

[54] **APPARATUS AND METHOD FOR PLASMA GENERATION AND MATERIAL TREATMENT WITH ELECTROMAGNETIC RADIATION**

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

[58] Field of Search..... 315/3, 3.5, 39, 111; 331/78, 126; 313/231

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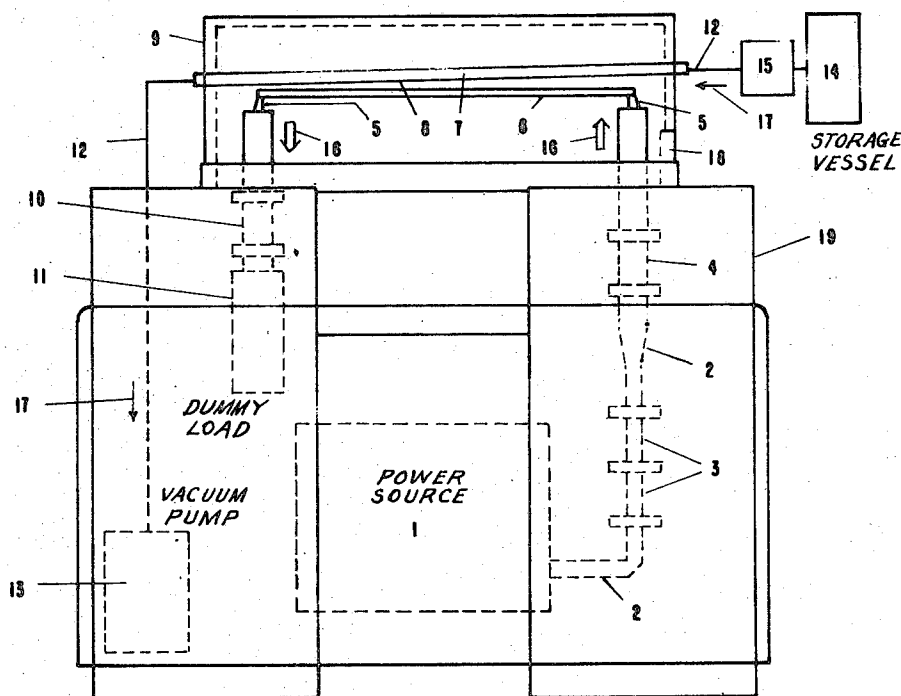
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[57] **ABSTRACT**

Apparatus for generating plasmas using electromagnetic energy in the microwave frequency range, having a source of microwave energy, a slow wave structure, conveying means for conveying microwave energy from the source to the slow wave structure, a plasma container and means for maintaining conditions of pressure and gas flow in the container. There is also provided a novel transparent radiation shield for use with such an apparatus. In another embodiment, there is also provided a slow wave structure and microwave energization means so that a region adjacent the structure will contain a predominance of degenerate $\pi/2$ mode or near degenerate $\pi/2$ mode electric field energy. Methods are also disclosed for treating various types of material to alter their properties using the above-described apparatus.

