United States Patent [19]

Spero et al.

[11] **3,872,349**

[45] **Mar. 18, 1975**

[54] **APPARATUS AND METHOD FOR GENERATING RADIATION**

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[73] Assignee: **Fusion Systems Corporation,** Rockville, Md.

[22] Filed: **Aug. 22, 1973**

[21] Appl. No.: **390,659**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 239,149, March 29, 1973.

[52] **U.S. Cl.** **315/39,** 250/542, 313/231, 315/111

[51] **Int. Cl.** **H01j 7/46,** H01j 19/80

[58] **Field of Search** 313/63, 231; 315/39, 111; 250/542

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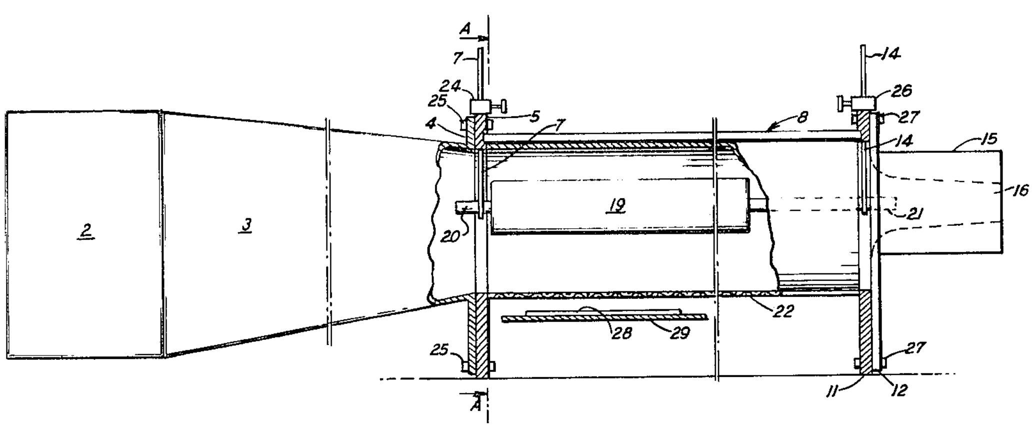
Primary Examiner—Alfred E. Smith
Assistant Examiner—Saxfield Chatmon, Jr.

[57] **ABSTRACT**

An improved structure for a microwave generated plasma light source for emitting radiation in the ultraviolet and visible portions of the spectrum. Microwave energy generated by a microwave source is coupled to a plasma forming medium which is confined in a longitudinally extending tube. The tube is surrounded along its length by a microwave chamber, a portion of which comprises a means for reflecting the emitted radiation and a portion of which comprises a mesh-like member which is substantially transparent to the emitted radiation, but which is relatively opaque to the microwave energy. The microwave energy may be fed to the microwave chamber either from the end thereof, or from the top or sides if the microwave sources is housed in a waveguide located on the top or sides of the chamber. The plasma forming medium is confined at a relatively high pressure and the microwave energy is coupled thereto at a high enough power density to create electron densities in the plasma in excess of the cutoff density. Electrons are excited by the transformation of waves and wave absorption and collide with the heavy particles of the plasma which emit ultraviolet and visible radiation upon de-excitation.

25 Claims, 23 Drawing Figures



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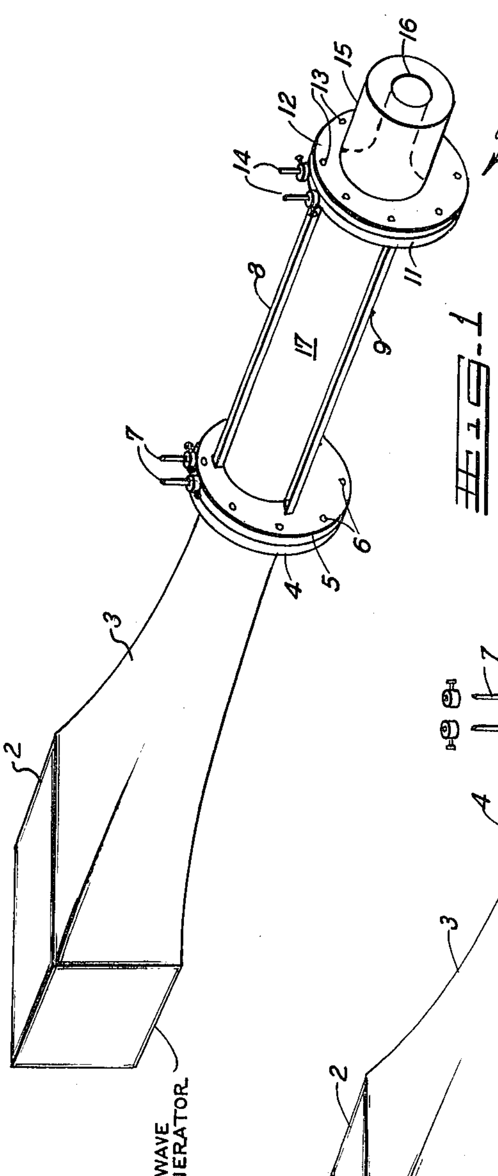

