it contains a longer probe which provides the same coupling efficiency as probe **134A**. Although the  $TM_{0,1,0}$  mode is used here as an example, higher order cavity modes, including but not limited to transverse electric field ("TE") and transverse magnetic field ("TM") modes, can also be used.

Drive probe design is critical for proper lamp operation. The probe must provide the correct amount of coupling between the microwave source and lamp chamber to maximize light emitting efficiency and protect the source. There are four major cavity loss mechanisms reducing efficiency: chamber wall dissipation, dielectric body dissipation, plasma dissipation, and probe coupling loss. As defined herein, probe coupling loss is the power coupled out by the drive probe and other probes in the cavity. Probe coupling loss is a major design consideration because any probe can couple power both into and out of the cavity. If the coupling between the source and cavity is too small, commonly known as "under-coupling", much of the power coming from the source will not enter the cavity but be reflected back to the source. This will reduce light emission efficiency and microwave source lifetime. If initially the coupling between the source and cavity is too large, commonly known as "over-coupling", most of the power from the source will enter the cavity. However, the cavity loss mechanisms will not be able to consume all of the power and the excess will be coupled out by the drive probe and other probes in the cavity. Again, light emission efficiency and microwave source lifetime will be reduced. In order to maximize light emission efficiency and protect the source, the drive probe must provide an appropriate amount of coupling such that reflection from the cavity back to the source is minimized at the resonant frequency. This condition, commonly known as "critical coupling", can be achieved by adjusting the configuration and location of the drive probe. Probe design parameters depend on the losses in the cavity, which depend on the state of the plasma and the temperature of the lamp body. As the plasma state and/or body temperature change, the coupling and resonant frequency will also change. Moreover, inevitable inaccuracies during DWIPL manufacture will cause increased uncertainty in the coupling and resonant frequency.

It is not practical to adjust probe physical parameters while a lamp is operating. In order to maintain as close to critical coupling as possible under all conditions, a feedback configuration is required (see FIG. 6 of the '718 application), such as lamp configurations **140A**, **140B** shown, respectively, in FIGS. **18A** and **18B** for a rectangular prism-shaped cavity and a cylindrical cavity. A second "feedback" probe **142A**, **142B**, respectively, is introduced into a cavity **144A**, **144B**, respectively. Feedback probe **142A**, **142B**, respectively, is connected to input port **146A**, **146B**, respectively, of a combined amplifier and control circuit (ACC) **148A**, **148B**, respectively, and a drive probe **150A**, **150B**, respectively, is connected to ACC output port **152A**, **152B**, respectively. Each configuration forms an oscillator. Resonance in the cavity enhances the electric field strength needed to create the plasma and increases the coupling efficiency between the drive probe and bulb. Both the drive

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probe and feedback probe may be located anywhere in the cavity except near an electric field minimum for electric field coupling, or a magnetic field minimum for magnetic field coupling. Generally, the feedback probe has a lesser amount of coupling than the drive probe because it samples the electric field in the cavity with minimum increase in coupling loss.

From a circuit perspective, a cavity behaves as a lossy narrow bandpass filter. The cavity selects its resonant frequency to pass from the feedback probe to the drive probe. The ACC amplifies this preferred frequency and puts it back into the cavity. If the amplifier gain is greater than the insertion loss at the drive probe entry port vis-a-vis insertion loss at the feedback probe entry port, commonly known as  $S_{21}$ , oscillation will start at the resonant frequency. This is done automatically and continuously even when conditions, such as plasma state and temperature, change continuously or discontinuously. Feedback enables manufacturing tolerances to be relaxed because the cavity continually "informs" the amplifier of the preferred frequency, so accurate prediction of eventual operating frequency is not needed for amplifier design or DWIPL manufacture. All the amplifier needs to provide is sufficient gain in the general frequency band in which the lamp is operating. This design ensures that the amplifier will deliver maximum power to the bulb under all conditions.

In order to maximize light emission efficiency, a drive probe is optimized for a plasma that has reached its steady state operating point. This means that prior to plasma formation, when losses in a cavity are low, the cavity is over-coupled. Therefore, a portion of the power coming from the microwave source does not enter the cavity and is reflected back to the source. The amount of reflected power depends on the loss difference before and after plasma formation. If this difference is small, the power reflection before plasma formation will be small and the cavity will be near critical coupling. Feedback configurations such as shown in FIG. **18A** or **18B** will be sufficient to break down the gas in the bulb and start the plasma formation process. However, in most cases the loss difference before and after plasma formation is significant and the drive probe becomes greatly over-coupled prior to plasma formation. Because much of the power is reflected back to the amplifier, the electric field strength may not be large enough to cause gas breakdown. Also, the large amount of reflected power may damage the amplifier or reduce its lifetime.

