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

(75) Inventors: **Frederick M. Espiau**, Topanga, CA (US); **Yian Chang**, Los Angeles, CA (US)

(73) Assignee: **Luxim Corporation**, Sunnyvale, CA (US)

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(58) **Field of Classification Search** 315/39, 315/248

See application file for complete search history.

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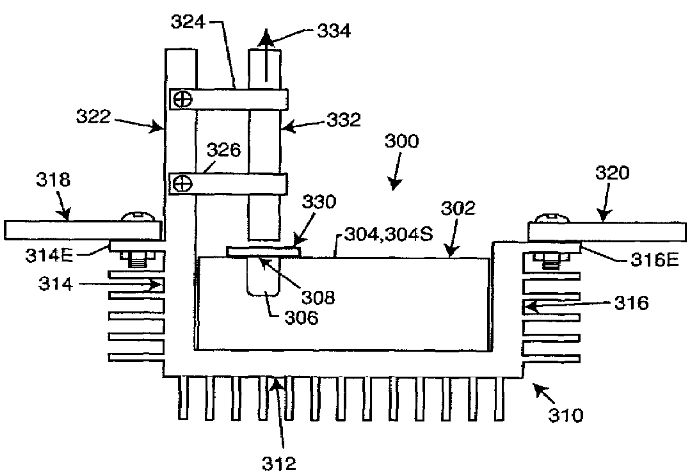
Primary Examiner—David Hung Vu
(74) *Attorney, Agent, or Firm*—Schwegman, Lundberg & Woessner, P.A.

(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 resonating 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.

9 Claims, 25 Drawing Sheets



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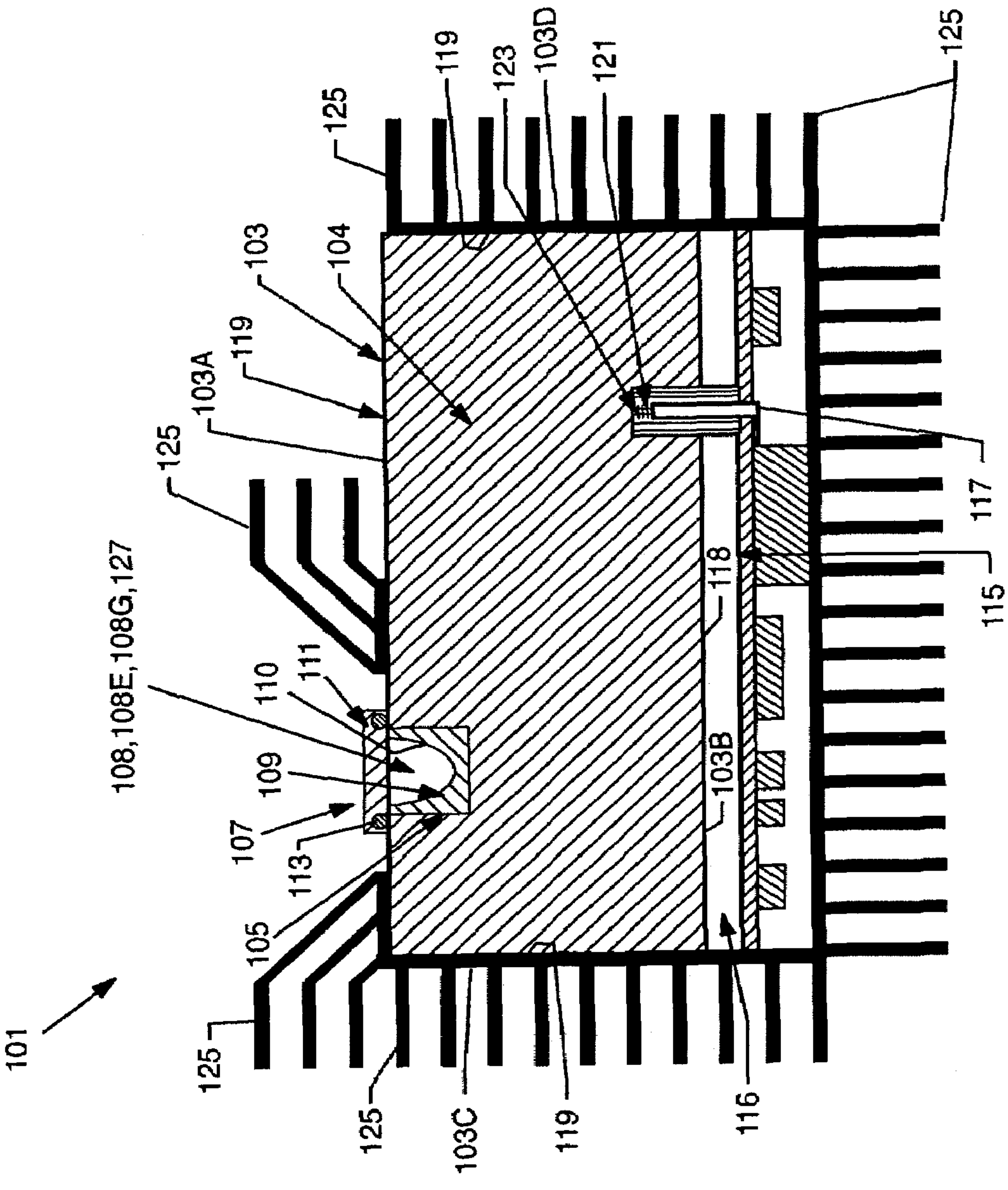
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FIG. 1

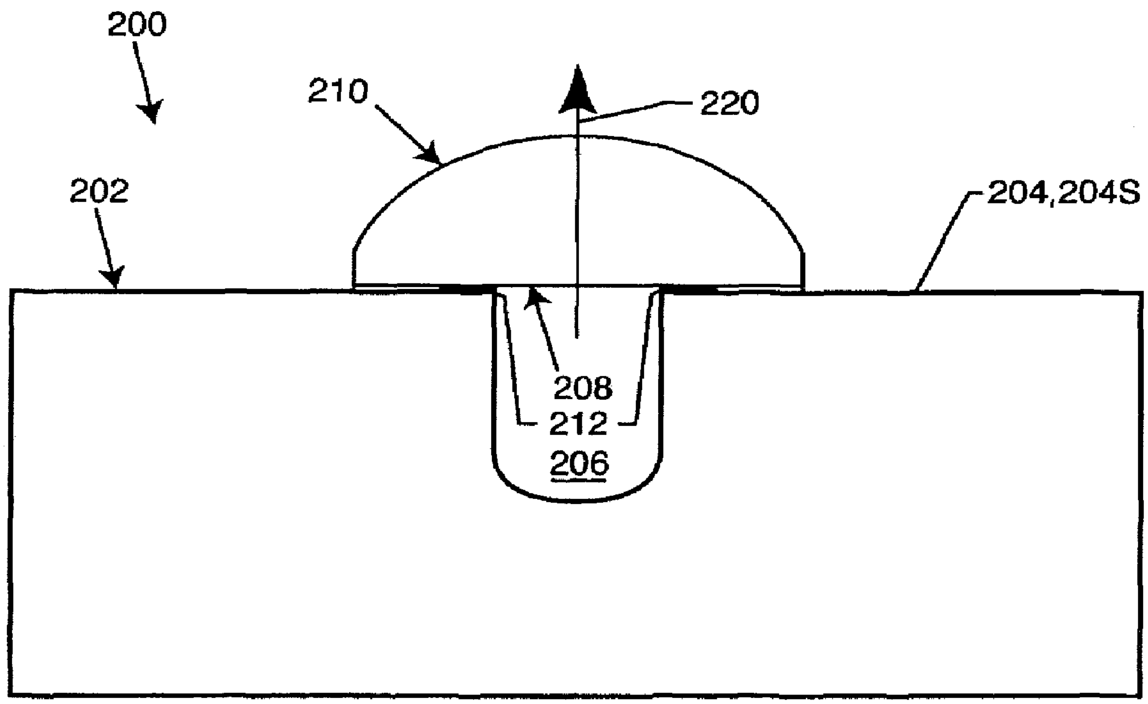

FIG. 2

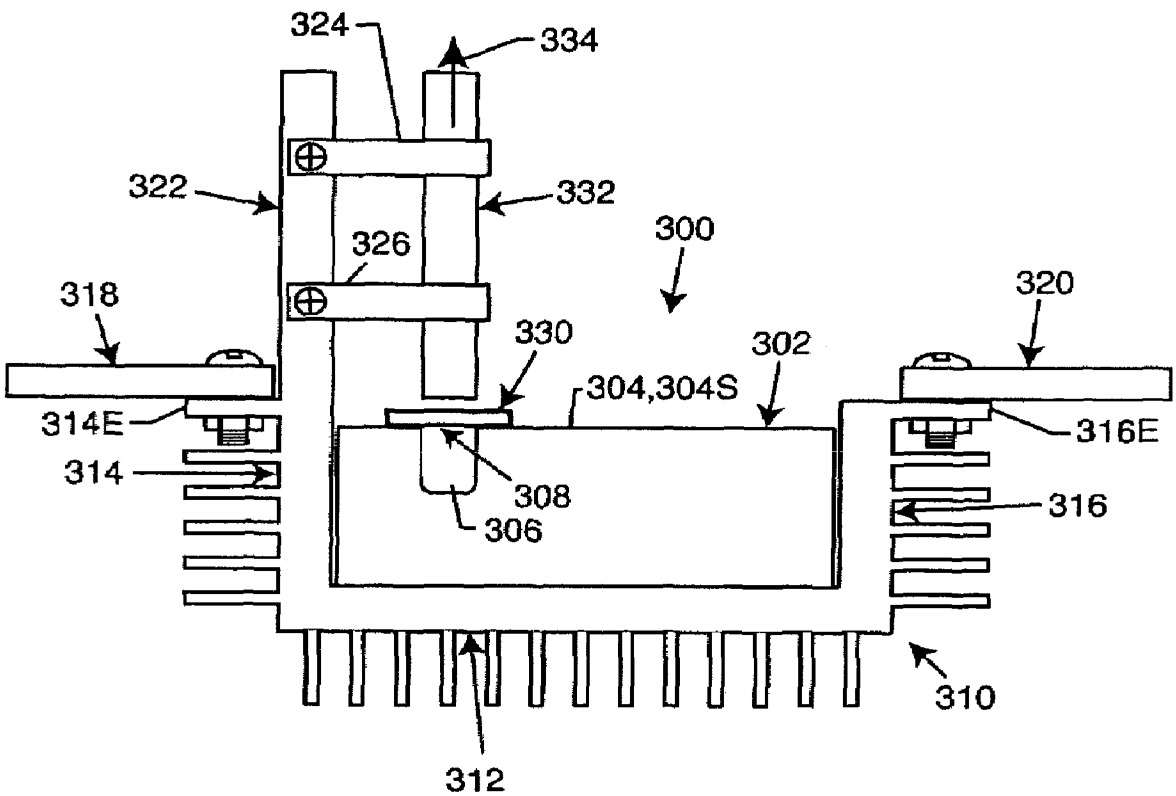
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FIG. 3