FIG. 1

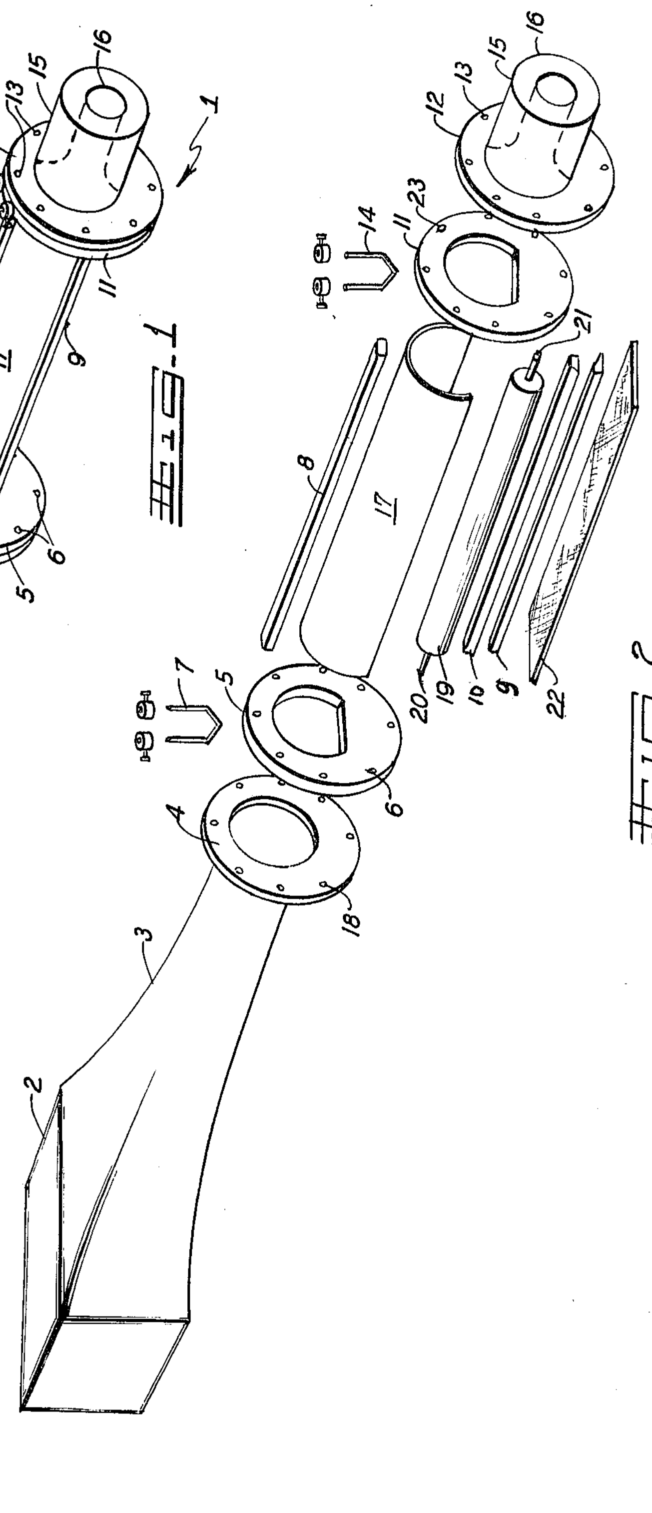

FIG. 2

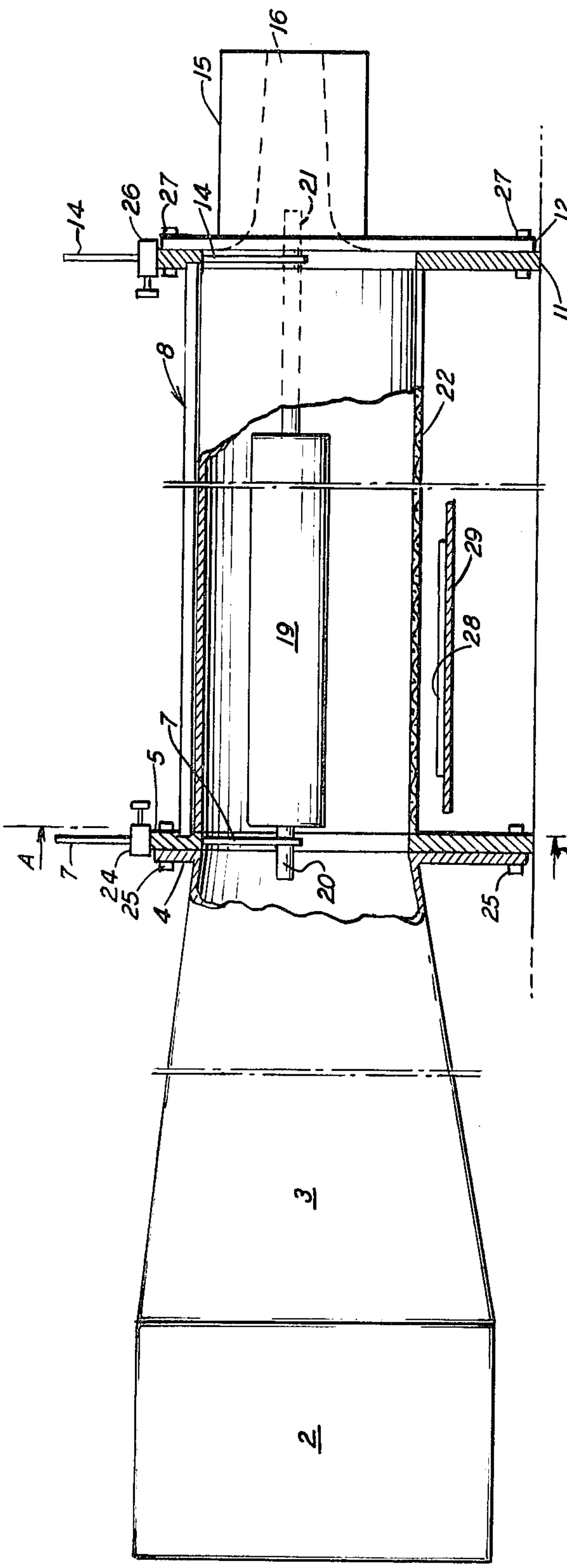

FIG. 3

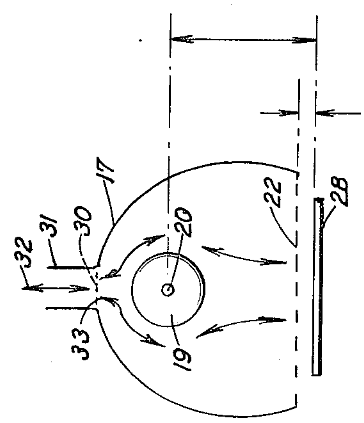

FIG. 5

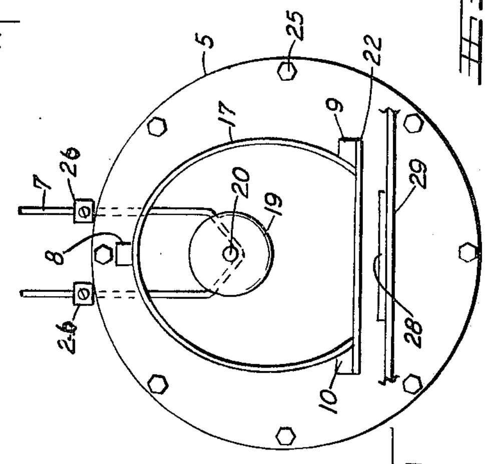

FIG. 4

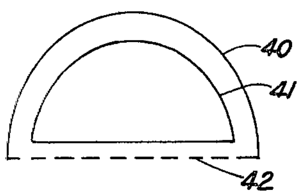

Fig. 6

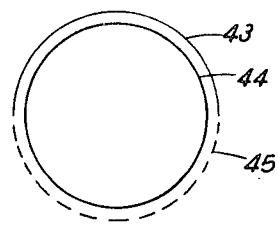

Fig. 7

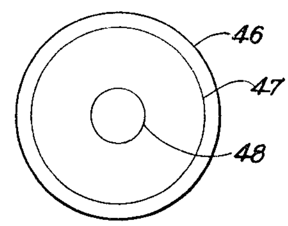

Fig. 8

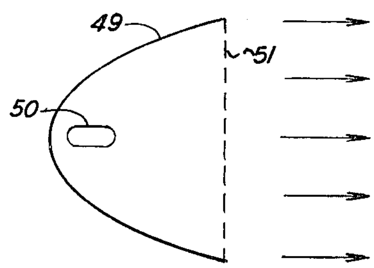

Fig. 9

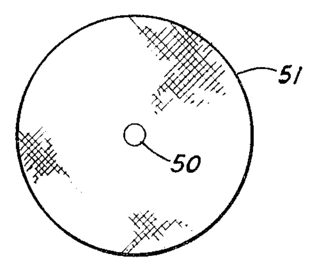

Fig. 10

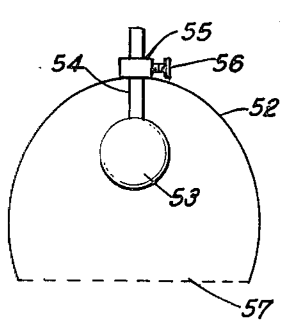

Fig. 11

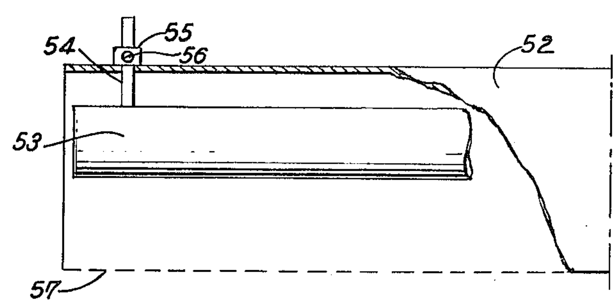

Fig. 12

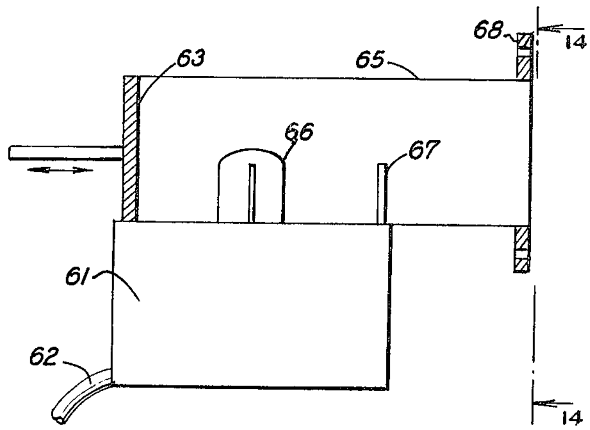

FIG. 13

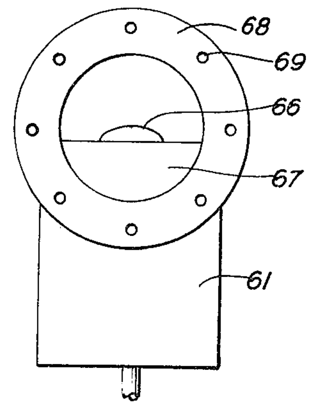

FIG. 14