FIG. **19** shows a lamp configuration **160** which solves the drive probe over-coupling problem wherein a third "start" probe **162**, optimized for critical coupling before plasma formation, is inserted into a cavity **164**. Start probe **162**, drive probe **166**, and feedback probe **168** can be located anywhere in the cavity except near a field minimum. Power from output port **170B** of an ACC **170** is split into two portions by a splitter **172**: one portion is delivered to drive probe **166**; the other portion is delivered to start probe **162** through a phase shifter **174**. Probe **168** is connected to input port **170A** of ACC **170**. Both the start and drive probes are designed to couple power into the same cavity mode, e.g.,  $TM_{0,1,0}$  for a cylindrical cavity as shown in FIG. **19**. The splitting ratio and amount of phase shift between probes **166** and **162** are selected to minimize reflection back to the amplifier. Values for these parameters are determined by network analyzer S-parameter measurements and/or simulation software such as High Frequency Structure Simulator (HFSS) available from Ansoft Corporation of Pittsburgh, Pa. In summary, the start probe is critically coupled before plasma formation and the drive probe is critically coupled

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when the plasma reaches steady state. The splitter and phase shifter are designed to minimize reflection back to the combined amplifier and control circuit.

FIG. 20 shows a second lamp configuration 180 which solves the drive probe over-coupling problem. Both start probe 182 and drive probe 184 are designed to couple power into the same cavity mode, e.g.,  $TM_{0,1,0}$  for a cylindrical cavity such as cavity 186. Configuration 180 further includes a feedback probe 188 connected to input port 190A of an ACC 190. The three probes can be located anywhere in the cavity except near a field minimum. Power from output port 190B of ACC 190 is delivered to a first port 192A of a circulator 192 which directs power from port 192A to a second port 192B which feeds drive probe 184. Prior to plasma formation, there is a significant amount of reflection coming out of the drive probe because it is over-coupled before the plasma reaches steady state. Such reflection is redirected by circulator 192 to a third port 192C which feeds the start probe 182. Before plasma formation, the start probe is critically coupled so that most of the power is delivered into the cavity 186 and start probe reflection is minimized. Only an insignificant amount of power goes into port 192C and travels back to ACC output port 190B. Power in the cavity increases until the fill mixture breaks down and begins forming a plasma. Once the plasma reaches steady state, the drive probe 184 is critically coupled so reflection from the drive probe is minimized. At that time, only an insignificant amount of power reaches the now under-coupled start probe 182. Although the start probe now has a high reflection coefficient, the total amount of reflected power is negligible because the incident power is insignificant. In summary, the start probe is critically coupled before plasma formation and the drive probe is critically coupled when the plasma reaches steady state. The circulator directs power from port 192A to 192B, from port 192B to port 192C, and from port 192C to port 192A.

FIGS. 21A and 21B show third and fourth lamp configurations 240A, 240B which solve the drive probe over-coupling problem. A "start" cavity mode is used before plasma formation, and a separate "drive" cavity mode is used to power the plasma to its steady state and maintain that state. Start probe 242A, 242B, respectively, operates in the start cavity mode, and drive probe 244A, 244B, respectively, operates in the drive cavity mode. As indicated by dashed curves 241A and 241B, preferably the drive cavity mode is the fundamental cavity mode and the start cavity mode is a higher order cavity mode. This is because normally it requires more power to maintain the steady state plasma with the desired light output than to break down the gas for plasma formation. Therefore it is more economical to design a DWIPL so the high power microwave source operates at a lower frequency. For a cylindrical cavity such as cavities 246A and 246B, the start probe 242A, 242B, respectively, can be critically coupled at the resonant frequency of the  $TM_{0,2,0}$  mode before plasma formation, and the drive probe 244A, 244B, respectively, can be coupled at the resonant frequency of the  $TM_{0,1,0}$  mode after the plasma reaches steady state. The feedback probe can be located anywhere in the cavity except near a field minimum of the drive cavity mode or a field minimum of the start cavity mode. The start probe can be located anywhere in the cavity except near any field minima of the start cavity mode. The drive probe should be located near or at a field minimum of the start cavity mode but not near a field minimum of the drive cavity mode. This minimizes the coupling loss of the drive probe before plasma formation so that the electric field in the cavity can reach a higher value to break down the gas. A