25 Claims, 27 Drawing Figures



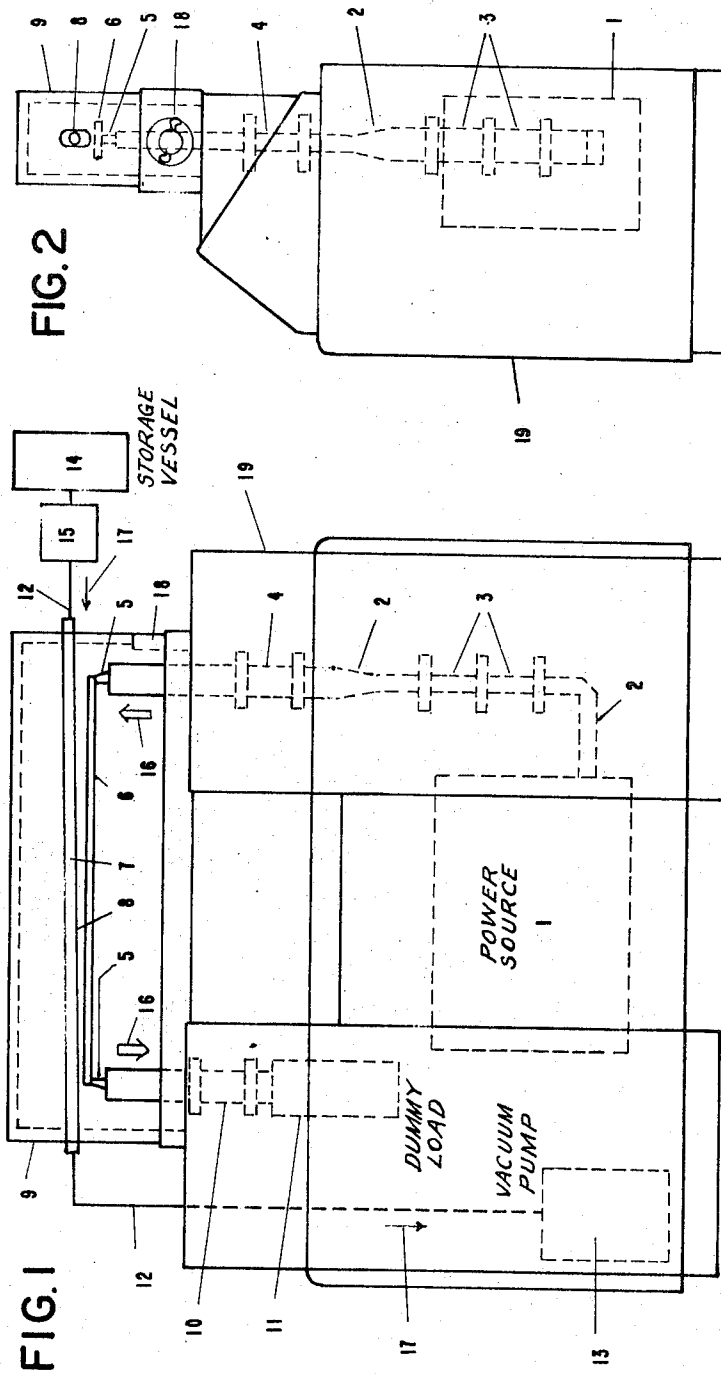


FIG. 3

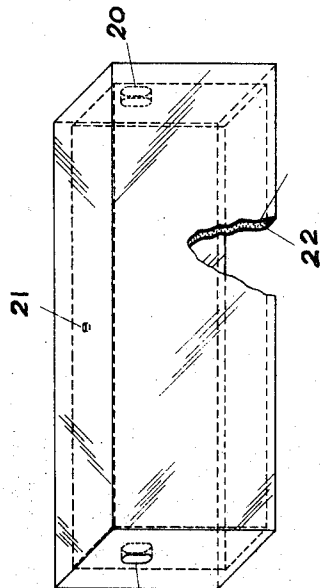


FIG. 4

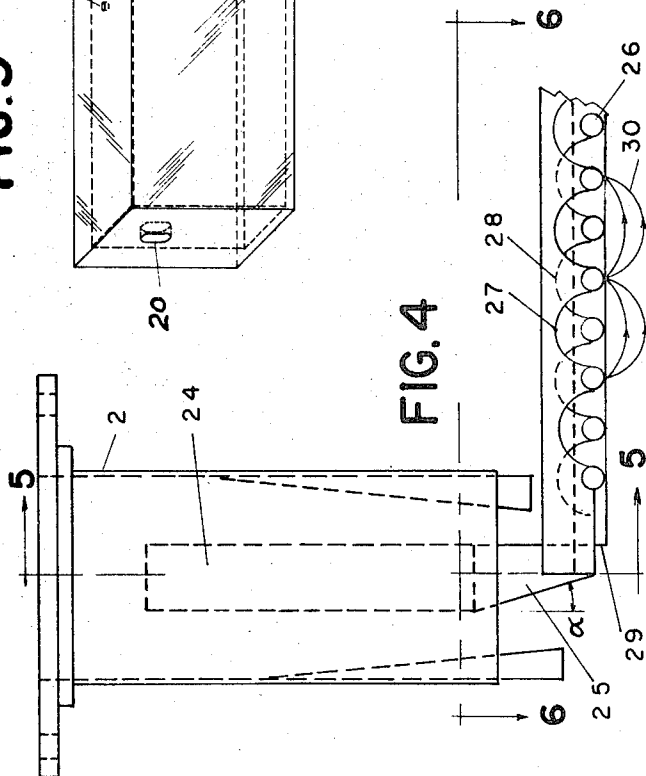


FIG. 5