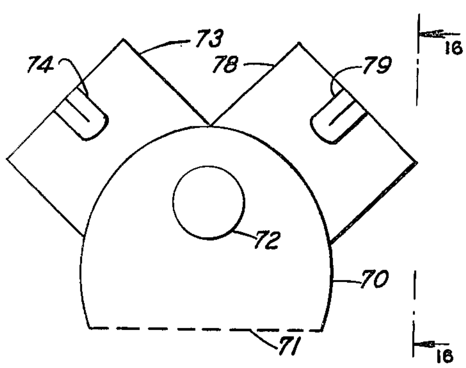

FIG. 15

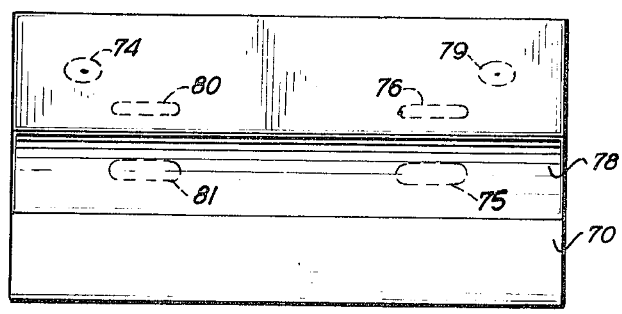

FIG. 16

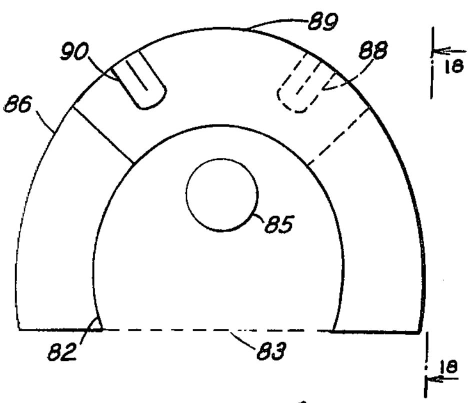

FIG. 17

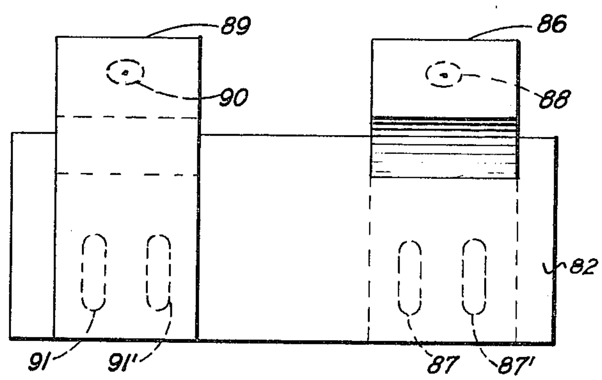

FIG. 18

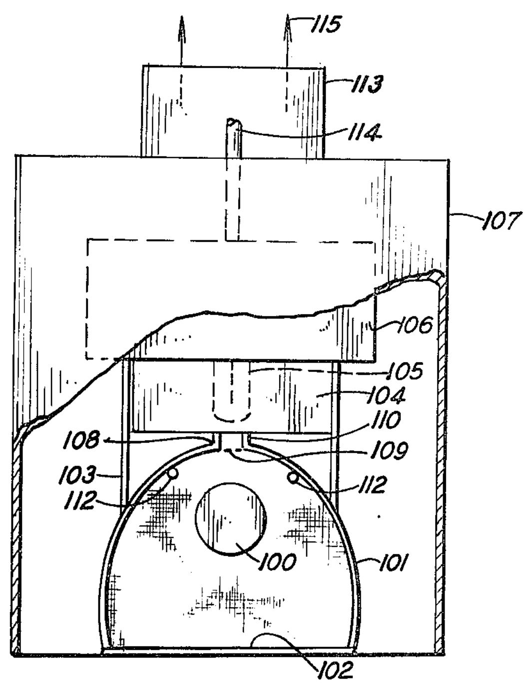
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FIG. 19

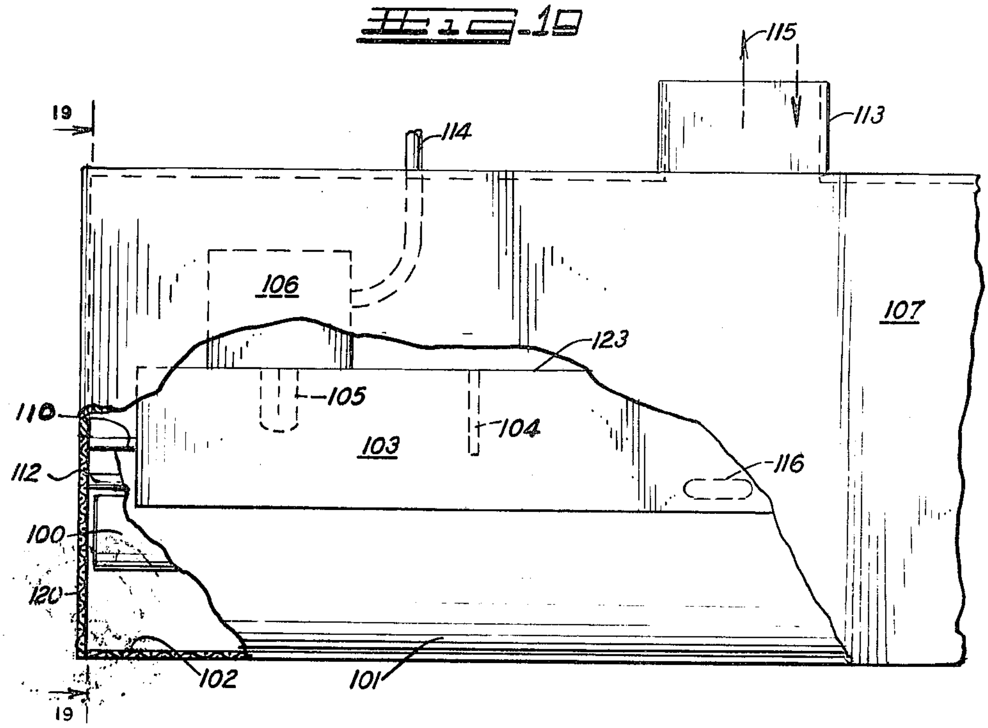
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FIG. 20

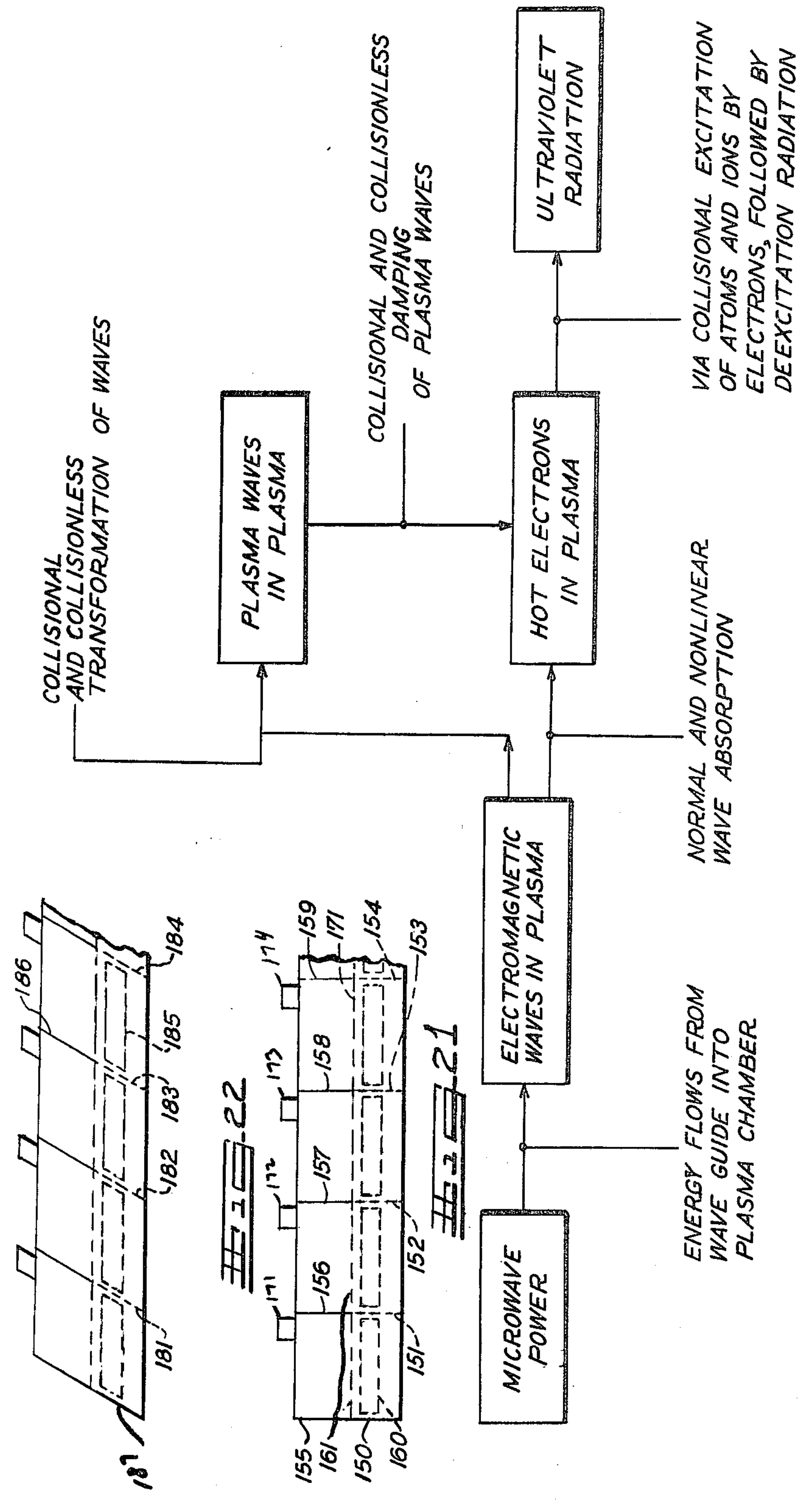

FIG. 22

FIG. 21

FIG. 23

APPARATUS AND METHOD FOR GENERATING RADIATION

This application is a continuation-in-part of U. S. Pat. application Ser. No. 239,149 filed Mar. 29, 1973, which copending application is incorporated herein by reference.