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diplexer 248A, 248B, respectively, is used to separate the two resonant frequencies. In FIG. 21A, a single ACC 250 connected at its input 250B to diplexer 248A is used to power both cavity modes. The two frequencies are separated by diplexer 248A and fed to the start probe 242A and drive probe 244A. Feedback probe 252A is connected to input port 250A of ACC 250. In FIG. 21B, two separate amplifiers 260, 262 are used to power the two cavity modes independently. Diplexer 248B separates the two frequencies coming out of feedback probe 252B. In summary, the start probe operates in one cavity mode and the drive probe operates in a different mode. The feedback probe can be located anywhere in the cavity except near a field minimum of either mode. The start probe can be located anywhere in the cavity except near a field minimum of the start cavity mode. The drive probe should be located near or at a field minimum of the start cavity mode but not near a field minimum of the drive cavity mode.

An alternative approach is to add a second feedback probe, which eliminates the need for a diplexer. The first feedback probe is located at a field minimum of the start cavity mode to couple out only the drive cavity mode. The second feedback probe is located at a field minimum of the drive cavity mode to couple out only the start cavity mode.

FIGS. 22A and 22B show lamp configurations 280A, 280B, respectively, which do not include a start probe but utilize two separate cavity modes. As indicated by curves 281A and 281B, respectively, in cavities 282A and 282B, a relatively high order start cavity mode is used before plasma formation and a relatively low order drive cavity mode is used to power the plasma to steady state and maintain the state. Preferably, for economy and efficiency, the drive cavity mode again is the fundamental cavity mode and the start cavity mode is a higher order cavity mode. For example, the  $TM_{0,2,0}$  mode of a cylindrical lamp cavity can be used before plasma formation, and the  $TM_{0,1,0}$  mode can be used to maintain the plasma in steady state. By utilizing two cavity modes, it is possible to design a single drive probe that is critically coupled both before plasma formation and after the plasma reaches steady state, thereby eliminating the need for a start probe. The feedback probe 284A, 284B, respectively, can be located anywhere in the cavity except near a field minimum of either cavity mode. The drive probe 286A, 286B, respectively, should be located near a field minimum of the start cavity mode but not near a field minimum of the drive cavity mode. By placing the drive probe near but not at a field minimum of the start cavity mode, the drive probe can be designed to provide the small amount of coupling needed before plasma formation and the large amount of coupling required after the plasma reaches steady state. In FIG. 22A, a single ACC 290 having input and output ports 290A, 290B, respectively, is used to power both cavity modes. In FIG. 22B, two separate ACC's 292, 294 are used to power the two cavity modes independently. A first diplexer 296B separates the two frequencies coming out of feedback probe 284B and a second diplexer 298B combines the two frequencies going into drive probe 286B. In summary, the drive probe is critically coupled at the start cavity mode resonant frequency before plasma formation and critically coupled at the drive cavity mode resonant frequency when the plasma reaches steady state. The feedback probe can be located anywhere in the cavity except near a field minimum of either cavity mode. The drive probe should be located near a field minimum of the start cavity mode but not near a field minimum of the drive cavity mode.

The '718 application disclosed a technique for drive probe construction wherein a metallic microwave probe is in intimate contact with the high dielectric material of the lamp body. This method has a drawback in that the amount of coupling is very sensitive to the exact dimensions of the probe. A further drawback is that due to the large temperature variation before plasma formation and after the plasma reaches steady state, a mechanism such as a spring is needed to maintain contact between the probe and body. These constraints complicate the manufacturing process and consequently increase production cost.

FIG. 23 shows a technique which avoids both problems. A metallic microwave probe 350 extending into a lamp body 352 is surrounded by a dielectric material 354 having a high breakdown voltage. Body 352 includes a lamp chamber 356. Due to the large amount of power delivered within a limited space, the electric field strength near tip 350T of probe 350 is very high; therefore a high breakdown voltage material is required. Typically, material 354 has a lower dielectric constant than that of the dielectric material forming body 352. Material 354 acts as a "buffer" which desensitizes the dependency of coupling on probe dimensions, thereby simplifying fabrication and reducing cost.

The amount of coupling between the microwave source and body can be adjusted by varying the location and dimensions of the probe, and the dielectric constant of material 354. In general, if the probe length is less than a quarter of the operating wavelength, a longer probe will provide greater coupling than a shorter probe. Also, a probe placed at a location with a higher field will provide greater coupling than a probe placed at a location where the field is relatively low. This technique is also applicable to a start probe or a feedback probe. The probe location, shape and dimensions can be determined using network analyzer S-parameter measurements and/or simulation software such as HFSS.