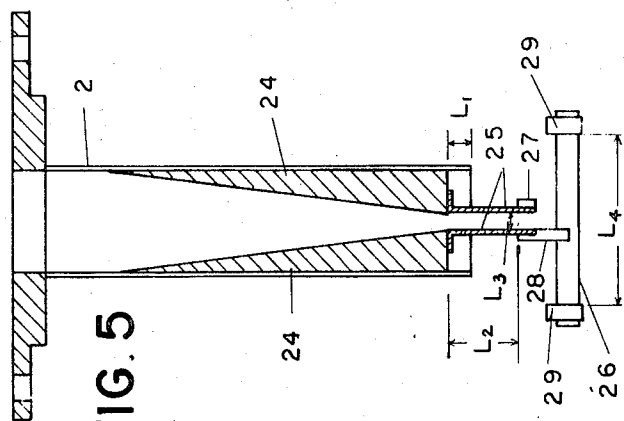


FIG. 6

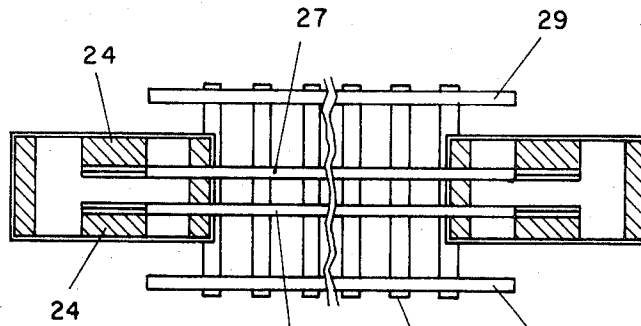


FIG. 7

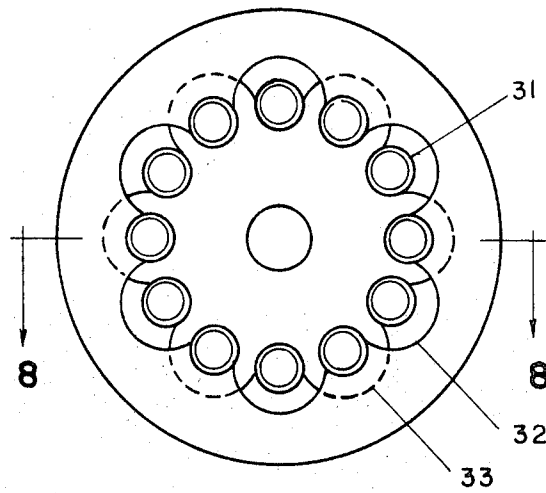
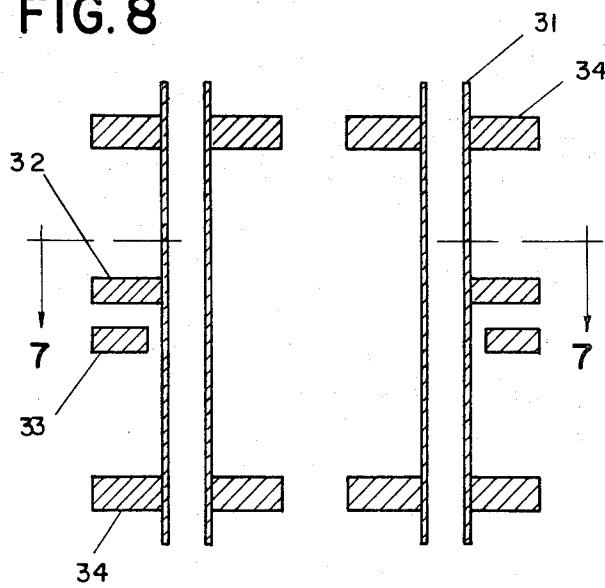