The present invention relates to an improved structure for a microwave generated plasma light source and to an improved method and apparatus for efficiently generating high power ultraviolet and visible radiation.

In recent years, sources of ultraviolet and visible radiation having emission wavelengths below 5000° A. have found widespread use in industry in applications such as curing paints and inks, other coating and surface treatment processes and in the industrial synthesis of certain chemicals by photochemical reaction. The light sources of the prior art which have been used in these processes have generally been limited by their low efficiencies and unwanted radiation by-products or by their limited output powers. As discussed in the Specification of co-pending application Ser. No. 239,149 the prior art light sources are generally either of the relatively high gas-pressure, DC or low frequency excited plasma type which may generate power at adequate levels but which are inefficient in that substantial portions of the power is in the unusable visible and infra-red portions of the spectrum, or of the relatively low gas-pressure, low frequency (approximately 10 Mhz) or microwave (approximately 1 Ghz) excited plasma type which may produce ultraviolet radiation fairly efficiently but which are limited as to their operating power densities and therefore as to their output power. Also the prior art light sources with electrodes have limited operating lifetimes. In contradistinction to the prior art light sources co-pending application Ser. No. 239,149 discloses a microwave generated plasma light source which produces ultraviolet radiation both highly efficiently and at a high output power.

In the industrial processes mentioned above, it is desirable to direct as much of the emitted ultraviolet radiation to the object being irradiated as possible. From the point of view of economy and compactness of structure, it is further desirable for the light source apparatus to be comprised of as few discrete components such as reflectors, lenses, etc. as possible. According to the present invention an improved structure for a microwave generated plasma light source is provided in which a portion of the microwave chamber also comprises a reflector means for the emitted radiation. In several embodiments of the invention, a further portion of the microwave chamber comprises an ultraviolet and visible light transparent mesh-like member or screen through which the reflected radiation can be transmitted. The mesh-like member or screen, while being transparent to the emitted radiation is relatively opaque to the microwave radiation and is therefore effective to keep the microwave energy confined in the microwave chamber. Hence a structure is provided which efficiently focuses the emitted radiation onto the surface to be irradiated and which does so without the necessity of employing a separate reflector member. Additionally, the novel microwave chamber of the invention provides its additional reflection function without compromising its properties as a microwave coupling means.

The microwave energy generated by the microwave source can be coupled to the microwave chamber either by a rectangular to circular waveguide transition section as disclosed in co-pending application Ser. No. 239,149, by other means, or according to a further aspect of the invention, by waveguide means mounted on top of the microwave chamber. Feeding the microwave power in from the top as opposed to from the end allows several light sources to be placed end to end to form a composite light source of a selected length.

According to a still further aspect of the invention a method and apparatus for efficiently generating a plasma with microwave energy to emit ultraviolet radiation at high power levels is provided which operates without the presence of a magnetic field.

Economic and operational advantages are obtained in the present source by eliminating the magnetic field and the apparatus for producing it required by many prior art microwave generated plasma light sources while retaining the high power and high efficiency characteristics of the discharge. The microwave energy which is at a high power density in the medium causes electrons to be generated in densities exceeding the cut-off density. The electrons are generated by processes including the collisionless and collisional transformation of waves and normal and non-linear wave absorption. The energetic electrons collide with the heavy particles of the plasma thereby exciting them and the heavy particles emit the desired radiation upon de-excitation.

It is therefore an object of the invention to provide an improved structure for a microwave generated plasma light source.

It is a further object of the invention to provide a structure for a microwave generated plasma light source in which a portion of the microwave chamber also comprises a means for reflecting the emitted radiation.

It is still a further object of the invention to provide a microwave generated plasma light source wherein the microwave energy is coupled to the plasma forming medium by waveguide means mounted on the top or side of a microwave chamber which encloses the container in which the plasma-forming medium is confined.

It is still a further object of the invention to provide a longitudinally extending microwave generated plasma light source having a structure which allows the source to be placed end to end with similar light sources on the right and left ends thereof and it is an object to provide a plurality of such light sources positioned end to end to provide a composite light source with a selected length of continuous spatial extent of ultraviolet emission.

It is still a further object of the invention to provide a microwave generated plasma light source which can efficiently generate high power ultraviolet and visible radiation without the use of a magnetic field.

It is still a further object of the invention to provide a method and apparatus for efficiently generating high power ultraviolet and visible radiation by coupling high power density microwave energy into plasma forming medium to create electron densities in excess of the cut-off density by processes including the transformation of waves and non-linear wave absorption.

The invention will be better understood by referring to the detailed description below when taken in conjunction with the drawings in which:

FIG. 1 is a perspective view of an embodiment of a microwave generated plasma light source according to the invention.

FIG. 2 is an exploded perspective view of the light source of FIG. 1.

FIG. 3 is a side view with portions cut away of the light source of FIG. 1, additionally illustrating the sample to be irradiated by the light source.

FIG. 4 is an end view taken at plane A—A of FIG. 3.

FIG. 5 is a schematic drawing of the light source of FIG. 1, additionally illustrating a cooling opening located in the top of the microwave chamber.

FIGS. 6 to 10 are schematic drawings of further embodiments of light sources according to the invention having different geometrical configurations.

FIGS. 11 and 12 are end and side views respectively of a light source according to the invention showing how the plasma container may be mounted.

FIG. 13 is a side-view of a power head which may be used instead of the microwave source and rectangular to circular waveguide transition section of FIG. 1.

FIG. 14 is an end view of the power head of FIG. 13 taken through plane 14—14 of FIG. 13.

FIG. 15 shows an embodiment of the light source shown in FIGS. 19 and 20.

FIG. 16 is a side view of the embodiment of FIG. 15 at plane 16—16.

FIG. 17 shows a further embodiment of the light source shown in FIGS. 19 and 20.

FIG. 18 is a side view of the embodiment of FIG. 17 at plane 18—18.

FIG. 19 is an end view with portions broken away of an embodiment of a light source according to the invention.

FIG. 20 is a side view with portions broken away of the light source of FIG. 19.

FIG. 21 shows a composite light source built of modular units such as shown in FIGS. 19 and 20 and FIGS. 15 to 18.

FIG. 22 shows another embodiment of a composite light source.

FIG. 23 is a block diagram depicting the steps involved in the generation of a plasma according to the invention.

FIGS. 1 to 4 show an embodiment of a microwave generated plasma light source having an improved structure according to the invention. The essence of the novel structure is a microwave chamber which functions both as a means for coupling microwave energy to to the plasma forming medium and as a reflector means for the emitted ultraviolet and visible radiation.

Referring to the exploded view of FIG. 2 the novel microwave chamber is comprised of longitudinally extending geometrically shaped member 17 and mesh, mesh-like surface or screen 22. In the embodiment shown, member 17 comprises a member of elliptical cross-section but as discussed in conjunction with FIGS. 6 to 11 the shape of member 17 as well as member 22 may be varied to suit the particular application. The chamber is constructed so that member 17 is sealed electromagnetically at the bottom thereof by mesh 22 thus forming a longitudinally extending chamber which is opaque to microwave energy and which

therefore can be used as a microwave coupling chamber. Member 17 is arranged to be reflective on its inside surface, for instance by polishing the inside surface and mesh 22 is arranged to be substantially light transmissive by control of the mesh spacing. Hence light emitted as lamp container 19 which is mounted inside the microwave chamber will be reflected by the inside surface of member 17 and will be transmitted through mesh 22 to the sample to be irradiated. The member 17 may be made of aluminum sheet which is polished and anodized on its inner surface for maximum ultraviolet reflectivity. A polished, anodized aluminum sold under the trademark Alzak may be used. Mesh sizes up to one-eighth inch spacing with 0.011 inch copper wire have been used. However, larger mesh sizes may result in unacceptably high microwave leakage and optimum mesh size appears to be 1/40 to 1/50 inch using 0.001 inch tungsten wire. This gives excellent microwave shielding and allows transmission of about 90 percent of the lamp radiation in the ultraviolet, visible and infrared regions. The wire mesh has the added advantage of helping to prevent unwanted materials, such as ink droplets or paper fragments from hitting the lamp in production line environments.