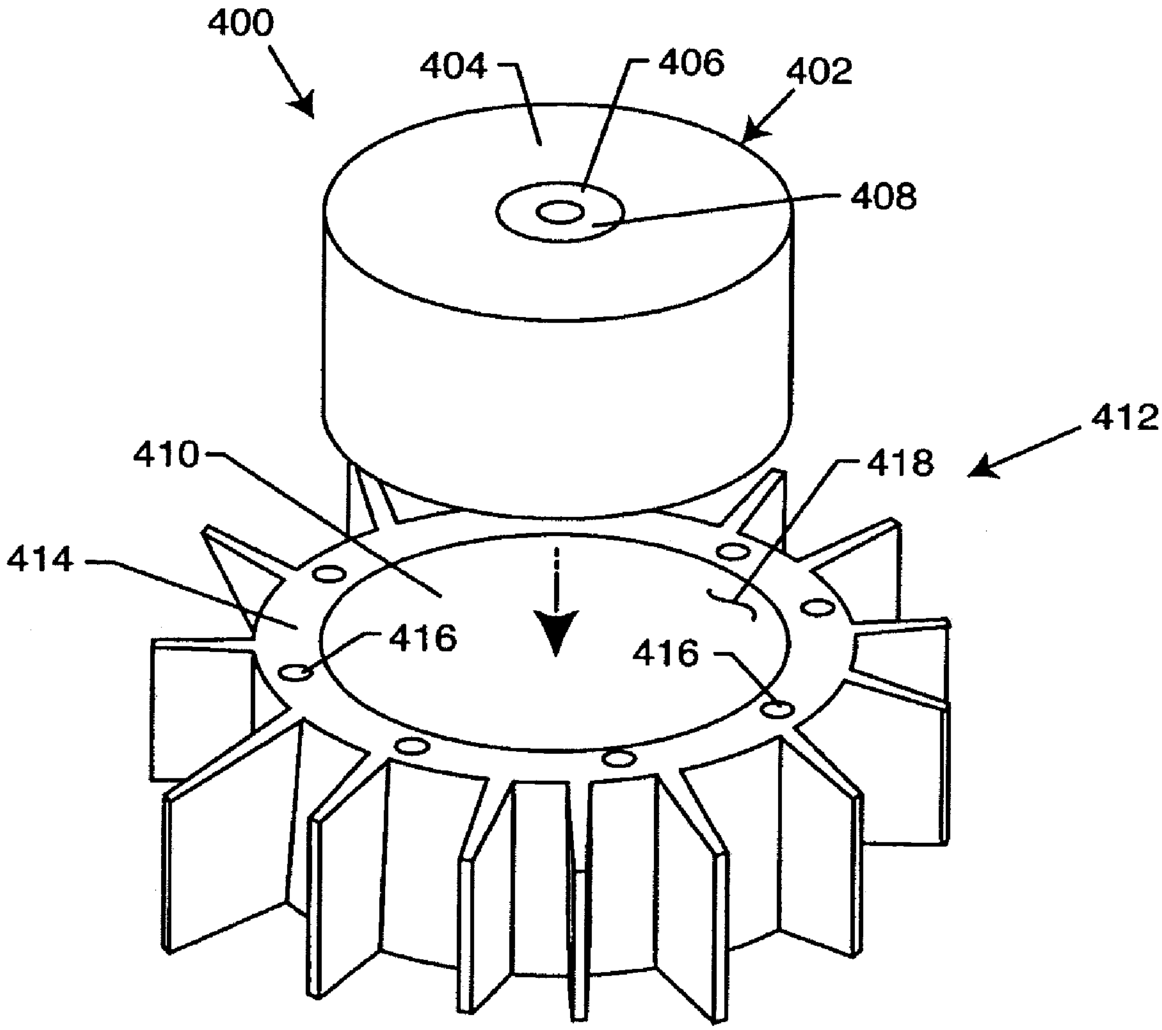
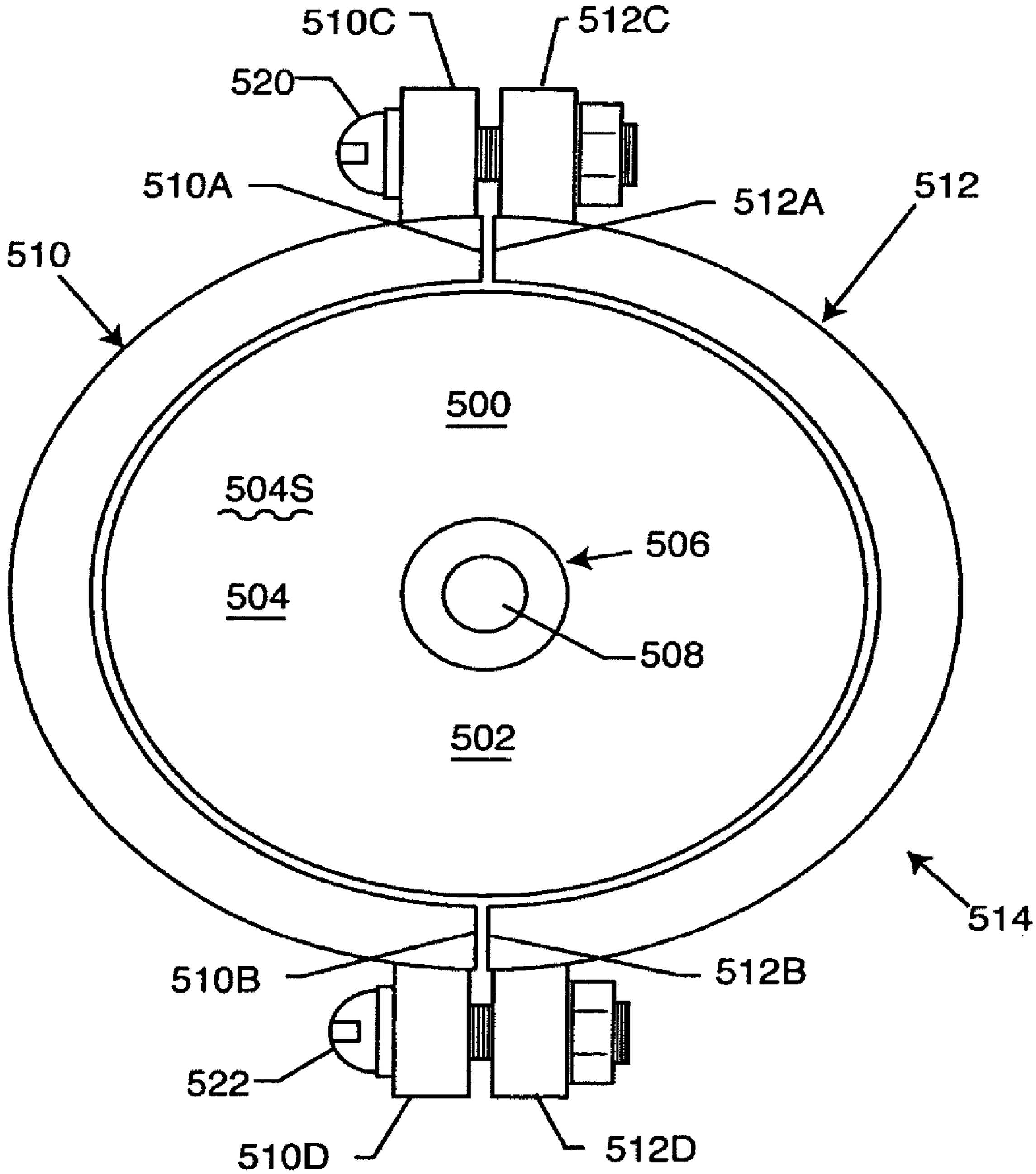


FIG. 4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512B
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510D
512D

FIG. 5

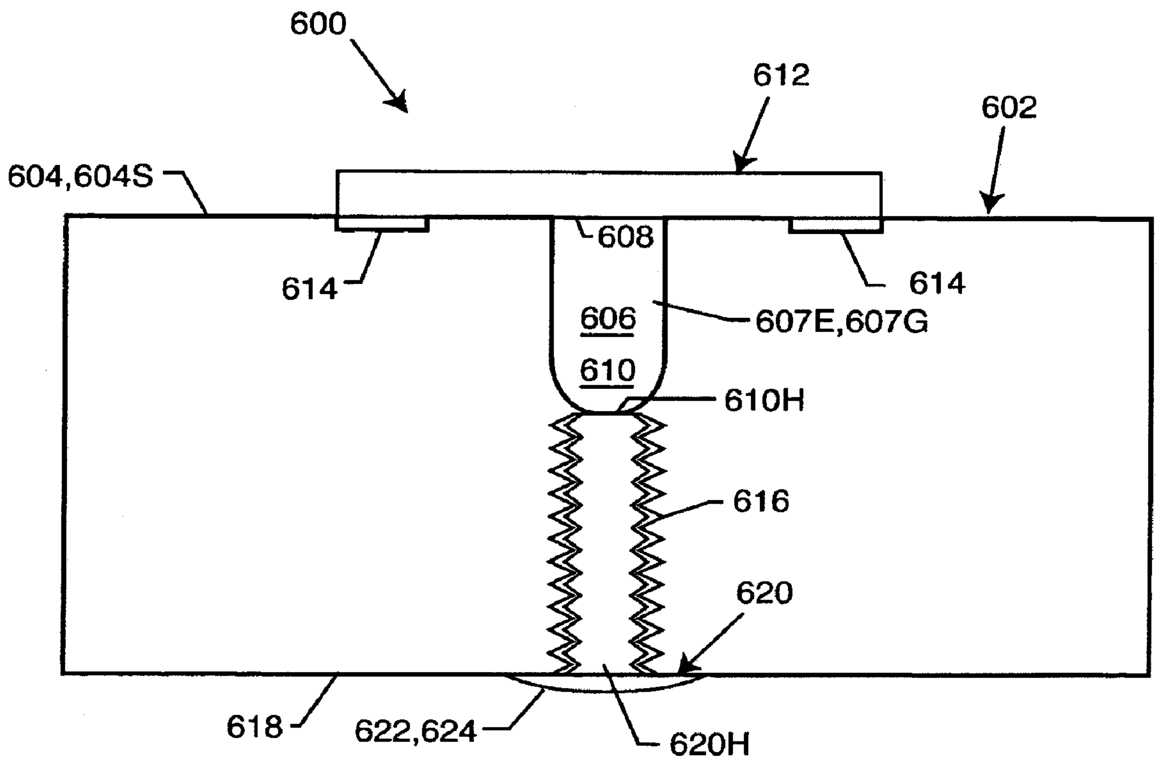

600
612
602
604,604S
608
614
614
606
607E,607G
610
610H
616
620
618
622,624
620H

FIG. 6

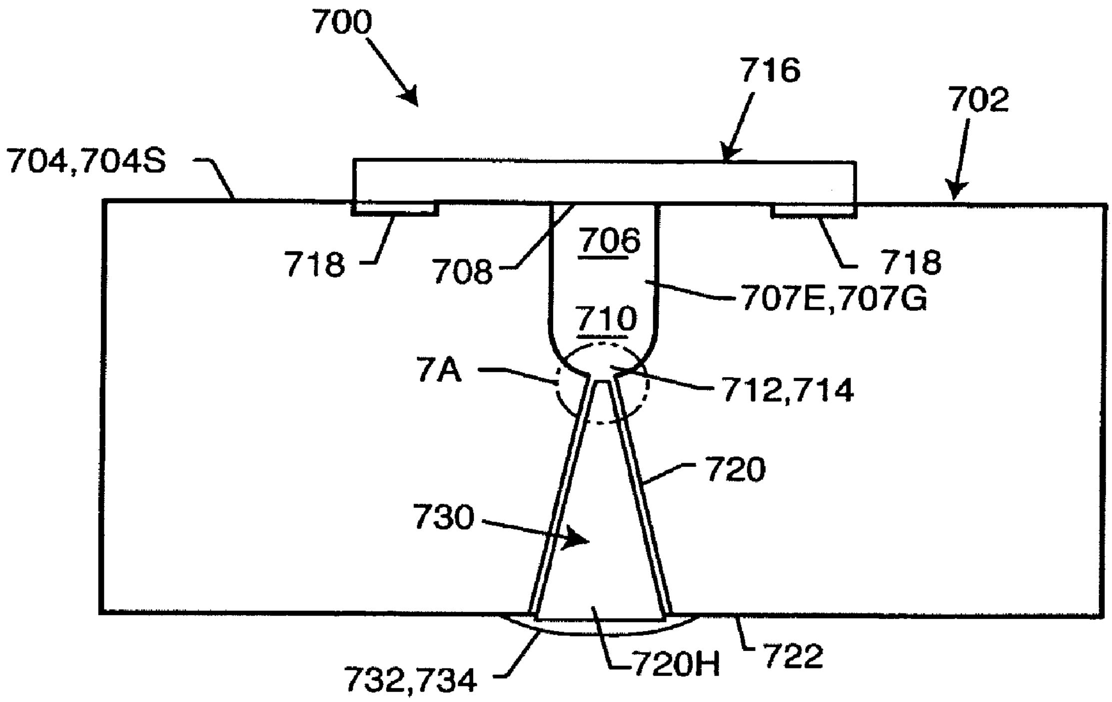
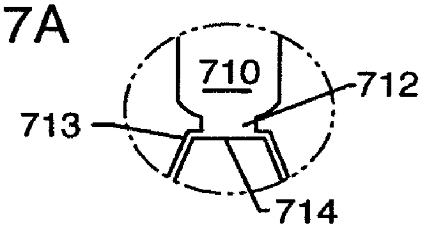