FIG. 8



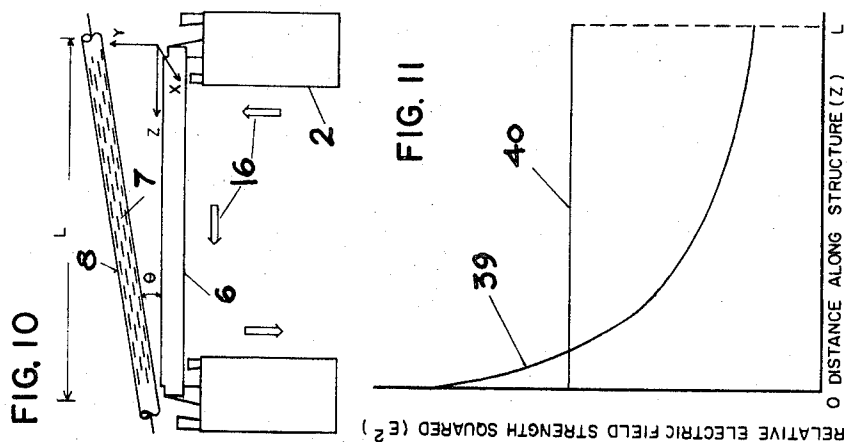
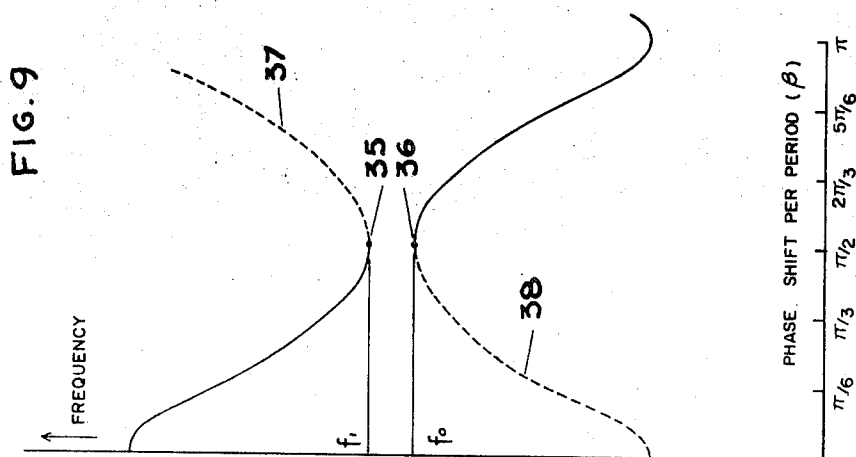