FIG. 24 shows a circuit 430 including an amplifier 432 and a control circuit 434, suitable for DWIPLs having only a drive probe 436 and feedback probe 438 such as shown in FIGS. 18A, 18B, 22A and 22B, and exemplified here by lamp 420. The function of amplifier 432 is to convert DC power into microwave power of an appropriate frequency and power level so that sufficient power can be coupled into lamp body 440 and lamp chamber 442 to energize a fill mixture and form a light-emitting plasma.

Preferably, amplifier 432 includes a preamplifier stage 450 with 20 to 30 dBm of gain, a medium power amplifier stage 452 with 10 to 20 dB of gain, and a high power amplifier stage 454 with 10 to 18 dB of gain. Preferably, stage 450 uses the Motorola MHL21336, 3G Band RF Linear LDMOS Amplifier, stage 452 uses the Motorola MRF21030 Lateral N-Channel RF Power MOSFET; and stage 454 uses the Motorola MRF21125 Lateral N-Channel RF Power MOSFET. These devices as well as complete information for support and bias circuits are available from Motorola Semiconductor Products Sector in Austin, Tex. Alternatively, stages 450, 452 and 454 are contained in a single integrated circuit. Alternatively, stages 450 and 452, and control circuit 434 are packaged together, and high power stage 454 is packaged separately.

Amplifier 432 further includes a PIN diode attenuator 460 in series with stages 450, 452 and 454, preferably connected to preamplifier stage 450 to limit the amount of power which the attenuator must handle. Attenuator 460 provides power control for regulating the amount of power supplied to lamp body 440 appropriate for starting the lamp, operating the lamp, and controlling lamp brightness. Since the amplifier

chain formed by stages 450, 452 and 454 has a fixed gain, varying the attenuation during lamp operation varies the power delivered to body 440. Preferably, the attenuator 460 acts in combination with control circuit 434, which may be analog or digital, and an optical power detector 462 which monitors the intensity of the light emitted and controls attenuator 460 to maintain a desired illumination level during lamp operation, even if power conditions and/or lamp emission characteristics change over time. Alternatively, an RF power detector 464 connected to drive probe 436, amplifier stage 454 and control circuit 434 is used to control the attenuator 460. Additionally, circuit 434 can be used to control lamp brightness, i.e., controlling the lamp illumination level to meet end-application requirements. Circuit 434 includes protection circuits and connects to appropriate sensing circuits to provide the functions of over-temperature shutdown, over-current shutdown, and over-voltage shutdown. Circuit 434 can also provide a low power mode in which the plasma is maintained at a very low power level, insufficient for light emission but sufficient to keep the fill mixture gas ionized. Circuit 434 also can shut down the lamp slowly by increasing the attenuation. This feature limits the thermal shock a lamp repeatedly experiences and allows the fill mixture to condense in the coolest portion of the lamp chamber, promoting easier lamp starting.

Alternatively, attenuator 460 is combined with an analog or digital control circuit to control the output power at a high level during the early part of the lamp operating cycle, in order to vaporize the fill mixture more quickly than can be achieved at normal operating power. Alternatively, attenuator 460 is combined with an analog or digital control circuit which monitors transmitted and/or reflected microwave power levels through an RF power detector and controls the attenuator to maintain the desired power level during normal lamp operation, even if the incoming power supply voltage changes due to variations in the ac supply or other loads.

FIG. 25 shows an alternative circuit 540 including an amplifier 542 and a control circuit 544, suitable for supplying and controlling power to the body 546 and lamp chamber 548 of a DWIPL 550 having a drive probe 552 and feedback probe 554, such as shown in FIGS. 18A, 18B, 22A and 22B. A "starting" bandpass filter 560A and an "operating" bandpass filter 560B, in parallel and independently selectable and switchable, are in series with the FIG. 24 amplifier chain and preferably, as in FIG. 24, on the input side of the chain. Filters 560A and 560B filter out frequencies corresponding to undesired resonance modes of body 546. By selecting and switching into the circuit a suitable filter bandpass using first and second PIN diode switches 562A, 562B, the DWIPL 550 can operate only in the cavity mode corresponding to the selected frequency band, so that all of the amplifier power is directed into this mode. By switching in filter 560A, a preselected first cavity mode is enabled for starting the lamp. Once the fill mixture gas has ionized and the plasma begun to form, a preselected second cavity mode is enabled by switching in filter 560B. For a short time, both filters provide power to the lamp to ensure that the fill mixture remains a plasma. During the period when both filters are switched in, both cavity modes propagate through body 546 and the amplifier chain. When a predetermined condition has been met, such as a fixed time delay or a minimum power level, filter 560A is switched out, so that only the cavity mode for lamp operation can propagate through the amplifier chain. Control circuit 544 selects, deselects, switches in, and switches out filters 560A and 560B, following a predetermined operating sequence. An optical power detector 564