FIG. 7

FIG. 7A



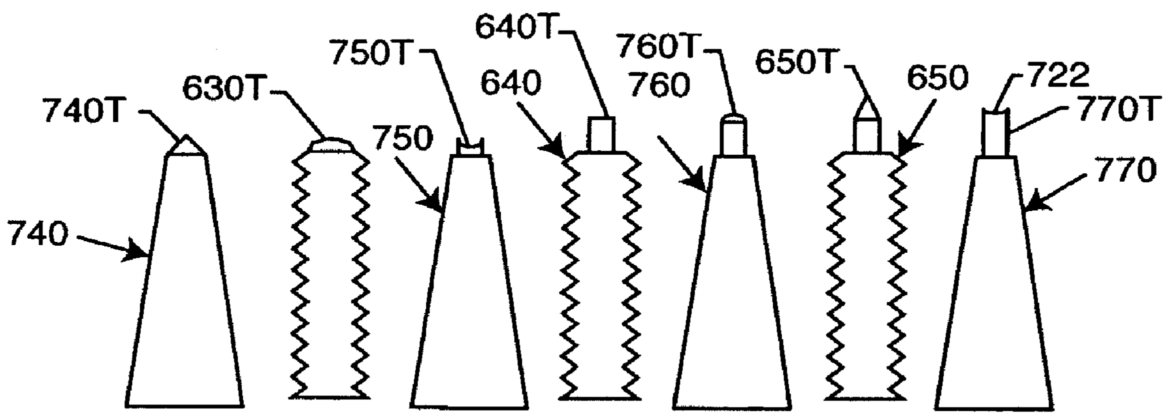


FIG. 8

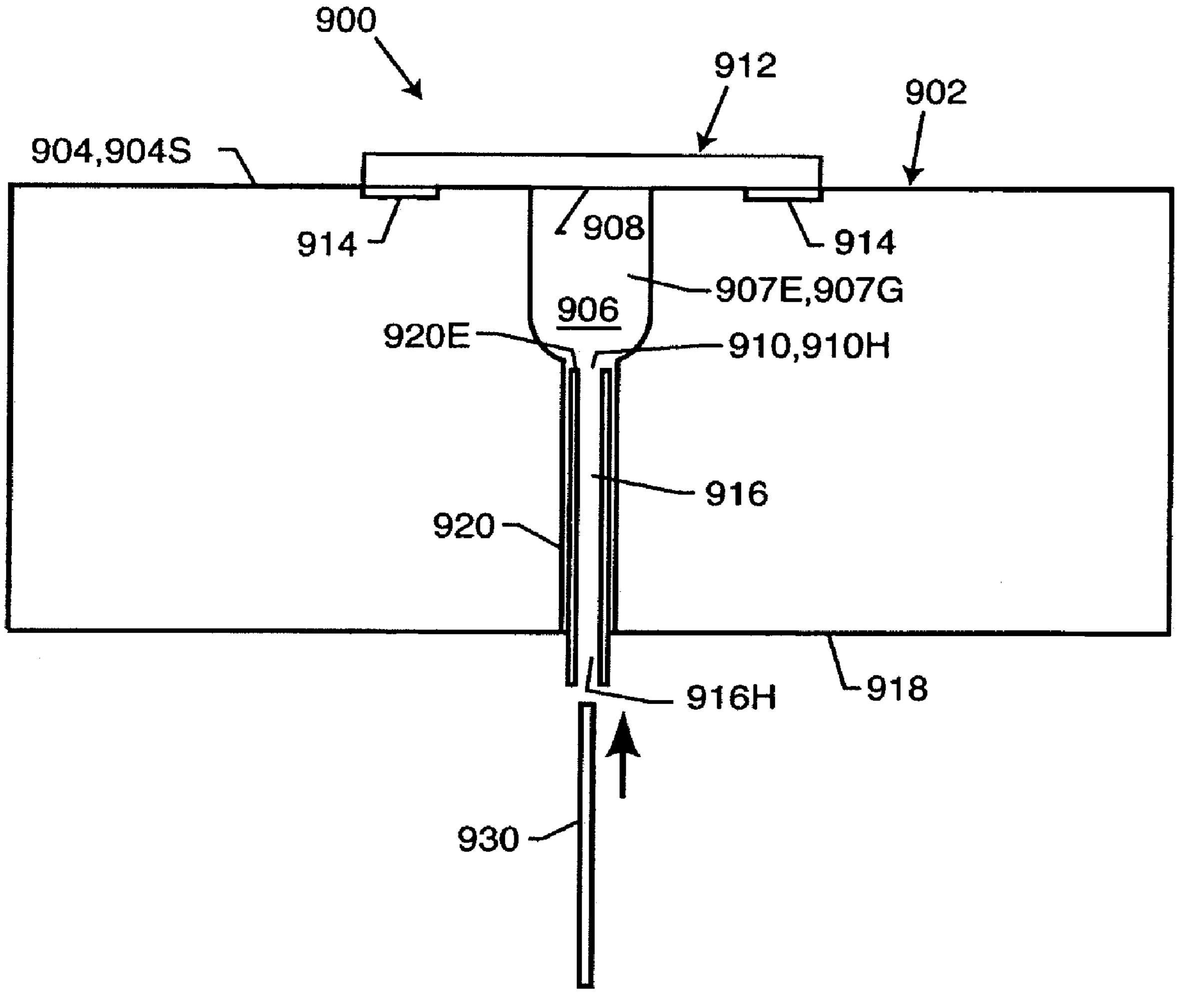

900
912
902
904,904S
914
908
914
907E,907G
906
920E
910,910H
916
920
918
916H
930

FIG. 9

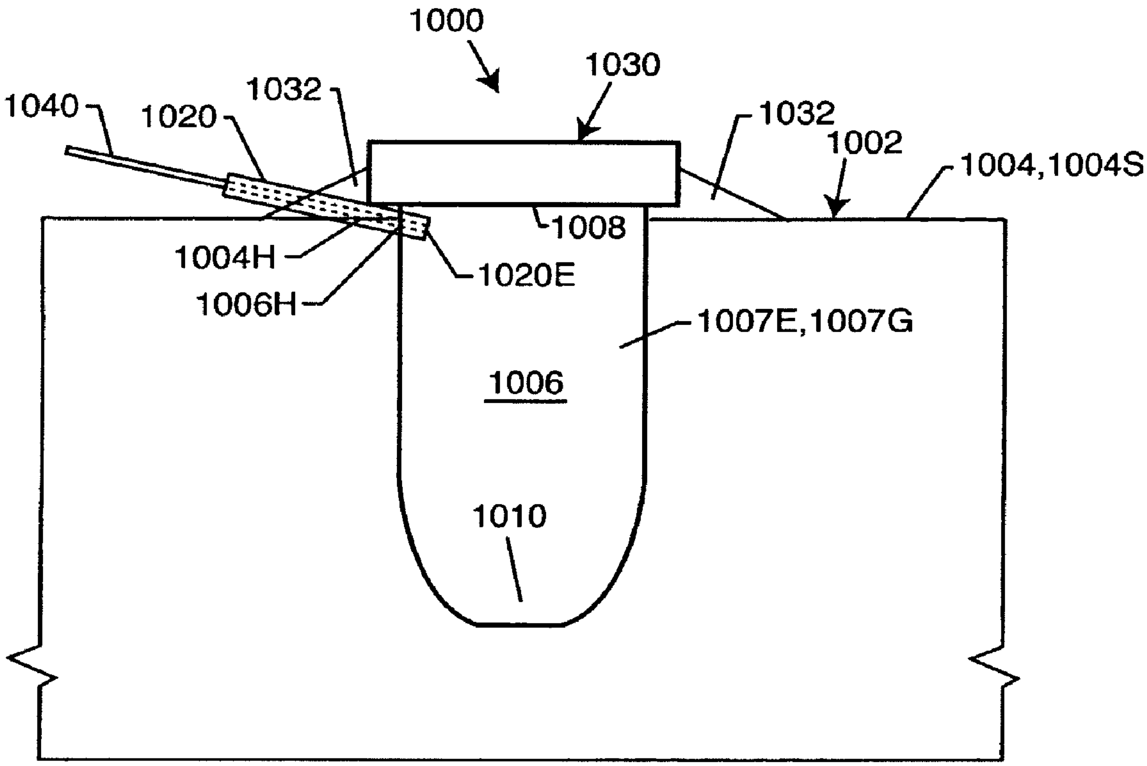

1000
1030
1032
1040
1020
1032
1002
1004,1004S
1008
1004H
1020E
1006H
1007E,1007G
1006
1010

FIG. 10

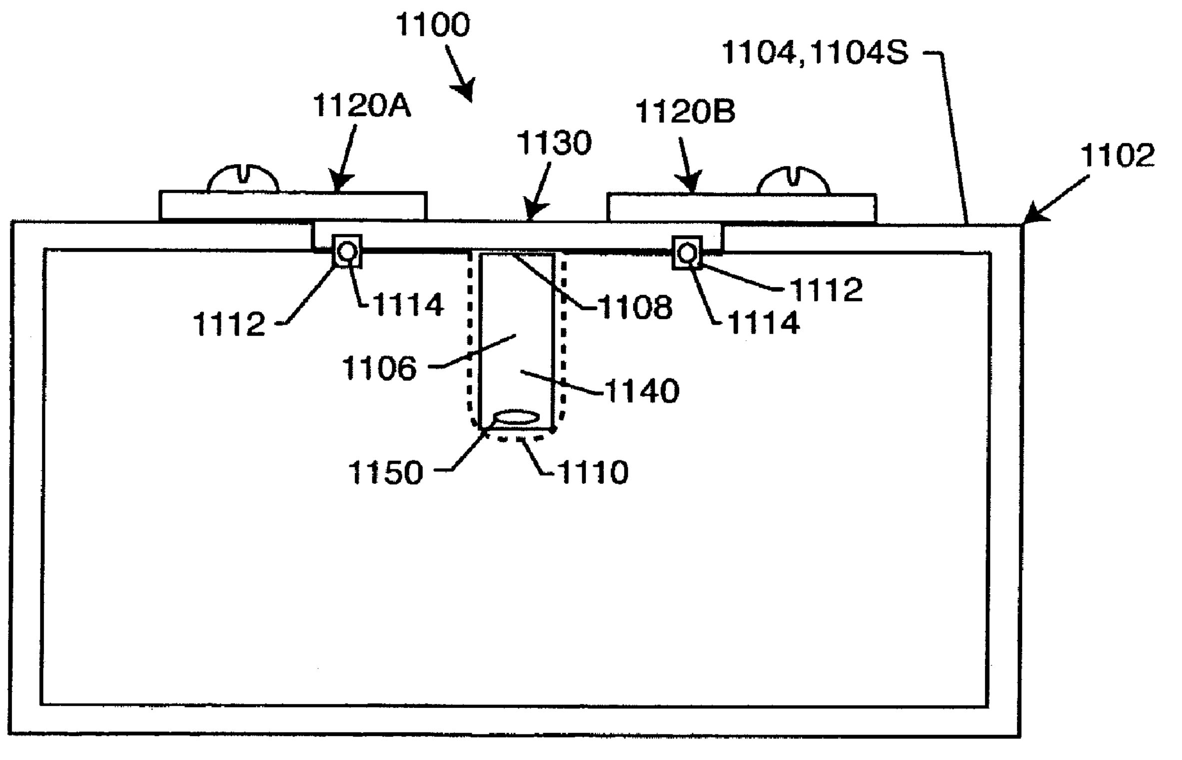

1100
1104,1104S
1120A
1120B
1130
1102
1112
1114
1108
1112
1114
1106
1140
1150
1110

FIG. 11

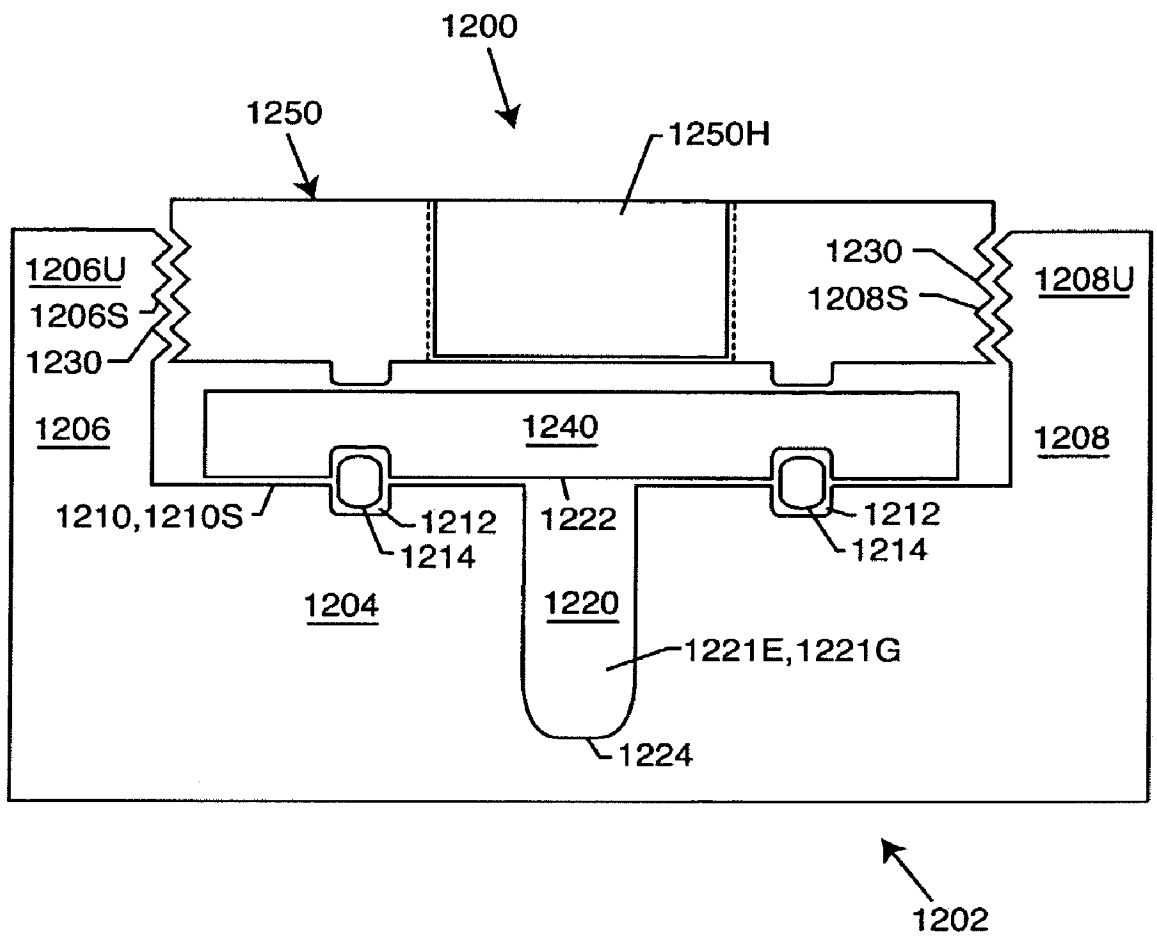

1200
1250
1250H
1230
1208S
1208U
1206U
1206S
1230
1206
1240
1208
1210,1210S
1212
1222
1212
1214
1214
1204
1220
1221E,1221G
1224
1202