As shown in FIG. 4, 22 may be somewhat wider than member 17 at the bottom thereof and the two members may be secured to each other by conventional means such as soldering or welding. In the embodiment shown for structural rigidity mesh 22 is secured to side support bars 9 and 10 and the side support bars as well as top support bar 8 are secured at each end to flanges 5 and 11. As will be apparent to those skilled in the art, other mechanical means to ensure structural rigidity may be utilized. The end surfaces of microwave chamber 17, 22 are adhered to flanges 5 and 11 in a manner which prevents escape of microwaves, for instance by soldering, welding, conductive epoxy, or various mechanical means employing slots, lips or the like.

Tube 19 is formed with mounting extensions 20 and 11 which are supported by holding brackets 7 and 14 as shown in FIGS. 3 and 4. Brackets 7 and 14 are inserted in vertically extending slots (not shown) in flanges 5 and 11 respectively and are retained in position by collars 24 and 26 respectively which may for instance be of the set screw type. In the alternative lamp bulb 19 may be supported in the microwave chamber of the invention by any conventional support means apparent to those skilled in the art. Lamp bulb 19 is filled with an appropriate mixture of gasses, is sealed and is provided with extensions to form supports 20 and 21 which are unfilled and unsealed. The lamp bulb as well as the holding brackets may be made of quartz. The ends of bulb 19 may be flat as shown or tapered as described in copending U.S. application Ser. No. 239,149.

Flange 11 having holes 23 therein is secured to end flange 13 by bolts extending through holes 23 inflange 11 and holes 13 in flange 12. End flange 12 has a flange collar 15 thereon which forms the termination for the microwave chamber. Flange collar 15 is designed with a sufficiently large length to diameter ratio as known to those skilled in the art to attenuate the escape of microwave energy and has an inside flange taper 16 to reduce field enhancement which would otherwise encourage arcing. Additionally it is noted that flange collar 15 is mounted somewhat above the middle of flange 12 so that its axis coincides with that of lamp bulb 19.

The plasma light source thus far described actually is a coaxial microwave in which the outer conductor is the microwave chamber and the inner conductor is a lossy conductor consisting of the lampbulb and its contents. One way of coupling microwave energy to the microwave cavity for interacting with the plasma forming medium is shown in FIGS. **1** to **3.** Microwave energy generator **2** which may be a magnetron, klystron, other known microwave generator or a standard microwave power pack including power meters and a tuner, is provided. In the preferred embodiment of the invention a microwave frequency of 2450 MHZ is used (915 MHZ can be used if cavity dimensions are increased) and the generator output is a series of pulses at a rate of 120 per second. The output of microwave generator **2** is coupled to a rectangular to circular S-Band waveguide transition section **3** which terminates in a flange **4.** Flange **4** is secured to flange **5** of the lamp assembly by bolts **25** which are passed through holes **18** and **6** of flanges **4** and **5** respectively. To ensure proper mating flanges, **4** and **5** are arranged so that the radius of curvature of the top of the opening in flange **5** is approximately the same as the radius of curvature of the top of the opening of flange **4** and further that the top surfaces of these openings are positioned next to each other to provide a smooth transition into the microwave chamber.

As shown in FIGS. **3** and **4** object **28** which is to be irradiated is moved past the source in a direction perpendicular to the plane of the paper, for instance by conveying means **29,** motion **34** is as shown. The light source would be mounted on a frame or other support for instance by securing flanges **5** and **11** thereto. If member **17** is elliptical in cross-section as shown in embodiment of FIG. **1** then lamp bulb **19** would be located at or near one focus of the ellipse while the object **28** to be irradiated would be located at the other focus. Ultraviolet and visible radiation emitted by lamp bulb **19** is reflected by the inside reflector surface of member **17** downwardly through ultraviolet and visible light transmissive mesh **22** and to the surface **28** to be irradiated.

The lamp is ignited by turning on the microwave power. In some cases, a momentary discharge from a high voltage tesla coil is required to initiate break-down by means of a wire inserted through the flange collar **15.** In order in flange prevent the wire from conducting large levels of microwave energy out of the chamber a resistor in the form of a graphite rod or other material of similar conductivity may be used. The resistor is inserted into the chamber but insulated from the chamber walls so its end is near the lamp bulb. When the starting pulse is applied the resistor transmits the high voltage, low current pulse to the lamp causing the required breakdown for starting. Subsequently, the resistor appears as an insulator to the microwave field and therefore causes no radiation leakage from the chamber.

Within several minutes after starting the lamp warms up to the operating wall temperature, which in the case of mercury fills is approximately 400° C. Once the operating temperature is reached, if the microwave power pack is properly adjusted, the reflected microwave power falls to a minimum value and the lamp operates steadily for as long as it is required. The lamp may be turned off and then instantly restarted, usually with the aid of another high voltage spark, as long as its temperature does not fall so low as to re-condense the mercury.

During operation of the lamp, water cooling is provided for end flange **12** for the rectangular to circular waveguide transition section **3** and if desired for reflector member **17.** The lamp itself may be air-cooled by: (1) air fed in through the transition section and blowing from left to right in the chamber; (2) a direct air stream blowing from beneath the chamber upward through the wire mesh and onto the lamp, and/or (3) a suction provided through the flange collar **15.** Depending on the power level of operation, one, two, or three of the foregoing cooling sources may be used to prevent the lamp bulb from overheating and melting. Additionally, or instead of the air cooling described above as is shown in FIG. **5** a cooling slot may be added to chamber member **17.** The cooling slot runs longitudinally along the length of the chamber at the top thereof. Air **32** may be drawn out of or forced into the slot which causes air flow around the lamp as shown by the arrows to effect cooling. The advantage of providing the cooling slot is that uniform cooling along the entire lamp length is effected. Additionally, this type of cooling has the advantage of removing harmful ozone from the vicinity of the lamp which may have been generated during operation. Alternatively, it provides a convenient means for blowing inert gas into the lamp chamber and out over the irradiated surface **28,** a desirable procedure in some applications. A wire mesh **30** choke collar **31** are provided at the slot to prevent the escape of microwave energy. The choke collar should have a sufficiently large height to width ratio to prevent the escape of microwave energy.

FIGS. **6** to **10** are schematic illustrations of variations of the light source of FIG. **1** in which the cross-sectional areas of the lampo tube and reflector member are of different geometrical configurations. While the embodiment of FIG. **1** illustrates a relatively focused system, in applications requiring large total ultraviolet radiation doses but not requiring locally high energy density the unfocused systems shown in FIGS. **6** to **8** are more appropriate. FIG. **6** shows a reflector **40** having a thickness of parabolic cross-section which encloses a lamp bulb **41** of semicircular cross-section. The microwave chamber is completed by plane mesh member **42** and the sample to be irradiated would pass underneath and parallel to mesh **42.**

FIG. **7** illustrates a further embodiment in which the thicknesses of both reflector **43** and mesh **45** are of semi-circular cross-section, together forming a microwave cavity of circular cross-section. The lamp bulb **44** is also of circular cross-section and has a diameter nearly equal to the diameter of the cross-section of the chamber. In the embodiment of FIG. **7,** the sample to be irradiated would pass underneath mesh **45.**

FIG. **8** shows a further embodiment utilizing a lamp bulb **47** of annular cross-section and a reflector **46** having a thickness of circular cross-section. In this embodiment, the sample to be irradiated is passed within the cut-out portion **48** of the annular lamp bulb. Further, in this embodiment to prevent the electrical properties of the material being treated from affecting lamp operation it may be desirable to add an inner cylindrical mesh inside of and concentric with the inner lamp wall.

FIGS. **9** and **10** show an embodiment for producing a parallel collimated beam of radiation. Parabolic point-source lamp **50** shown in side view in FIG. **9** and in end view in FIG. **10** is located inside of reflector **49** having inside and outside surfaces which are parabolic surfaces of revolution and which is sealed by mesh **51.** Light emitted by bulb **50** is reflected in parallel fashion from reflector **49** and through mesh **51.** It should be understood that different reflector/lamp bulb geometries may be used depending on the particular application and are considered to be within the scope of the invention.

A further mounting technique for the lamp bulb is shown in FIGS. **11** and **12.** In the embodiments of these FIGS., lamp bulb **53** is formed with extensions **54** extending in the radial direction, one of which is shown in the drawings. Extensions **54** are mounted to reflector member **52** by set screw means **55, 56** and at least two such extensions would be provided for mounting the lamp bulb. The advantage of the mounting configuration illustrated in FIGS. **11** and **12** is that it allows the lamp bulb to extend very nearly to the end of the microwave chamber at both ends. This is of particular importance in the embodiment shown in FIG. **21** discussed below. Additionally, a support means comprising three dielectric rods extending from three different points on the periphery of the reflector may be used to support the lamp. The rods would be of equal length and each rod would terminate in a support bracket for the lamp at its inner end.