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connected to control circuit 544 performs the same function as detector 462 in the FIG. 24 embodiment.

FIG. 26 shows a circuit 570 including an amplifier 572 and an analog or digital control circuit 574, suitable for supplying and controlling power to the body 576 and lamp chamber 578 of a DWIPL 580 having a drive probe 582, a feedback probe 586 and a start probe 584, such as shown in FIGS. 19, 20, 21A and 21B. The feedback probe 586 is connected to input 450A of preamplifier 450 through a PIN diode attenuator 588 and a filter 589. The start probe 584 is designed to be critically coupled when lamp 580 is off. To start the lamp, a small amount of microwave power is directed into start probe 584 from preamplifier stage 450 or medium power stage 452 of the amplifier chain. The power is routed through a bipolar PIN diode switch 590 controlled by control circuit 574. Switch 590 is controlled to send RF microwave power to start probe 584 until the fill mixture gas becomes ionized. A sensor 592A monitors power usage within body 576, and/or a sensor 592B monitors light intensity indicative of gas ionization. A separate timer control circuit, which is part of control circuit 574, allocates an adequate time for gas breakdown. Once the gas has been ionized, control circuit 574 turns on switch 590 which routes microwave power to high power stage 454 which provides microwave power to drive probe 582. For a short time, start probe 584 and drive probe 582 both provide power to the lamp to ensure that the fill mixture remains a plasma. When a predetermined condition has been met, such as a fixed time period or an expected power level, control circuit 574 turns off switch 590 thereby removing power to start probe 584 so that the plasma is powered only by drive probe 582. This provides maximum efficiency.

To enhance the Q-value (i.e., the ratio of the operating frequency to the resonant frequency bandwidth) of the DWIPL 580 during starting, the control circuit 574 can bias the transistors of high power stage 454 to an impedance that minimizes leakage out of probe 582 into stage 454. To accomplish this, circuit 574 applies a DC voltage to the gates of the transistors to control them to the appropriate starting impedance.

What is claimed is:

1. A lamp comprising:
  - a waveguide having a body comprising at least one dielectric material having a dielectric constant greater than approximately 2;
  - a first microwave probe positioned within the body, connected to an output of a source of microwave power operable at at least one frequency such that the body resonates in at least one resonant mode having at least one electric field maximum;
  - a second microwave probe positioned within the body, connected to an input of the source;
  - a fill mixture which when receiving microwave power provided by the resonating body forms a light-emitting plasma; and
  - circuitry configured to control reflection of power from the body back to the source.
2. The lamp of claim 1, further comprising a bulb containing the fill mixture proximate the lamp body.
3. The lamp of claim 2, wherein the bulb comprises a convex portion located within the lamp chamber.
4. The lamp of claim 1, wherein the first probe is a drive probe and the second probe is a feedback probe, the lamp comprising an amplifier connected in an electrical path between the feedback probe and the drive probe.

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5. A lamp comprising:

- a lamp body comprising at least one dielectric material having a dielectric constant greater than 2;
- a power source configured to provide radio frequency power at at least one frequency that resonates within the lamp body;
- a first probe configured to provide the radio frequency power from the power source to the lamp body at the frequency that resonates within the lamp body;
- a fill proximate the lamp body, the fill forming a light-emitting plasma when the radio frequency power is received by the fill from the lamp body; and
- circuitry configured to control a reflection of power from the lamp body back to the power source.

6. The lamp of claim 5, wherein the circuitry comprises a controller configured to adjust the power reflected from the body back to the source.

7. The lamp of claim 5, wherein the circuitry includes a phase shifter.

8. The lamp of claim 5, wherein the circuitry includes an attenuator.

9. The lamp of claim 5, wherein the circuitry includes a circulator.

10. The lamp of claim 5, further comprising at least one sensor for monitoring a lamp operating condition, wherein the circuitry is responsive to a signal from the sensor.