FIG. 12

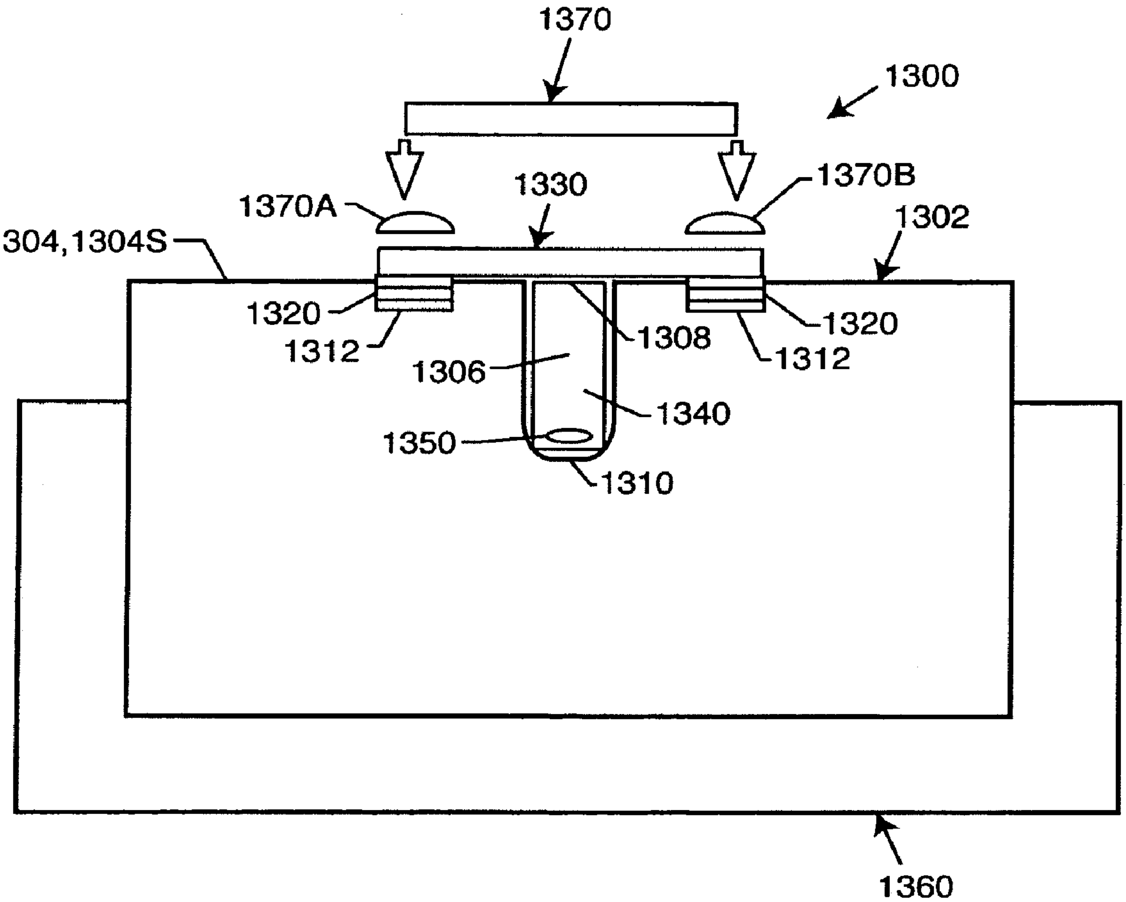

1370
1300
1370A
1330
1370B
1302
1304,1304S
1320
1312
1308
1320
1312
1306
1340
1350
1310
1360

FIG. 13

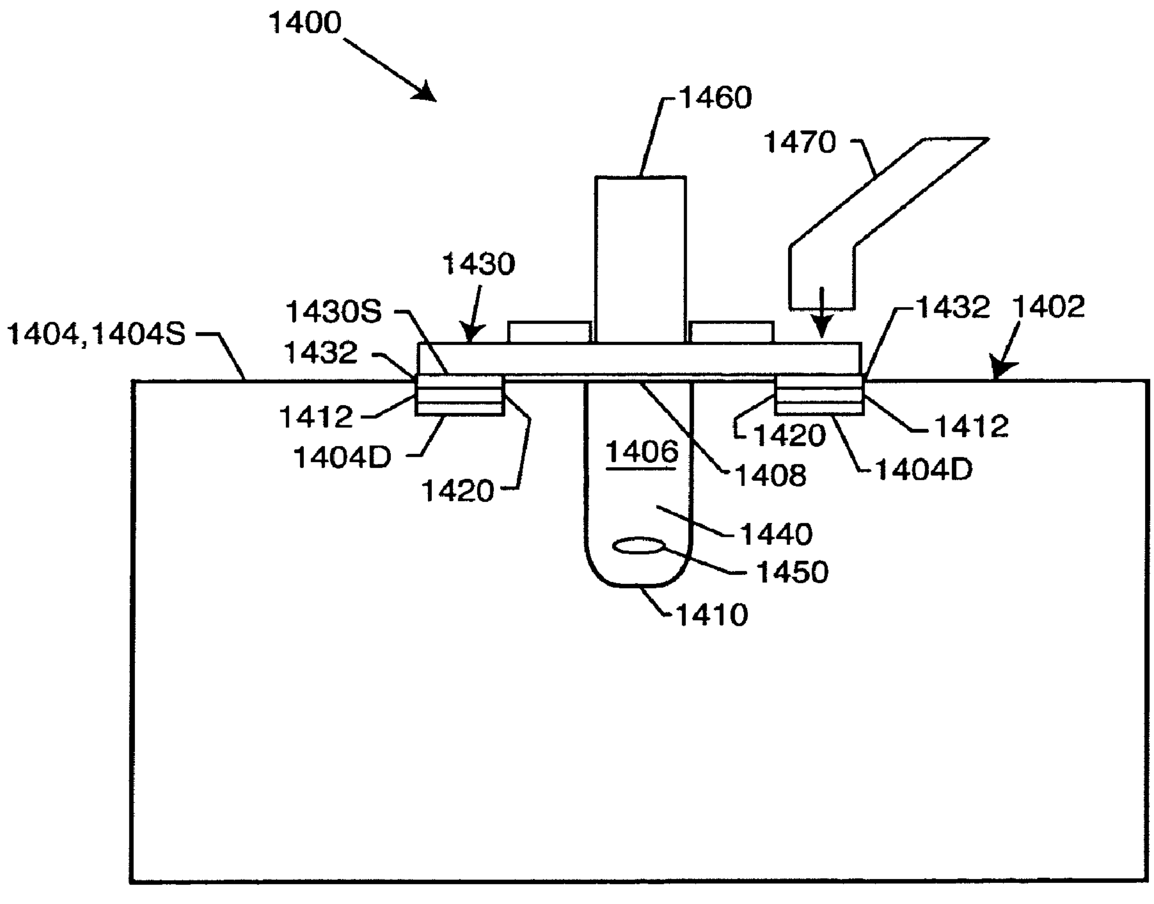
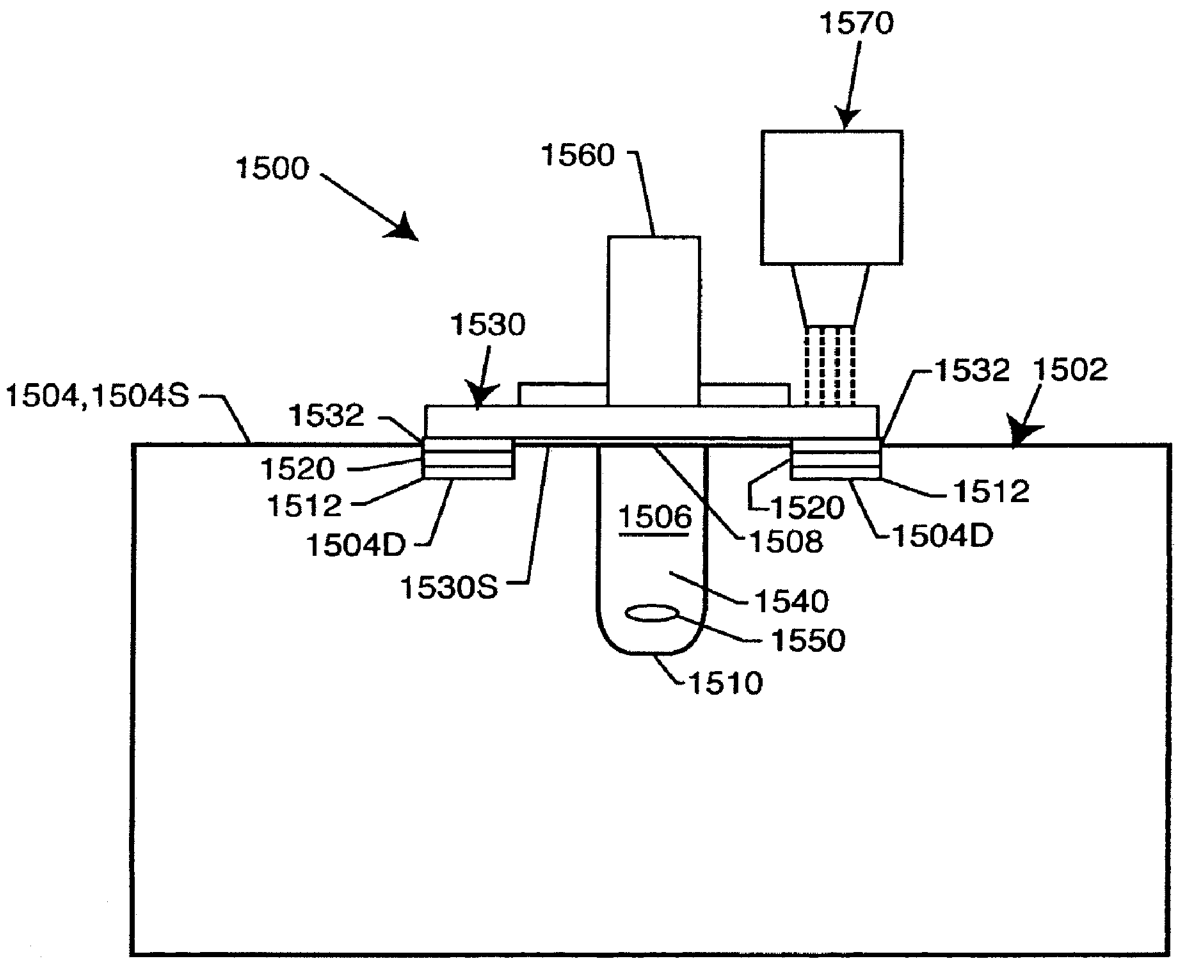