Instead of coupling the microwave energy to the microwave chamber by a rectangular to circular transition section as shown in FIG. **1,** it may be desirable to mount the microwave power tube in a microwave power head which bolts directly to the lamp chamber. FIG. **13** is a schematic illustration of such a microwave power head which it is seen is comprised of circular waveguide section **65,** flange **68** for connection to the lamp chamber flange, magnetron **66** mounted inside the power head, magnetron anode, filament, cooling, and magnet structures **61,** and connection cables **62** for connection to a remotely located high voltage and filament power supply. Also provided is a quarter wave tuning stub **63** with the direction of motion indicated by the arrow which may be used instead or in addition to a quarter wave fixed reflector **67.** Flange **68** would be secured to flange **5** in FIGS. **1** to **4** to attach the power head to the microwave chamber. The waveguide **65** may be varied in size and shape for convenience in mating to the lamp chamber and for optimum microwave tuning. Instead of utilizing a magnetron in the power head, a klystron or other microwave power tube may be utilized.

For increased lamp power, a power head can be mounted at both ends of the lamp chamber. In this case, for improved power tube lifetime, it is preferable to arrange the outputs of the 60 cycle power tube power supplies so that the output microwave power also at 60 cycle repetition rates occurs on alternate half-cycles for each of the two tubes. It is also possible to increase the power by mounting a second power tube in the same power head at a different axial location or on top of the waveguide section pointing downward. In this case also, running the power tubes on alternate 60 cycle pulses will improve their lifetimes.

Additionally, increased lamp power and a more unifrom light output (in time) can be obtained by mounting two or three power heads on one chamber. If each power supply is hooked to different phases of a three phase power supply (120 electrical degrees out of phase) and a full wave rectification system is used for each magnetron power supply (120 microwave pulses per second, each pulse 60 electrical degrees out of phase with an adjacent pulse) then a smoothing effect will take place. In addition, it appears that a lag of several *m* sec occurs in ionizing the plasma at the onset of each microwave pulse. If microwave pulses are only 60 electrical degrees apart then this lag should be substantially reduced and the net system efficiency increased.

FIGS. **19** and **20** illustrate a further embodiment of the invention in which the microwave power is coupled into the top of the microwave chamber as opposed to into an end thereof. An advantage of this mode of microwave coupling is that a plurality of light sources can be positioned in end-to-end fashion to form a composite light source of desired length. Referring to FIGS. **19** and **20** lamp bulb **100** is located within a microwave chamber comprised of reflecting member **101** of elliptical cross-section and mesh **102** which form a chamber similar to that illustrated in FIGS. **1** to **4.** The chamber of FIGS. **19** and **20,** however, unlike the chamber of FIGS. **1** to **4** is terminated at each end thereof by a mesh surface such as **120** shown at the left end. Hence, the reflector **101** is sealed electromagentically by mesh surfaces at the bottom and at each end thereof. Lamp bulb **100** is mounted in the chamber preferably by the method illustrated in FIGS. **11** and **12** so that the lamp bulb can extend nearly to the end of the chamber at each end.

Cooling slot **108,** mesh, **109,** and cut-off collar **110** run longitudinally along the top of reflecting member **101** as described in conjunction with FIG. **5.** A waveguide section **102** having three longitudinally extending sides at right angles to each other is mounted on top of the reflector member. The fourth side of the waveguide is the reflector member itself which has coupling slot or slots **116** therein to allow microwave energy to enter the chamber. The waveguide section contains the magnetron dome **105** and possibly quarterwave tuning plate **104.** The position, size and shape of the coupling slots in the reflector may be varied to obtain maximum coupling of microwave power into the lamp. Additionally, a tuning capability can be obtained by providing a mechanical means such as a sliding slot cover for adjusting the slot sizes. The magnetron body **106** containing anode, filament, magnets and cooling structures is mounted above the waveguide. The most compact form of magnetron cooling is water cooling, but air cooling can be used if necessary. Magnetron power and cooling connections **114** are fed to external power supply and controls. Lamp bulb cooling is provided by air flow **115** through duct **113.** In FIGS. **19** and **20** slot **108** is made accessible to the cooling air flow by constructing portions of waveguide section **103** out of screen mesh or otherwise ventilating the waveguide. The entire module is enclosed by an outer metal casing **107** which facilitates cooling by suction or blowing, offers mechanical protection, and provides microwave shielding for the module. Where the module is to be used as one module in a composite light source as shown in FIG. **21** the housing at the ends of each module would cover the entire end except for the end meshes which would be left uncovered so that the emitted radiation could pass therethrough. The embodiment may also include pre-heater elements **112** which may be nichrome wires through which current is passed when the lamp is in the quiescent OFF state so that the lamp will start instantly. In the operation of the device, microwave power generated by magnetron **105, 106** is coupled through coupling slot **116** to the microwave chamber **101, 102,** where it interacts with the plasma forming medium contained in lamp bulb **100** to cause the medium to emit radiation.

Two high power embodiments of the light source of FIGS. **19** and **20** are shown in FIGS. **15** and **16,** and **17** and **18** respectively. In FIGS. **15** and **16,** dual waveguide structures **73** and **78** are positioned parallel to the lamp axis at different azimuthal positions on reflector member **70.** In FIGS. **15** to **18** the magnetron bodies such as **106** in FIG. **19** which would be mounted on top of the waveguide sections are not shown. Waveguide **73** contains magnetron dome **74** and the energy generated thereby coupled to the chamber through slots **75** and **76** in the reflector member shown in FIG. **16.** Waveguide **78** includes magnetron dome **79** and the energy generated thereby is coupled to the chamber through slots **80** and **81.** As may be seen in FIG. **16,** magnetron dome **74** is located in a relatively forward position of the waveguide and its associated coupling slots **75** and **76** are located in a relatively rearward position of the reflector member while magnetron dome **79** is located in a relatively rearward position of its waveguide and associated coupling slots **80** and **81** are located in a relatively forward position of the reflector member. The distance between the magnetron dome and its associated coupling slots tends to be roughly half a wavelength of the microwave radiation. Similarly in FIGS. **18** and **20.**

In the embodiment shown in FIGS. **17** and **18,** the waveguide structures **86** and **89** are positioned at different axial positions and are curved azimulthally around reflector member **82.** Waveguide **89** includes magnetron dome **90** and is associated with coupling slots **91** and **91'** in one side of the reflector member while waveguide **86** includes magnetron dome **88** and is associated with coupling slots **87** and **87'** in the other side of the reflector member. In the embodiments of FIGS. **15** to **18,** half-power lamp operation is obtainable by turning off one of the two magnetrons. Higher power operation is obtainable in any of the embodiments of FIGS. **19** and **20** and **15** to **18** by mounting more than one magnetron in a waveguide structure.

According to a further aspect of the invention a plurality of lamps of the type illustrated in FIGS. **19** and **20** and FIGS. **15** to **18** are placed in end-to-end relationship with each other to form a light source of a selected length. Each lamp is then a modular unit and the length of the composite light source may be varied by increasing or decreasing the number of modular units used. This type of system is made possible by the fact that the microwave energy in the embodiments of FIGS. **19** and **20** and FIGS. **15** to **18** is fed to the lamp from the top of the microwave chamber as opposed to from one of the ends and such a composite light source is illustrated in FIG. **21.** End mesh sections **151, 152** and **153** and **154** are placed in end to end relationship and the solid end plates **156, 157, 158** and **159** of the housings such as housing **107** in FIG. **19** extending above the mesh are bolted rigidly together to form a single rigid light source in which it is possible for light emitted by one lamp, for instance **160** to pass through the end mesh **151** of that lamp into the chamber of the adjacent lamp and to possibly be reflected by the reflecting member **161** of the adjacent lamp onto an irradiated surface. The effect is thus similar to that obtained by a single lamp bulb and a single reflector of a length equal to the composite length of the modular units. Each modular unit would be fed with power from a different power supply and all of the power supplies would be mounted together in a single cabinet located remotely from the lamp. Similarly, all of the modular units would be operated simultaneously by a single master control unit.

FIG. **22** illustrates a further embodiment of a composite light source in which end mesh sections **181,** 182, 183 and **184** are angled with respect to the axis of the bulb. The technique of canting the end mesh sections as shown has the effect of eliminating regions of diminished emitted ratiation which may tend to exist at the regions of the end meshes in the embodiment of FIG. **21.** The outer housings **186** of the modules in FIG. **22** need not be shaped as shown and the end section **187** could be perpendicular to the lamp axis instead of canted relative thereto. Other modifications of a composite light source will be obvious, such as replacing multiple exhaust ducts **171, 172, 173** and **174** in FIG. **21** with a single duct, while also replacing solid end plates **156, 157, 158** and **159** with screened sections.