FIG. 12

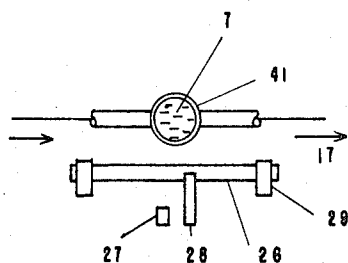


FIG. 13

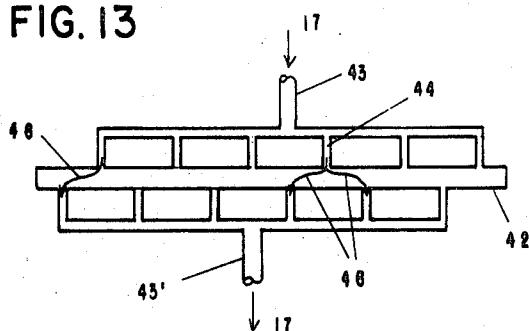


FIG. 14

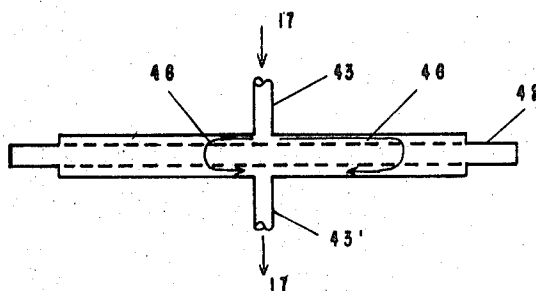


FIG. 15

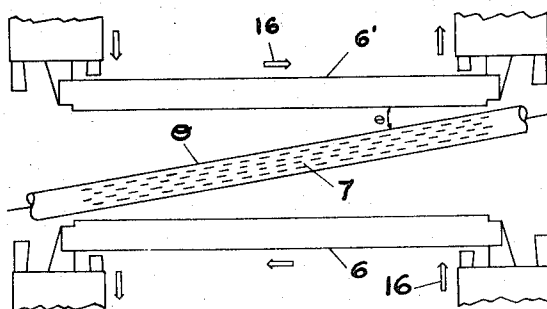


FIG. 16

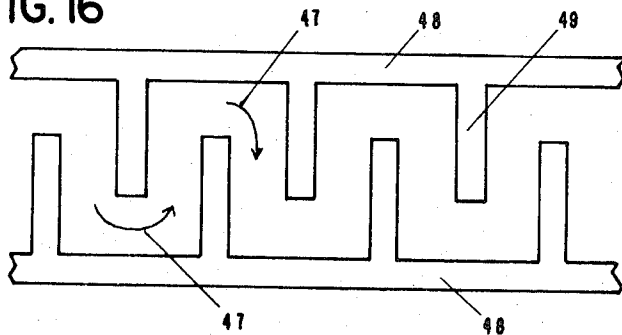


FIG. 17