1400
1460
1470
1430
1430S
1432
1402
1404,1404S
1432
1412
1420
1412
1404D
1406
1408
1404D
1420
1440
1450
1410

FIG. 14



1570
1500
1560
1530
1532
1502
1504,1504S
1532
1520
1512
1504D
1530S
1506
1508
1520
1504D
1512
1540
1550
1510

FIG. 15

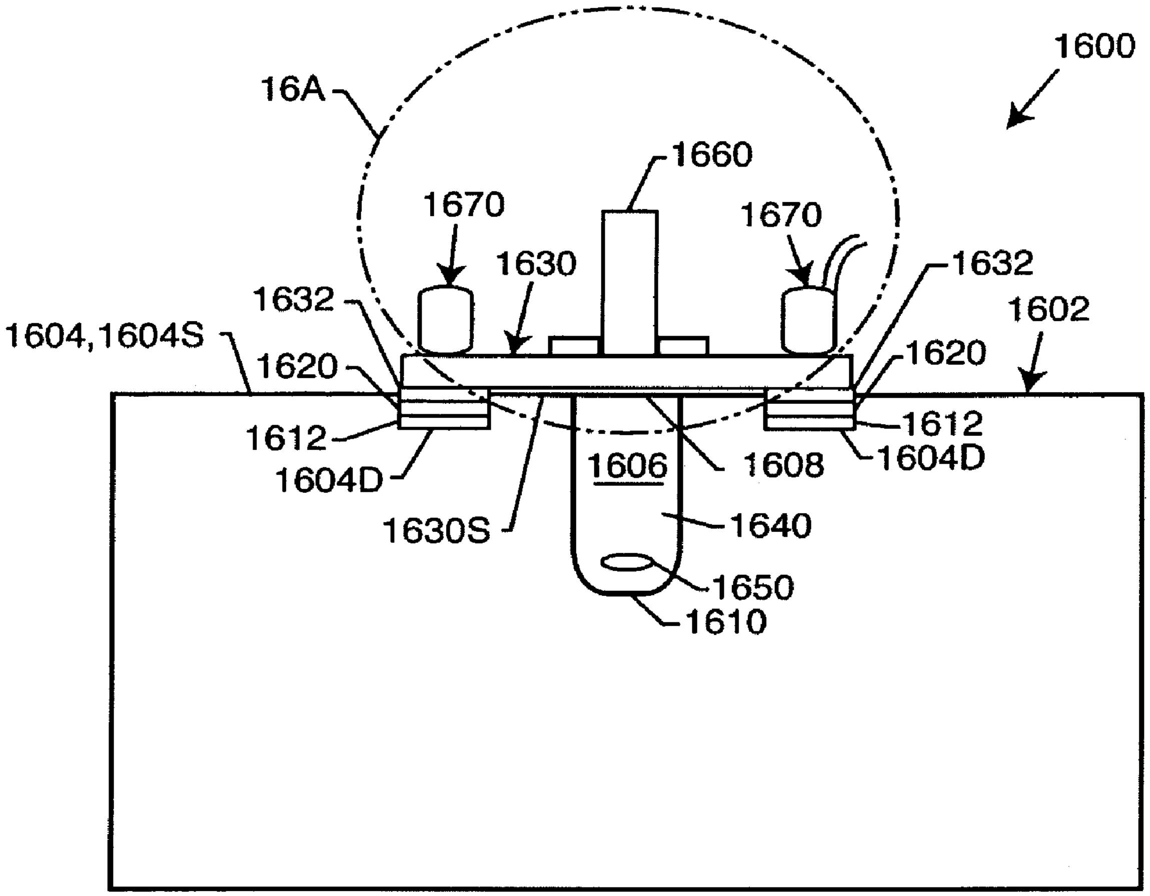


FIG. 16

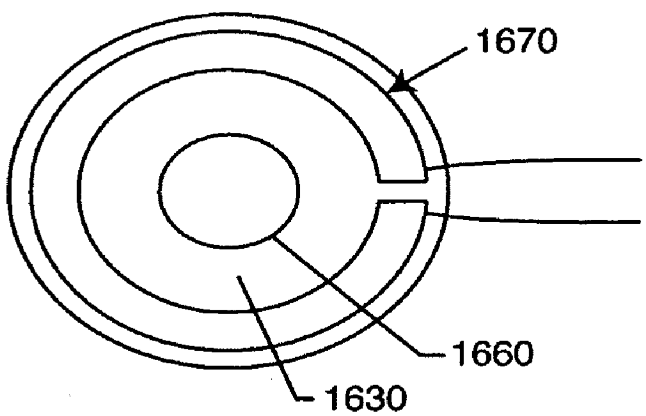


FIG. 16A

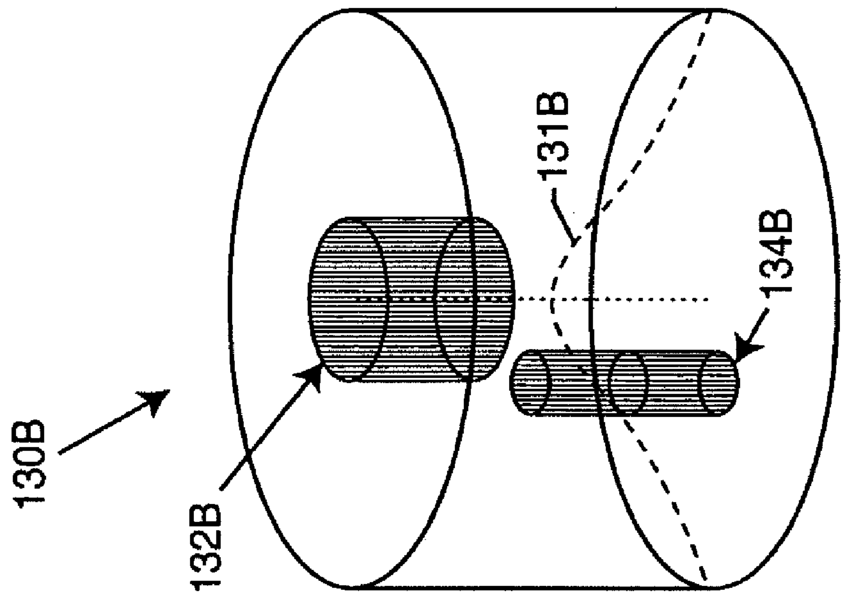


FIG. 17B

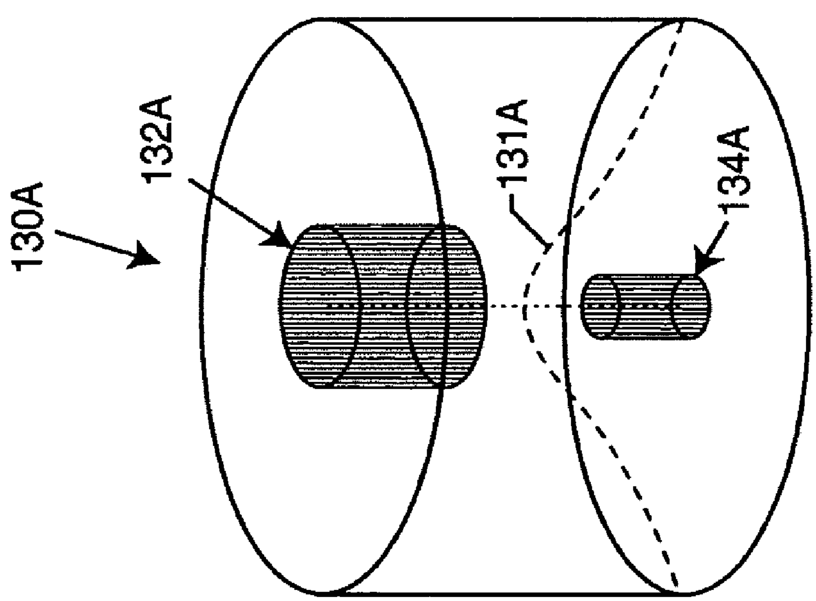


FIG. 17A

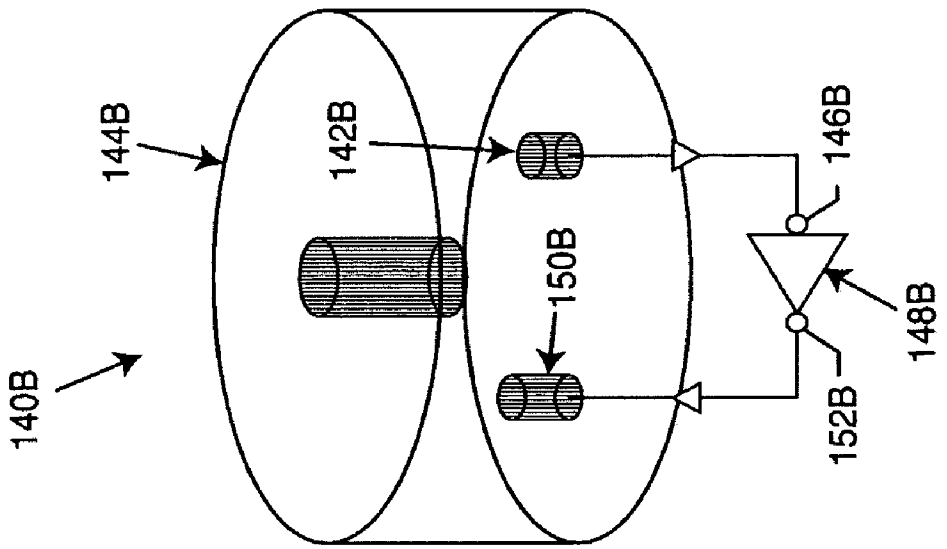


FIG. 18B

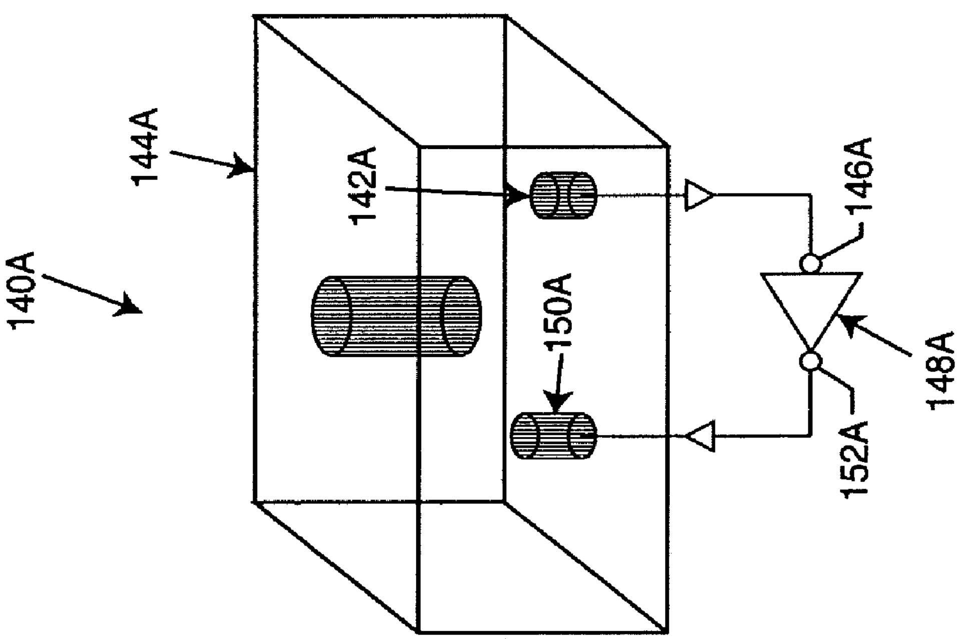


FIG. 18A

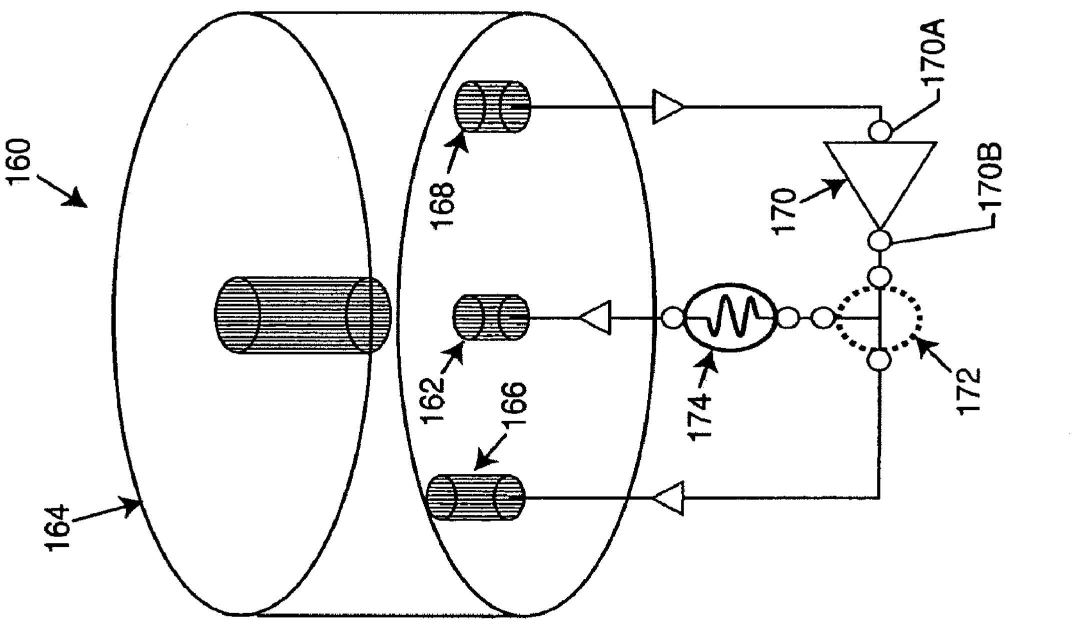


FIG. 19

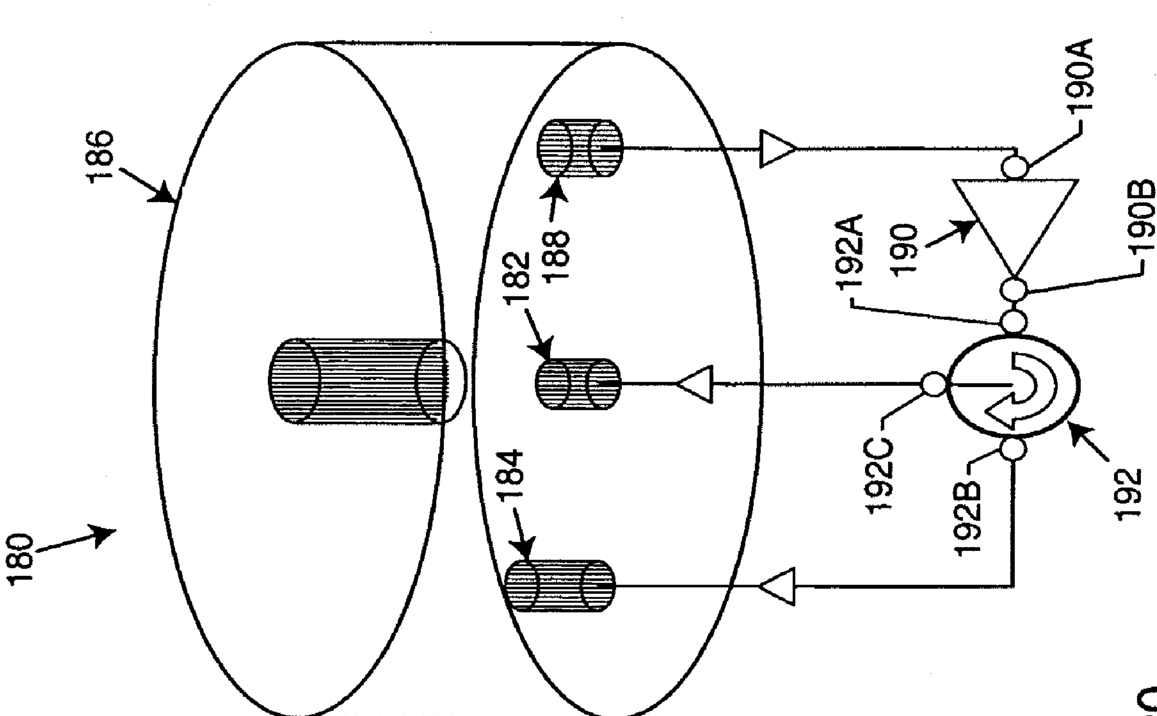


FIG. 20

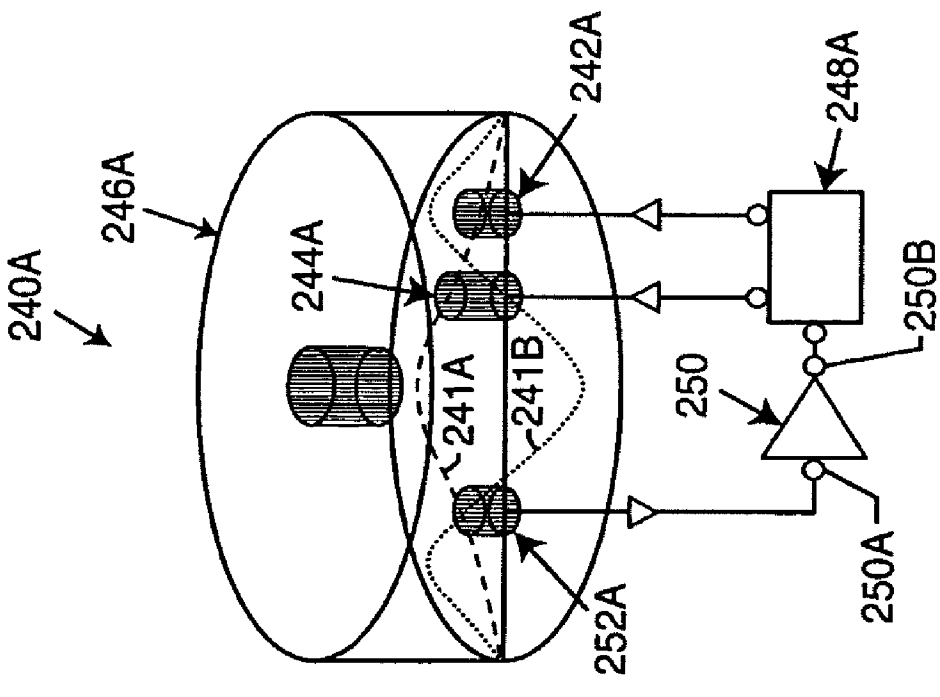


FIG. 21A

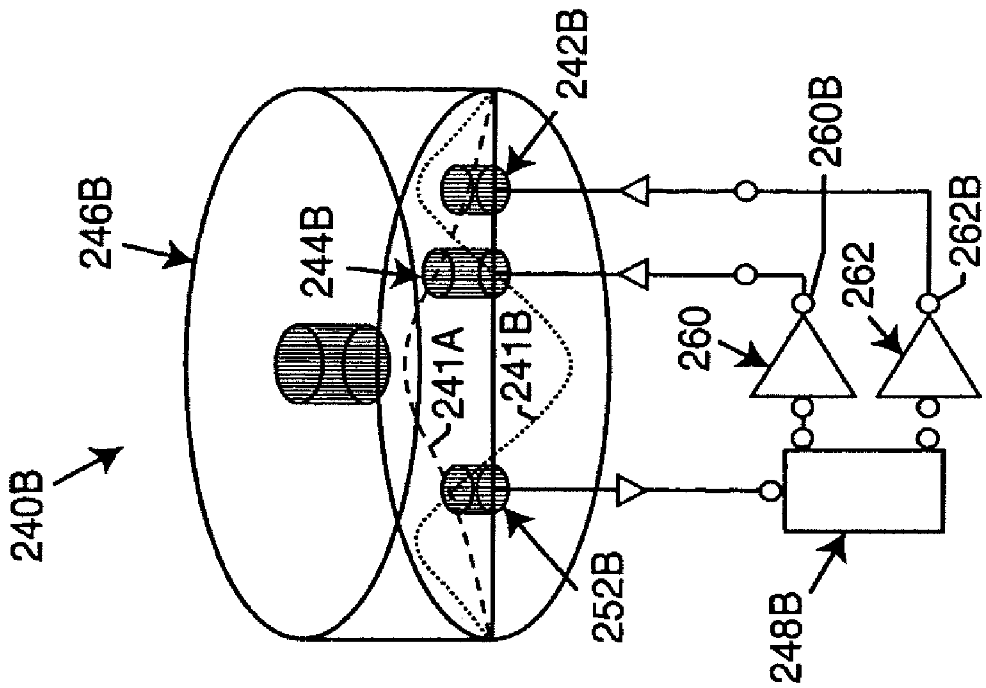


FIG. 21B

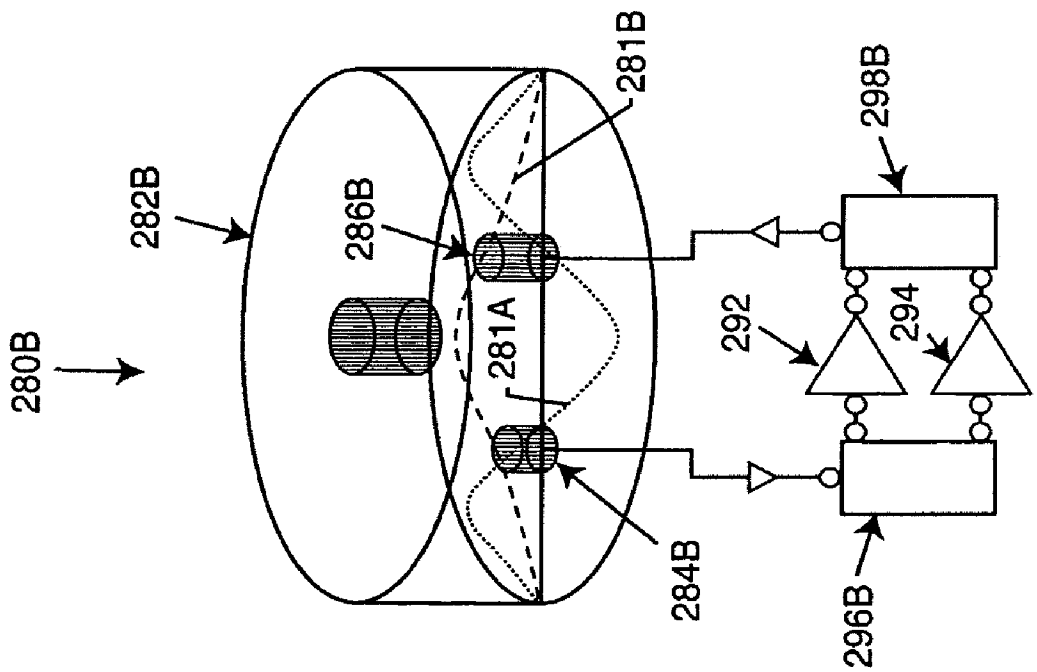


FIG. 22B