The advantage of using modular units as is shown in FIGS. **21** and **22** instead of a single long light source is that a substantial savings in power supply component costs and engineering production costs results. Thus, power supply components are much cheaper at the 700 to 3000 watt levels than at the 5 to 30 kilowatt levels and it has been determined that a lamp system of approximately 3 kilowatts and 10 inches length may be optimum from the cost/power viewpoint. Also, if 10 inch lamp modules are joined end to end to form useful commercial lamp systems in lamps of 30 inches, 40 inches, 60 inches, etc., then the number of modules manufactured will be 3, 4, 6 etc. times the number of lamp systems manufactured and design and engineering costs will be reduced because only one product, instead of a number of products need be produced. Furthermore, production costs will decrease because larger numbers of components will be purchased from vendors. Also, the modular lamp units have the advantage of having no end overhand of the lamp housing (space between the end of the lamp bulb and the end of the chamber), which facilitates installation of lamps on certain production lines. Finally, a composite light source built up of modular units affords quick and easy servicing by permitting the removal of a faulty module with the lamp bulb inside and replacement of the entire unit instead of having to utilize a procedure which involves handling of lamp bulbs on the production line.

While the improved structure of the lamp disclosed in FIGS. **1** to **22** may be utilized with different plasmas, in a preferred embodiment of the invention a novel and improved plasma resulting in the production of high-power ultraviolet radiation not requiring a magnetic field is utilized. The plasma is generated by interacting high power density microwave energy with a mixture of gases maintained at a relatively high pressure to create electron densities in the plasma which are in excess of the cut-off density.

The theory of operation of the lamp as it is presently understood is described with reference to the block diagram of FIG. **23.** As used above, as well as in the discussion below, by the term "plasma" is meant a partially or highly ionized gas composed of atomic or molecular particles having one or more orbital electrons removed and thus constituting ions, together with a sufficient number of free electrons to balance the electrical charge of the ions, so that the resultant plasma is substantially electrically neutral. By the term "cut-off density" is meant the minimum density of electrons which in "classical" microwave plasmas leads to reflection of microwave power.

The choice of gases to be used as a fill for the lamp is determined by the exact spectral output that is desired. In a preferred embodiment of the invention, a mixture of mercury and a xenon background fill gas is used. The mixture of gases is confined in the lamp at a pressure of between 1 torr and 2 atm. This is a relatively high range of pressures compared to these discussed in copending application Ser. No. 239,149. A consequence of these high operating pressures is the fact that collisional phenomena are involved in generating the plasma and the electromagnetic radiation. In the operation of the lamp, microwave energy is coupled to the plasma forming medium by any of the modes heretofore described. The dimensions of the lamp, the output power of the microwave generator, and the microwave coupling mode are arranged so that microwave energy at a power density of greater than 50 watts /cm^3 is coupled to the plasma forming medium. The high power density interacting with the high pressure gas creates extremely high electron densities in a large volume of the gas. The electron densities in portions of the gas actually exceed the cut-off density by as much as 100 or 1000 times. Equivalently, the frequency ω of the input microwave energy is less than the plasma frequency ω_p where $\omega_p = \sqrt{4\pi n e^2/m}$ and where n is the number density of electrons per cubic centimeter and e and m are the electron charge and mass, respectively. As n increases ω_p also increases. The value of n at which ω_p becomes equal to ω is termed the cut-off density, because for $\omega_p > \omega$, "classical" plasmas reflect all the incident microwave energy, and consequently result in a limitation of the absorbed power. In the present plasma, the extremely high electron densities which result in the high ultraviolet power outputs are possible because of two unique non-classical effects which are discussed below in conjunction with the block diagram of FIG. 23.

The first of these effects is the collisional and collisionless transformation of waves which is effective to transform the electromagnetic waves in the plasma to electrostatic plasma waves, which are in turn damped by collisional and collisionless processes thereby exciting electrons. The second effect is "anomolous" or "non-linear" wave absorption by which the electromagnetic waves are directly damped resulting in the absorption of power levels not possible in "classical" plasmas. The electrons which are energized by the transformation of waves and wave absorption phenomena collide with the heavier atoms and ions of the plasma thereby exciting them and the heavy particles radiate the ultra-violet and visible radiation in the process of de-excitation.

Describing the operation of the plasma system in greater detail, electromagnetic energy is coupled into the plasma forming medium and the waves flow into the less dense regions of the plasma until they reach regions where the electron density is just below the cut-off density for the microwaves. In these regions, the transformation of waves phenomenon occurs and the electromagnetic waves are transformed into electrostatic plasma waves which propogate on the surface or through the volume of the plasma.

The transformation of waves phenomenon is discussed in co-pending U.S. Pat. application Ser. No. 239,149 which application disclosed the generation of a lower pressure plasma in the presence of a magnetic field. Because of the lower pressure of the plasma in the co-pending application, the transformation of waves in that application was referred to as "collisionless transformation of waves." In the present application, because of the higher pressures involved, collisons will play a greater part in the generation and energizing of electrons and the transformation of waves will no longer be "collisionless" but as predicted by theory will be both collisionless and collisional. It was shown in the co-pending application that transformation of waves for the case $B = 0$, where B is the magnetic field, would take place over the range $0 < \omega < \omega_p$, and in the present application where $B = 0$ this equation is also valid notwithstanding the fact that plasma operates at a higher pressure and collisions occur.

The plasma waves produced by the transformation of waves phenomenon propagate further into the plasma and are slowed down and have their energy absorbed through "collisionless Landau damping" as discussed in the co-pending application, and because of the higher pressures involved also through collisional damping. The effect of either damping mechanism is to dissipate the energy introduced by the high power electromagnetic waves into local regions of the plasma in the form of excited electrons uniformly throughout the plasma.

The second mechanism by which electrons are excited in the present plasma system occurs simultaneously with the transformation of waves and is referred to as normal and non-linear wave absorption. These effects involve the direct collisional damping of the electromagnetic waves in the plasma. This damping takes place in the lower density regions of the plasma where the density is less than the cut-off density or equivalently where the microwave frequency is greater than the plasma frequency, and is effected by electrons in these regions being set in motion by the electromagnetic waves and obtaining thermal energy by randomizing collisions with background gas atoms and ions.

"Normal" collisional wave absorption has heretofore been observed and analysed. It occurs in regions of the plasma where the electron density is equal to the cut-off density (or the microwave frequency is equal to the plasma frequency) over depths within the plasma of the order of C/ω_p, the plasma skin depth, where C is the speed of light. In a plasma at high electron densities (so that in most of the plasma volume, the density is greater than the cut-off density) this means that the absorption occurs in a narrow sheath or skin near the outside of the plasma column. A consequence of this is that, in a given plasma system, as the average electron density of neutral gas pressure is increased, the absorbed microwave power will reach a maximum and then decrease because the skin depth becomes smaller. The "normal" or "linear" wave absorption has been observed at moderately high microwave powers (greater than 10 (watts/cm^3)) and these observations have discouraged consideration of very high power densities of gas pressures.

The present invention, however, by working at higher power density levels than have generally been used in the prior art has harnessed the effect of "anomalous" or "non-linear" wave absorption to result in increased power absorption at depths greater than C/ω_p. While all of the phenomenon involved in "anomalous" wave absorption are not yet fully understood, the physical origin of the absorption appears to be due to the fact that at very high microwave power densities the incident electromagnetic waves can themselves have a strong effect on the plasma. Thus, for example, high power microwave energy can cause additional ionization in a high pressure plasma. This in turn increases the electron density at a given point and changes the way that the plasma responds. In one theoretical analysis of such a situation it was calculated that the skin depth for wave absorption is increased from (C/ω_p) to $C/\omega_p \times (\nu/\omega)^{1/2} \times (Teo/I)^{1/3}$ where ν is the gas collision frequency, Teo is the electron temperature of the undisturbed plasma, and I is the ionization potential of the gas. These factors can considerably enhance the skin depth and therefore the plasma uniformity and the fraction of incident energy finally absorbed by the electrons. This is particularly true when a gas of relatively low ionization potential such as mercury is used.

The electrons in the plasma which are excited by both transformation of waves and normal and non-linear wave absorption collide with the heavy particles of the plasma including atoms and ions and thereby excite the heavy particles. The desired ultraviolet and visible radiation is then emitted by the heavy particles during the process of de-excitation.

The resulting plasma thus results in the high efficiency production of ultraviolet and visible radiation at high power levels without the necessity of using a magnetic field.