11. The lamp of claim 10, wherein the circuitry is responsive to the sensor to maintain a power level provided to the lamp body during steady state operation of the lamp.

12. The lamp of claim 10, wherein the sensor is a radio frequency power detector that monitors reflected power.

13. The lamp of claim 10, wherein the sensor is a radio frequency power detector that monitors transmitted power levels.

14. The lamp of claim 10, wherein the sensor monitors light intensity emitted from the plasma.

15. The lamp of claim 5, wherein the power source includes an amplifier and the circuitry is configured to provide a bias to the amplifier.

16. The lamp of claim 5, wherein the circuitry includes a timer control circuit and a controller responsive to the timer control circuit.

17. The lamp of claim 5, wherein the circuitry includes a timer control circuit and is configured to adjust the power provided to the lamp body after formation of the plasma responsive to the timer control circuit.

18. The lamp of claim 5, further comprising a second probe for obtaining feedback from the lamp body, wherein the power source is connected in an electrical path between the second probe and the first probe.

19. The lamp of claim 18, wherein the circuitry includes at least one switch configured to switch at least one circuit element from the electrical path.

20. The lamp of claim 19, wherein the at least one circuit element is a filter.

21. The lamp of claim 18, further comprising a phase shifter in the electrical path between the second probe and the first probe.

22. The lamp of claim 5, further comprising a second probe and a third probe coupled to the lamp body.

23. The lamp of claim 5, further comprising a bulb containing the fill proximate the lamp body.

24. The lamp of claim 5, wherein the first probe and circuitry are configured to over-couple power to the lamp body from the power source prior to formation of the plasma.

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25. The lamp of claim 5, wherein the first probe and the circuitry are configured to couple power to the lamp body from the power source with reduced reflection after formation of the plasma than before the formation of the plasma.

26. The lamp of claim 5, wherein the power source includes an LDMOS amplifier.

27. The lamp of claim 5, wherein the lamp body further comprises a second dielectric material.

28. The lamp of claim 5, wherein the dielectric material has:

- a loss tangent less than approximately 0.01;
- a DC breakdown threshold greater than approximately 200 kilovolts/inch;
- a thermal shock resistance quantified by a failure temperature greater than approximately 200° C.;
- a coefficient of thermal expansion less than approximately 10<sup>5</sup>/° C.; and
- stoichiometric stability over a temperature range from about -80° C. to about 1000° C.

29. The lamp of claim 5, wherein the first probe is positioned in the lamp body at a position that is not at an electric field maximum of the radio frequency power resonating in the lamp body.

30. The lamp of claim 29, wherein the first probe and circuitry are configured to over-couple power to the lamp body from the power source prior to formation of the plasma.

31. The lamp of claim 30, wherein the radio frequency power provided by the power source causes the lamp body to resonate in a fundamental resonant mode, and wherein the lamp body has an outer surface that is coated with an electrically conductive material except in regions where the radio frequency power is coupled into the lamp body and in the region where the radio frequency power is coupled from the lamp body to the fill.

32. The lamp of claim 31, further comprising at least one sensor for monitoring a lamp operating condition, wherein the circuitry is responsive to a signal from the sensor.

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33. The lamp of claim 5, further comprising a second probe for obtaining feedback from the lamp body, wherein the power source is connected in an electrical path between the second probe and the first probe and wherein the second probe is positioned in the lamp body at a position that is not at an electric field maximum of the radio frequency power resonating in the lamp body.

34. The lamp of claim 33, wherein the position of the second probe is not at an electric field minima of the radio frequency power resonating in the lamp body.

35. The lamp of claim 34, wherein the position of the first probe is not at an electric field minima of the radio frequency power resonating in the lamp body.

36. The lamp of claim 35, wherein the radio frequency power provided by the power source causes the lamp body to resonate in a fundamental resonant mode.

37. The lamp of claim 36, further comprising a phase shifter in the electrical path between the second probe and the first probe.

38. The lamp of claim 5, wherein the radio frequency power provided by the power source causes the lamp body to resonate in a fundamental resonant mode.

39. The lamp of claim 38, wherein the lamp body has an outer surface that is coated with an electrically conductive material except in regions where the radio frequency power is coupled into the lamp body and in the region where the radio frequency power is coupled from the lamp body to the fill.

40. The lamp of claim 5, wherein the lamp body has an outer surface that is coated with an electrically conductive material except in regions where the radio frequency power is coupled into the lamp body and in the region where the radio frequency power is coupled from the lamp body to the fill.

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