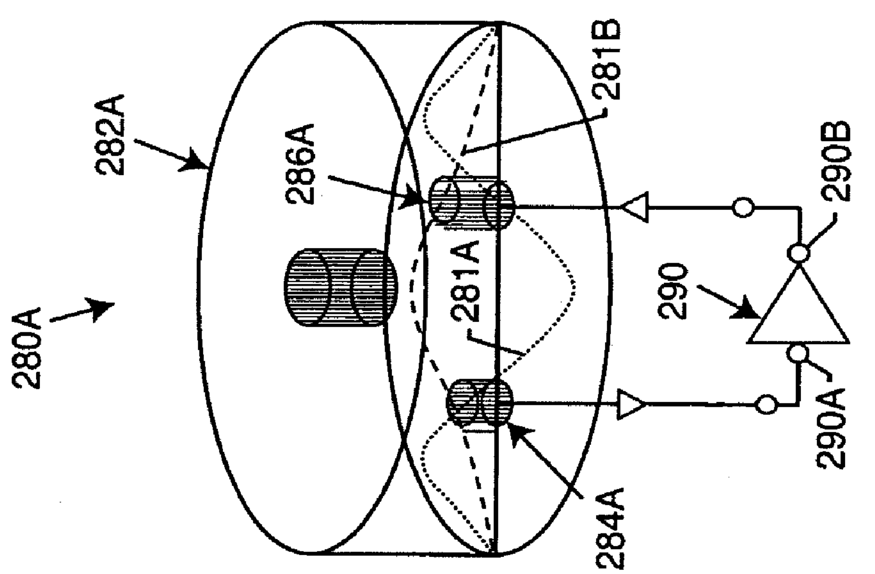


FIG. 22A

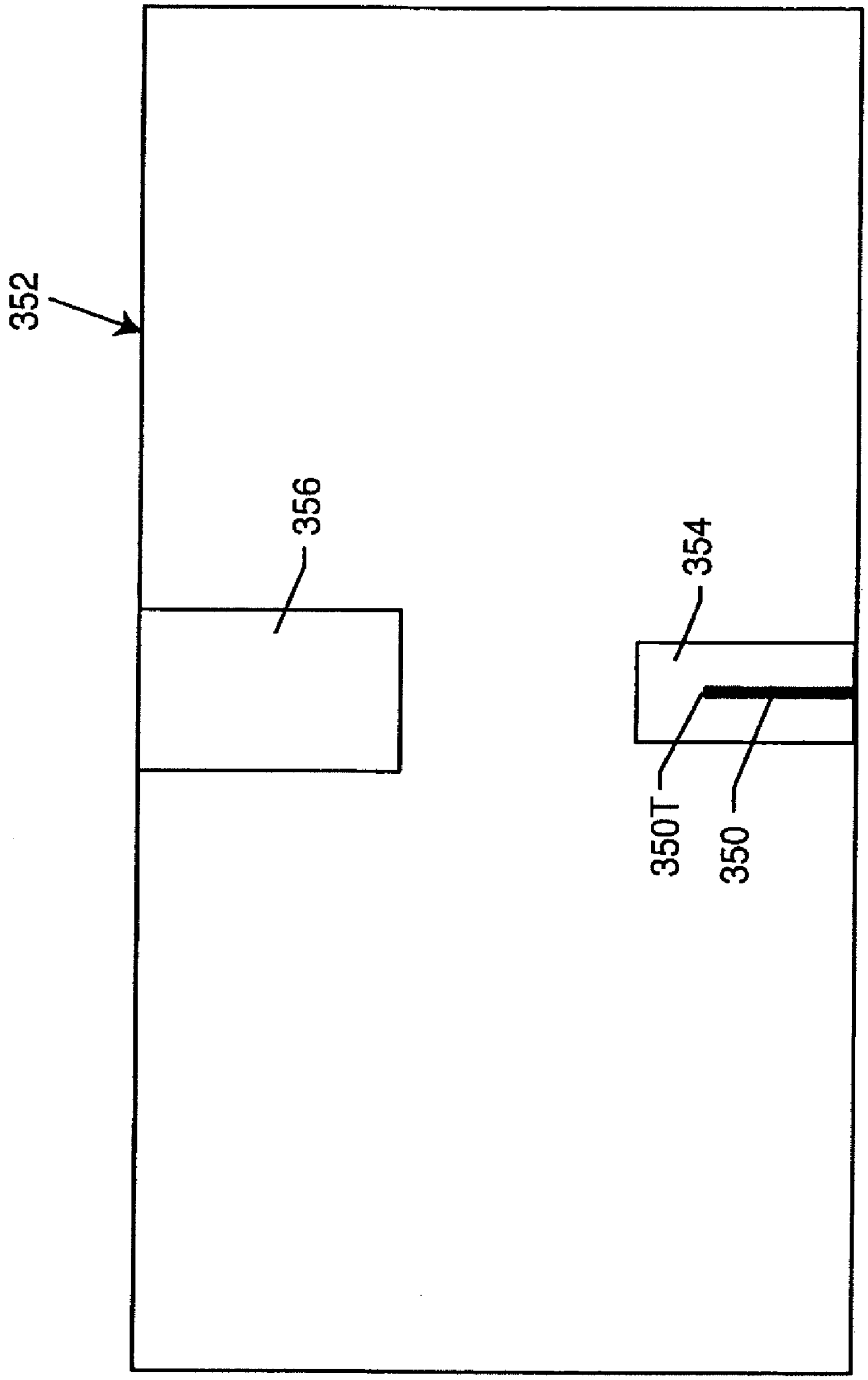


FIG. 23

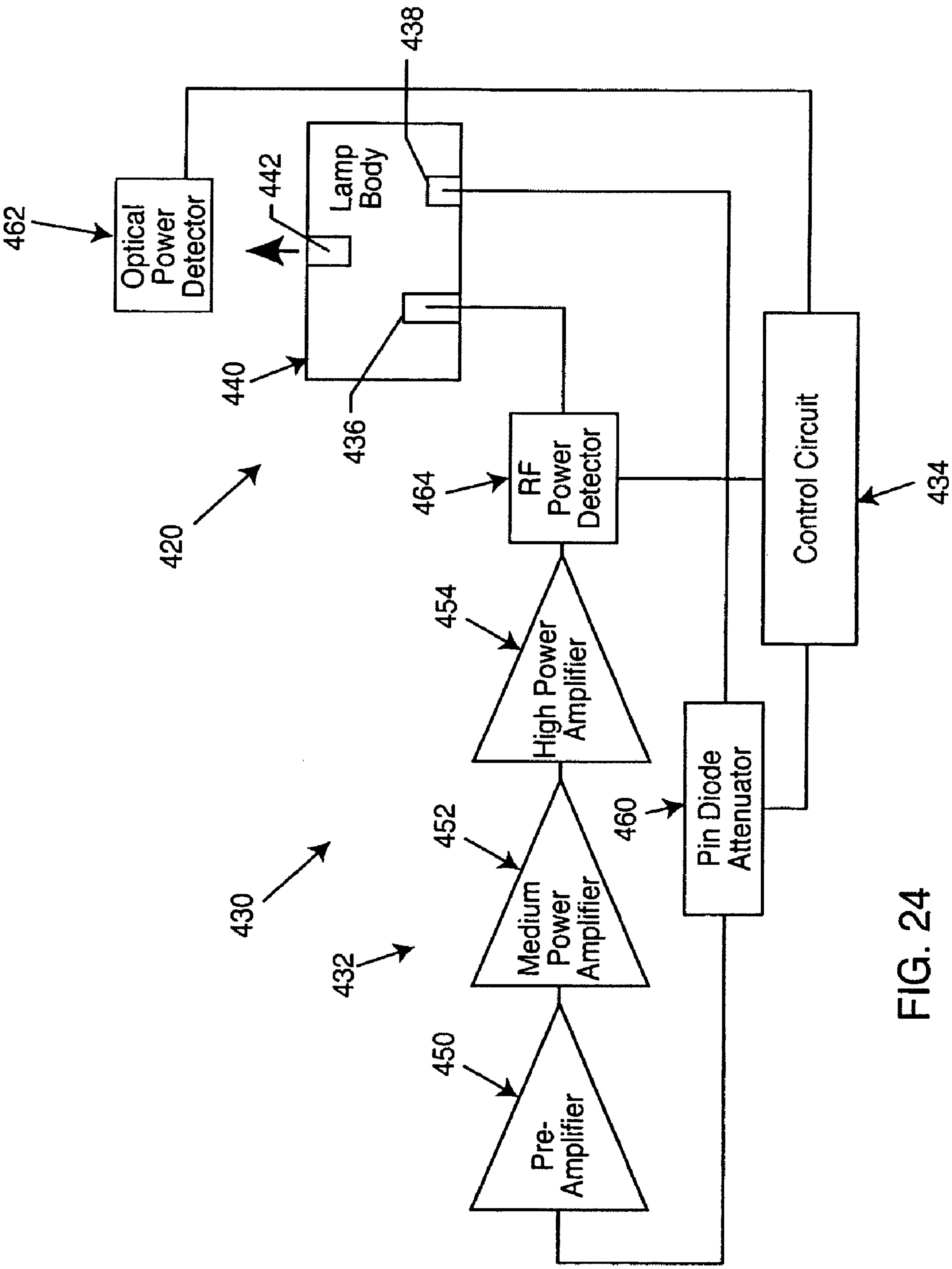
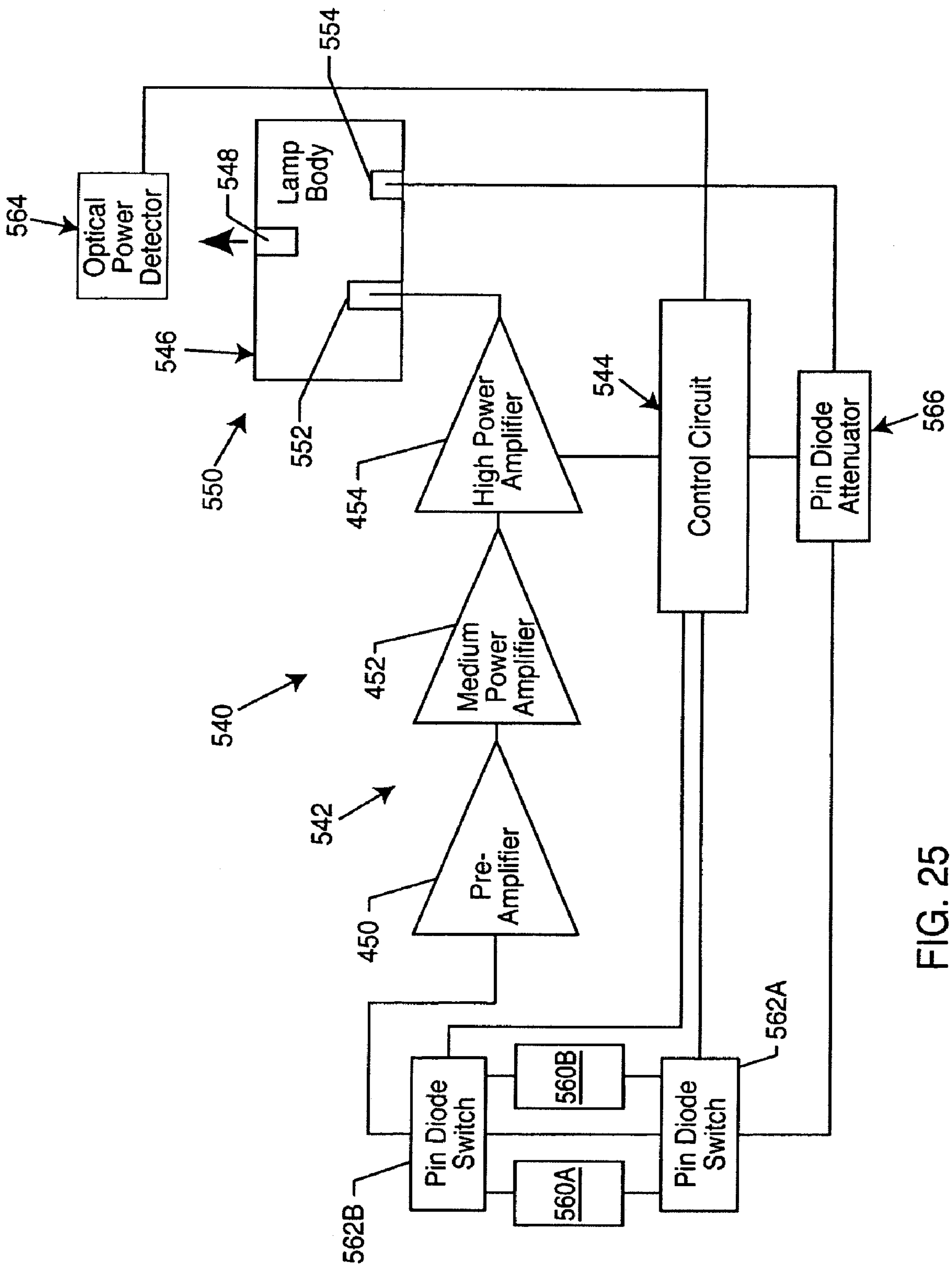
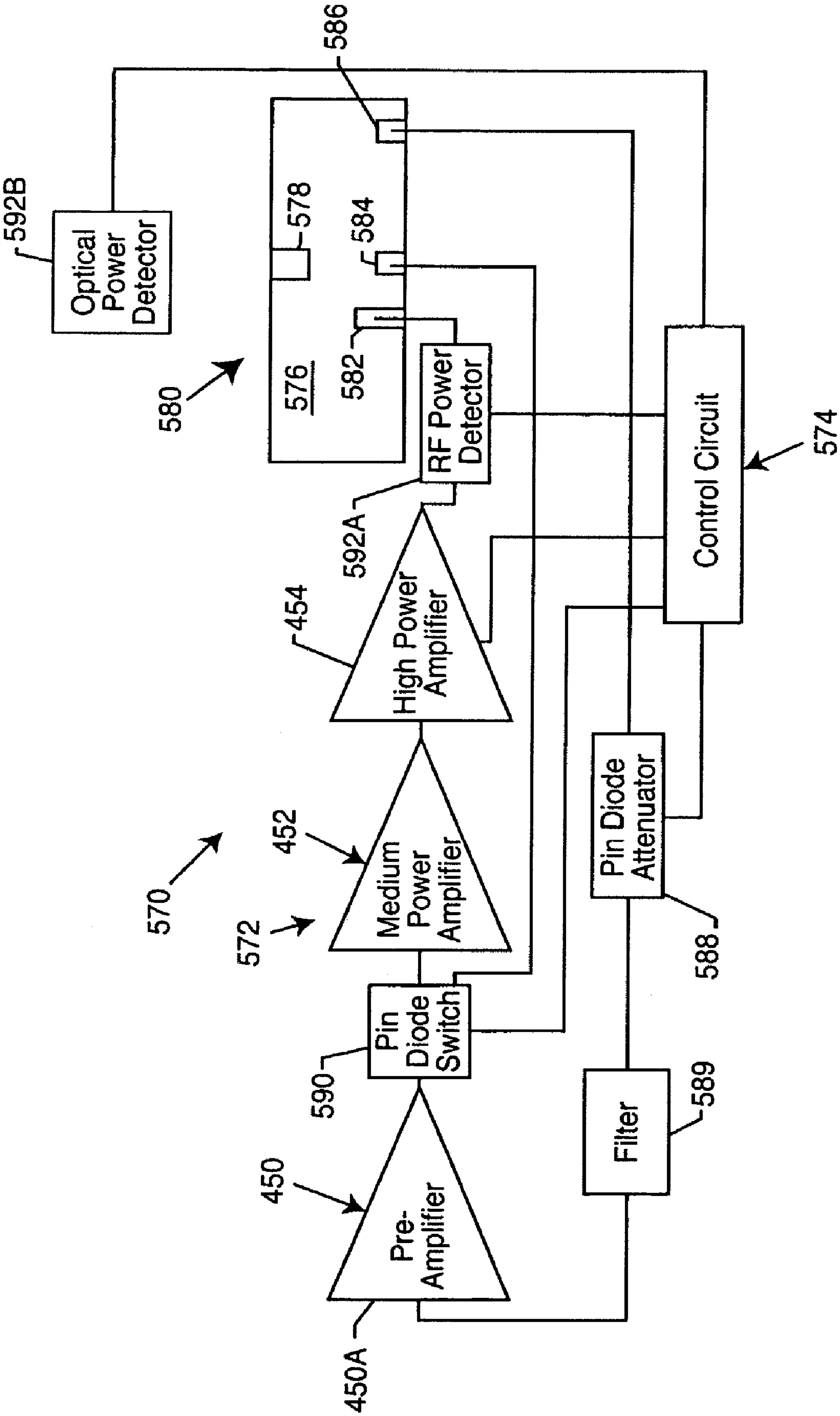

438
442
Lamp Body
462
Optical Power Detector
440
436
420
464
RF Power Detector
Control Circuit
434
454
High Power Amplifier
Pin Diode Attenuator
460
452
430
Medium Power Amplifier
432
450
Pre-Amplifier

FIG. 24



Optical Power Detector
564
Lamp Body
548
554
546
552
550
High Power Amplifier
454
544
Control Circuit
Pin Diode Attenuator
566
Medium Power Amplifier
452
540
542
Pre-Amplifier
450
Pin Diode Switch
562B
560B
560A
Pin Diode Switch
562A

FIG. 25



Optical Power Detector
592B
586
578
584
576
582
580
RF Power Detector
592A
Control Circuit
574
High Power Amplifier
454
Medium Power Amplifier
452
572
570
Pin Diode Attenuator
588
Pin Diode Switch
590
Filter
589
Pre-Amplifier
450
450A

FIG. 26

MICROWAVE ENERGIZED PLASMA LAMP WITH SOLID DIELECTRIC WAVEGUIDE

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. application Ser. No. 11/010,093, filed on Dec. 11, 2004 now U.S. Pat. No. 7,372,209 and entitled “MICROWAVE ENERGIZED PLASMA LAMP WITH SOLID DIELECTRIC WAVEGUIDE”, which is a continuation of U.S. 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 U.S. application Ser. No. 09/809,718, filed on Mar. 15, 2001 and issued as U.S. Pat. No. 7,737,809 B2 and entitled “PLASMA LAMP WITH DIELECTRIC WAVEGUIDE”, which claimed the benefit of priority to U.S. Provisional Application Ser. No. 60/222,028, filed on Jul. 31, 2000 and entitled “PLASMA LAMP”, the contents of which are incorporated herein by reference in their entireties.