While we have disclosed and described the preferred embodiments of our invention, we wish it understood that we do not intend to be restricted solely thereto, but that we do intend to include all embodiments thereof which would be apparent to one skilled in the art and which come within the spirit and scope of our invention.

What is claimed is:

1. A microwave generated plasma light source for emitting a longitudinally extending sheet of light of arbitrary length comprising

means for generating microwave energy,

means for coupling said generated microwave energy to a discharge unit,

said discharge unit comprising a longitudinally extending non-resonant microwave chamber of an arbitrary length which encloses a sealed plasma-forming medium containing envelope which extends in said longitudinal direction in said chamber,

said chamber being comprised of a first longitudinally extending elliptically shaped reflecting member which is opaque to microwaves but is light reflective on its inside surface for reflecting light emitted by said envelope and a second longitudinally extending plane member joined to said elliptically shaped reflecting member along the bottom of said reflecting member to form said chamber,

said second member being substantially opaque to microwaves but substantially transparent to said emitted light, whereby light emitted along the entire length of said envelope is reflected as a sheet of light by said elliptical reflecting member through said transparent member and out of said chamber.

2. The light source of claim **1** wherein said longitudinally extending envelope is located approximately along the focus of said elliptical reflector.

3. A microwave generated plasma light source for emitting a longitudinally extending sheet of light of arbitrary length comprising means for generating microwave energy, means for coupling said generated microwave energy to a discharge unit, said discharge unit comprising a longitudinally extending nonresonant microwave chamber of an arbitrary length which encloses a sealed plasma-forming medium containing envelope which extends in said longitudinal direction in said chamber, said chamber being comprised of a first longitudinally extending shaped reflecting member which is opaque to microwaves but is light reflective on its inside surface for reflecting light emitted by said envelope and a second longitudinally extending member joined to said shaped reflecting member along the bottom of said reflecting member to form said chamber, said second member being substantially opaque to microwaves but substantially transparent to said emitted light, whereby light emitted along the entire length of said envelope is reflected as a sheet of light by said reflecting member through said transparent member and out of said chamber, said means for coupling comprising at least a microwave guiding enclosure in which said microwave energy generating means is located, one wall of said enclosure comprising a portion of said reflecting member, said portion having at least a slot antenna therein for coupling microwave energy to the interior of said chamber.

4. The light source of claim **3** wherein said enclosure comprises a waveguide and said portion comprises one side of said waveguide.

5. The light source of claim **4** wherein said microwave chamber is secured to an annular flange at each longitudinal end thereof to form an enclosure which prevents the escape of microwaves, and at least a pair of support bars are connected between said flanges for structural rigidity.

6. The light source of claim **5** wherein holding brackets for supporting said longitudinally extending envelope are secured in holes in said flanges, said envelope being formed with mounting extensions at each end thereof which extend parallel to said axis of said envelope and which are supported by said holding brackets.

7. The light source of claim **4** wherein said energy generating means is located near one end of said waveguide and said at least a slot antenna is located near said other end.

8. The light source of claim **7** wherein said at least a slot antenna comprises two slot antennae.

9. The light source of claim **7** wherein said waveguide is situated so that the long dimension thereof is parallel to the longitudinal direction of said reflecting member.

10. The light source of claim **9** wherein three sides of said waveguide are comprised of three longitudinally extending members at right angles to each other, and the fourth side is comprised of said curved portion of said reflecting member.

11. The light source of claim **10** wherein said at least a waveguide comprises two of said waveguides which are situated parallel to each other at different portions across the periphery of said reflecting member, the microwave energy generating means in one of said waveguides being located near the opposite end from the end that the microwave energy generating means in the other of said waveguides is located.

12. The light source of claim 7 wherein said waveguide is situated so that the long dimension thereof is perpendicular to the longitudinal direction of said reflecting member.

13. The light source of claim 12 wherein the cross-section of said waveguide is concentric with said portion of said reflecting member.

14. A microwave generated plasma light source for emitting a longitudinally extending sheet of light of arbitrary length comprising means for generating microwave energy, means for coupling said generated microwave energy to a discharge unit, said discharge unit comprising a longitudinally extending non-resonant microwave chamber of an arbitrary length which encloses a sealed plasma-forming medium containing envelope which extends in said longitudinal direction in said chamber, said chamber being comprised of a first longitudinally extending shaped reflecting member which is opaque to microwaves but is light reflective on its inside surface for reflecting light emitted by said envelope and a second longitudinally extending member joined to said shaped reflecting member along the bottom of said reflecting member to form said chamber, said second member being substantially opaque to microwaves but substantially transparent to said emitted light, whereby light emitted along the entire length of said envelope is reflected as a sheet of light by said reflecting member through said transparent member and out of said chamber, said means for coupling comprising a rectangular to circular waveguide transition section, the output of said generating means being coupled to the rectangular portion of the section and the circular portion being connected to an end of said microwave chamber for coupling energy into said chamber.

15. The light source of claim 4 wherein said reflecting member is elliptically shaped and said second member is a plane mesh-like member.

16. The light source of claim 4 wherein said reflecting member is parabolically shaped, the cross-section of said envelope is semi-circular and said second member is a plane mesh-like member.

17. The light source of claim 4 wherein said reflecting member is semi-circular in shape, said second member is a mesh-like member which is semi-circular in shape and the cross-section of said envelope is circular.

18. A microwave generated plasma light source of arbitrary length comprising means for generating microwave energy, means for coupling said generated microwave energy to a discharge unit, said discharge unit comprising a longitudinally extending non-resonant microwave chamber of an arbitrary length which encloses a sealed plasma-forming medium containing envelope which extends in said longitudinal direction in said chamber, said chamber being comprised of a first longitudinally extending cylindrical member which is opaque to microwaves but is light reflective on its inside surface for reflecting light emitted by said envelope having an annular cross-section whereby emitted light is reflected into the annulus of said envelope, said means for coupling comprising at least a microwave guiding enclosure in which said microwave energy generating means located one wall of said enclosure comprising a portion of said reflecting member, said portion having at least a slot antenna therein for coupling microwave energy to the interior of said chamber.

19. A microwave generated plasma light source of arbitrary length comprising means for generating microwave energy, means for coupling and generated energy to a discharge unit, said discharge unit comprising a microwave chamber which encloses a sealed plasma forming medium-containing envelope, said chamber being comprised of a first reflecting member having the shape of a parabolic surface of revolution, and a second plane mesh-like member which contacts said first member, said first member being opaque to microwaves but being reflective on its inside surface for reflecting said emitted light and said mesh-like member being substantially opaque to microwaves but substantially transparent to said emitted light, said sealed container being located at or near the focus of said parabolic surface and the longitudinal axis of said sealed envelope being parallel to the axis of revolution of said parabolic reflector, said means for coupling comprising at least a microwave guiding enclosure in which said energy generating means is located, one wall of said enclosure comprising a portion of said reflecting member, said portion having at least a slot antenna therein for coupling energy to the interior of said chamber.

20. The light source of claim 4 wherein said reflecting member has a cooling slot therein running longitudinally along said member.

21. The light source of claim 4 wherein said envelope has mounting extensions formed thereon oriented in a direction perpendicular to said longitudinal direction, said reflecting member having mounting holes therein and said extensions being secured in said holes to effect the mounting of said envelope in said chamber.

22. The light source of claim 4 wherein said reflecting member is a curved reflecting member and said second member is made of mesh-like material which is substantially opaque to microwaves and substantially transparent to said emitted radiation, said chamber further being sealed at each end thereof by a member of said mesh-like material, whereby the bottom and ends of said chamber are microwave opaque and emitted light transparent to facilitate end by end placement of said sources.

23. A plurality of light sources as recited in claim 22 placed with the mesh-like material at the right longitudinal end of one light source flat against the mesh-like material at the left longitudinal end of the adjacent light source to form a continuous straight row of light sources.

24. A plurality of light sources as recited in claim 23 wherein the mesh-like material at each longitudinal end forms a plane member and wherein said plane members of each light source are at an angle of other than 90° with respect to the longitudinal axis of the light sources.

25. A high efficiency high power microwave generated plasma light source for emitting radiation in the ultraviolet range comprising a plasma-forming medium confined in a longitudinally extending cylindrical container having a diameter much greater than twice the classical skin depth at a pressure of from 1 mm Hg to 2 atm., microwave energy source means for generating energy in the microwave range, means for coupling said microwave energy to said medium in said container so that the power density existing in said medium is at least 50 watts/cm^3 whereby electrons having densities far in excess of the cut-off density are created in said medium and anomalous absorption of said energy occurs at skin depths greater than C/ω_p where C is the speed of light and ω_p is the plasma frequency, which electrons collide with heavy particles of said medium to cause said heavy particles to become collisionally excited and to emit said radiation.

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