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 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 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 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.

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. **7**A is a detail view of the circled region "**7**A" 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. **16**A is a top plan view of the FIG. **16** DWIPL.

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

FIG. **18**A 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.

FIG. **18**B 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. **21**A 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. **21**B schematically depicts an alternative configuration of the FIG. **21**A 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. **22**A 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. **22**B schematically depicts an alternative configuration of the FIG. **22**A 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. **18**A, **18**B, **22**A and **22**B combined amplifier and control circuit.

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

FIG. **26** is a block diagram of a configuration of the FIGS. **19**, **20**, **21**A and **21**B 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 **103**A, **103**B, and opposed sides **103**C, **103**D generally transverse to sides **103**A, **103**B. DWIPL **101** further includes a bulb **107** of the (B) variety, disposed proximate to side **103**A and preferably generally opposed to probe **117**, containing a fill **108** including a “starting” gas **108**G, such as a noble gas, and a light emitter **108**E, 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 **103**A 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 **103**A, **103**B, **103**C, **103**D of waveguide **103**, with the exception of those surfaces depending from side **103**A 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 **103**A, **103**C and **103**D.

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 ($NaZr_2(PO_4)_3$) 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}/° 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 λ 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, $E=\pi A/4(f\#)^2$. 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. **7**A 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 **204**S from which depends a lamp chamber **206** having an aperture **208**. A ball lens **210** is attached to surface **204**S by a seal **212**. Preferably, lens **210** is made of sapphire. Indicium **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 **304**S 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 **314**E, **316**E 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 **304**S 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**. Indicium **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 **404**S 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 **504**S, and a window **506** attached to surface **504**S 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 **510**A, **510**B and **512**A, **512**B, respectively, attached to flanges **510**C, **510**D and **512**C, **512**D, respectively. First and second fasteners **520**, **522** are used to connect the aligned flanges, compressing portions **510**, **512** about the body **502**.

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 **604**S from which depends a lamp chamber **606** having an aperture **608** and a bottom **610** with a hole **610**H. A window **612**, preferably made of sapphire, is attached to surface **604**S by a seal **614**. Lamp body **602** further includes a tapped bore **616** extending between a hole **620**H in a body side **618** generally opposed to side **604**, and chamber bottom **610**, so that the bore is in communication with hole **610**H. The window **612** is sealed to surface **604**S 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 **607**G to be used in the lamp chamber, which is at or near the desired non-operating pressure for the lamp. The light emitter **607**E is then deposited in lamp chamber **606** through bore **616** and hole **610**H. Plug **620**, which provides a mechanical and gas barrier to contain the fill mixture, is then screwed into bore **616** through hole **620**H, and a metallic or glass material **624** deposited over head **622** to effect a final seal.

Referring to FIGS. **7** and **7**A, a DWIPL **700** includes a body **702** having a side **704** with a surface **704**S 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 **704**S by a seal **718**. Lamp body **702** further includes a tapered bore **720** extending between a hole **720**H 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 **704**S 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 **707**G to be used in the lamp chamber, which is at or near the desired non-operating pressure for the lamp. The light emitter **707**E is then deposited in lamp chamber **706** through bore **720** and aperture **714**. Plug **730** is then force-fitted through hole **720**H 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 **630**T, a rod-shaped tip **640**T, and a chisel-shaped tip **650**T. Plugs **740**, **750**, **760** and **770** have, respectively, a conical tip **740**T, a cup-shaped tip **750**T, a chisel-shaped tip **760**T, and a rod-shaped tip **770**T 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 **904**S from which depends a lamp chamber **906** having an aperture **908** and a bottom **910** with a hole **910**H. A window **912**, preferably made of sapphire, is attached to surface **904**S 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 **910**H. After window **912** is sealed to surface **904**S in an inert atmosphere, a glass or quartz tube **920** having an end **920**E is inserted into bore **916** through a hole **916**H so that end **920**E extends through hole **910**H into chamber **906**. The chamber is then evacuated by a vacuum pump connected to tube **920**. A fill mixture of starting gas **907**G and light emitter **907**E 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 **1004**S from which depends a lamp chamber **1006** having an aperture **1008** and a bottom **1010**. Side **1004** has a hole **1004**H in communication with a hole **1006**H in chamber **1006**. A glass or quartz tube **1020** having an end **1020**E is inserted through holes **1004**H and **1006**H so that the end penetrates the chamber. A window **1030** covering aperture **1008**, preferably made of sapphire, is then attached to surface **1004**S 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 **1004**S with the tube **1020** in place and hole **1004**H plugged by the sealing material, the chamber is evacuated by a vacuum pump connected to the tube. A fill mixture of starting gas **1007**G and light emitter **1007**E 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 **1104**S 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 **1206**, **1208**, respectively, which are generally orthogonal to body portion **1204** and extend in upper portions **1206**U, **1208**U, respectively. Body portion **1204** has a side **1210** with a surface **1210**S 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 **1206**U, **1208**U have, respectively, an interior surface **1206**S, **1208**S, 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 **1221**G and light emitter **1221**E 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 **1250**H 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 **1304**S 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 **1370**A and **1370**B 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 **1404**S 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 **1404**D in side **1404** is a first metallization ring **1412** circumscribing the aperture **1408**. Within detail **1404**D is a seal preform **1420**, such as a platinum ring, superposed on ring **1412**. A window **1430** has a lower surface **1430**S 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** 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 **1504**S 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 **1504**D in side **1504** is a first metallization ring **1512** circumscribing the aperture **1508**. Within detail **1504**D is a seal preform **1520**, such as a platinum or glass ring, superposed on ring **1512**. A window **1530** has a lower surface **1530**S 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 **16**A, a DWIPL **1600** includes a body **1602** having a side **1604** with a surface **1604**S 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 **1604**D of side **1604** is a first metallization ring **1612** circumscribing the aperture **1608**. Within detail **1604**D is a seal preform **1620**, such as a platinum or other conductive material, superposed on ring **1612**. A window **1630** has a lower surface **1630**S 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. **17**A and **17**B schematically show two cylindrical lamp configurations **130**A, **130**B, respectively, both operating at the fundamental cylindrical cavity mode, commonly known as $TM_{0,1,0}$, and having a bulb **132**A, **132**B, respectively, located at the single electric field maximum. Dashed curves **131**A, **131**B show, respectively, the electric field distribution in the cavity. In FIG. **17**A, a drive probe **134**A is located at the field maximum. In FIG. **17**B, drive probe **134**B is not located at the field maximum; however, it contains a longer probe which provides the same coupling efficiency as probe **134**A. 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 **140**A, **140**B shown, respectively, in FIGS. **18**A and **18**B for a rectangular prism-shaped cavity and a cylindrical cavity. A second "feedback" probe **142**A, **142**B, respectively, is introduced into a cavity **144**A, **144**B, respectively. Feedback probe **142**A, **142**B, respectively, is connected to input port **146**A, **146**B, respectively, of a combined amplifier and control circuit (ACC) **148**A, **148**B, respectively, and a drive probe **150**A, **150**B, respectively, is connected to ACC output port **152**A, **152**B, 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 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. **18**A or **18**B 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 **170**B 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 **170**A 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 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 **190**A of an ACC **190**. The three probes can be located anywhere in the cavity except near a field minimum. Power from output port **190**B of ACC **190** is delivered to a first port **192**A of a circulator **192** which directs power from port **192**A to a second port **192**B 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 **192**C 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 **192**C and travels back to ACC output port **190**B. 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 **192**A to **192**B, from port **192**B to port **192**C, and from port **192**C to port **192**A.

FIGS. **21**A and **21**B show third and fourth lamp configurations **240**A, **240**B 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 **242**A, **242**B, respectively, operates in the start cavity mode, and drive probe **244**A, **244**B, respectively, operates in the drive cavity mode. As indicated by dashed curves **241**A and **241**B, 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 **246**A and **246**B, the start probe **242**A, **242**B, respectively, can be critically coupled at the resonant frequency of the $TM_{0,2,0}$ mode before plasma formation, and the drive probe **244**A, **244**B, 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 diplexer **248**A, **248**B, respectively, is used to separate the two resonant frequencies. In FIG. **21**A, a single ACC **250** connected at its input **250**B to diplexer **248**A is used to power both cavity modes. The two frequencies are separated by diplexer **248**A and fed to the start probe **242**A and drive probe **244**A. Feedback probe **252**A is connected to input port **250**A of ACC **250**. In FIG. **21**B, two separate amplifiers **260**, **262** are used to power the two cavity modes independently. Diplexer **248**B separates the two frequencies coming out of feedback probe **252**B. 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. **22**A and **22**B show lamp configurations **280**A, **280**B, respectively, which do not include a start probe but utilize two separate cavity modes. As indicated by curves **281**A and **281**B, respectively, in cavities **282**A and **282**B, 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 **284**A, **284**B, respectively, can be located anywhere in the cavity except near a field minimum of either cavity mode. The drive probe **286**A, **286**B, 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. **22**A, a single ACC **290** having input and output ports **290**A, **290**B, respectively, is used to power both cavity modes. In FIG. **22**B, two separate ACC's **292**, **294** are used to power the two cavity modes independently. A first diplexer **296**B separates the two frequencies coming out of feedback probe **284**B and a second diplexer **298**B combines the two frequencies going into drive probe **286**B. 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 **350**T 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. **18**A, **18**B, **22**A and **22**B, 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 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. **18**A, **18**B, **22**A and **22**B. A "starting" bandpass filter **560**A and an "operating" bandpass filter **560**B, 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 **560**A and **560**B 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 **562**A, **562**B, 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 **560**A, 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 **560**B. 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 **560**A 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 **560**A and **560**B, following a predetermined operating sequence. An optical power detector **564** 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**, **21**A and **21**B. The feedback probe **586** is connected to input **450**A 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 **592**A monitors power usage within body **576**, and/or a sensor **592**B 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. An electrodeless plasma lamp comprising:

a lamp body comprising a dielectric material having a dielectric constant greater than 2;

an electrically conductive material forming an outer surface around the lamp body;

a power source configured to provide power to the lamp body at about a resonant frequency for the lamp body;

an electrodeless bulb containing a fill, the fill positioned within the lamp body to receive at least a portion of the power from the lamp body, the fill adapted to emit light when the power is received from the lamp body;

the electrically conductive material including an opening in the outer surface;

the bulb including at least a portion of light transmissive material recessed from the opening such that a light path is formed between the light transmissive material and the opening in the outer surface; and

the light transmissive material positioned between the fill and the opening in the outer surface such that the light emitted from the fill is transmitted through the light transmissive material and out of the opening.

2. The lamp of claim **1**, further comprising a reflector configured to direct the light out of the lamp body.

3. The lamp of claim **2**, wherein the reflector is formed on a surface of the solid dielectric material.

4. The lamp of claim **2**, wherein the reflector is spaced apart from the light transmissive material.

5. The lamp of claim **1**, wherein the light path is disposed within an opening formed by the dielectric material.

6. The lamp of claim **1**, wherein the light path comprises a light tunnel between the light transmissive material and the opening.

7. The lamp of claim **1** further comprising a hollow reflective optical element to direct light away from the lamp body.

8. The lamp of claim **7** wherein the optical element is a tube lined with a reflective material.

9. The lamp of claim **1** further comprising a light pipe to direct light away from the lamp body.

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