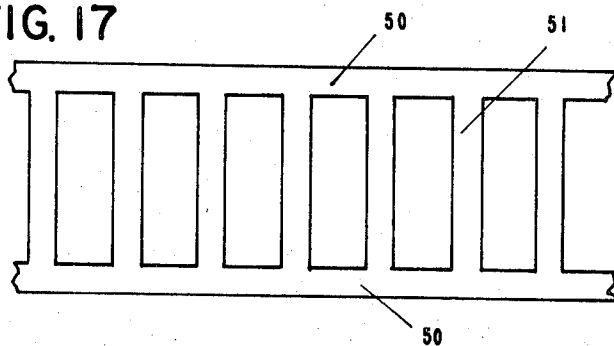


FIG. 18

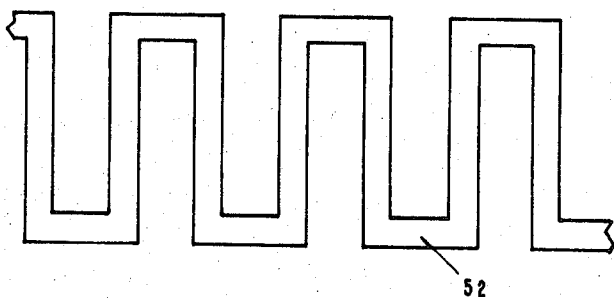


FIG. 19

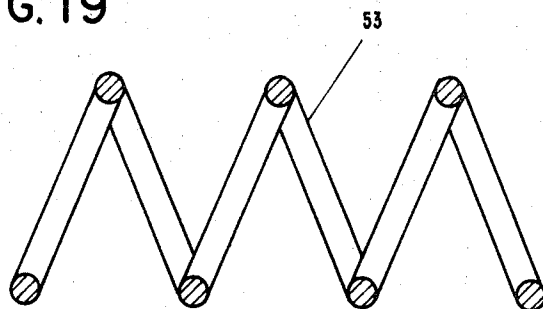


FIG. 20

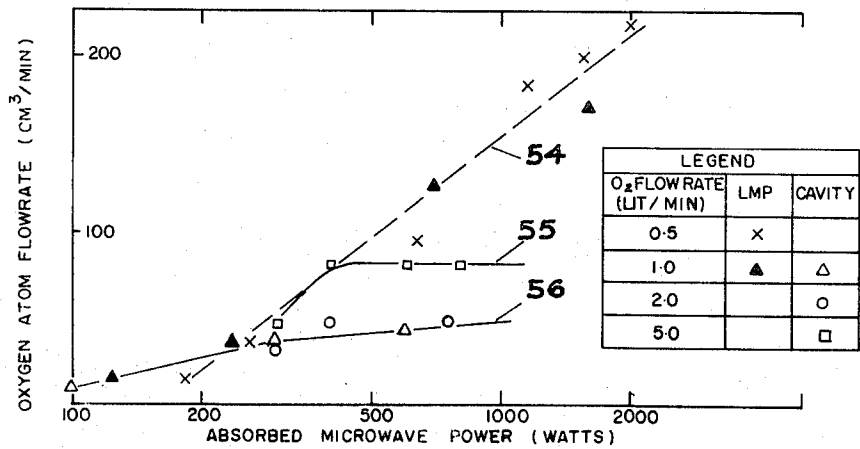
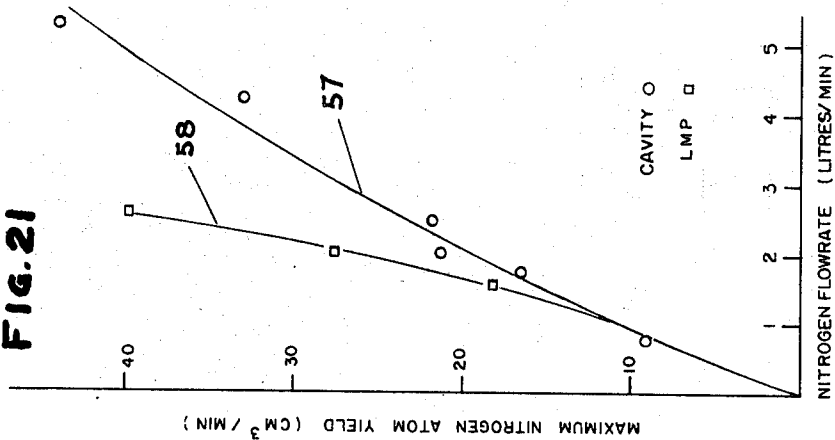


FIG. 21



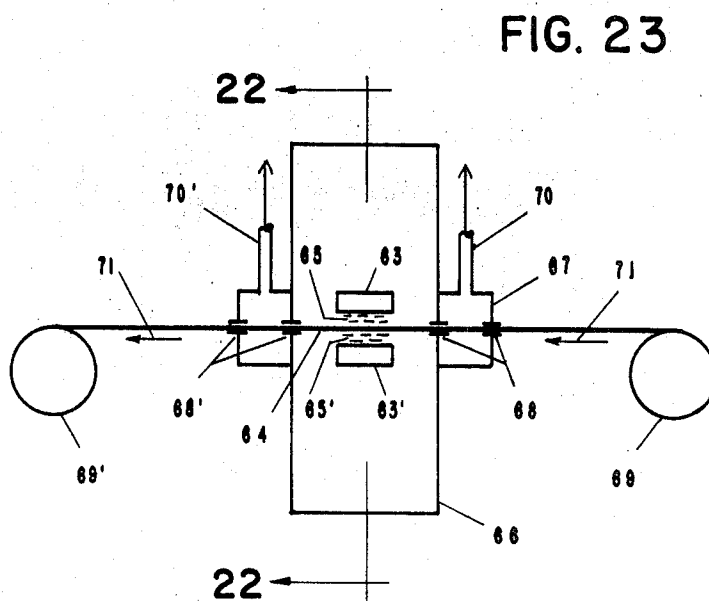
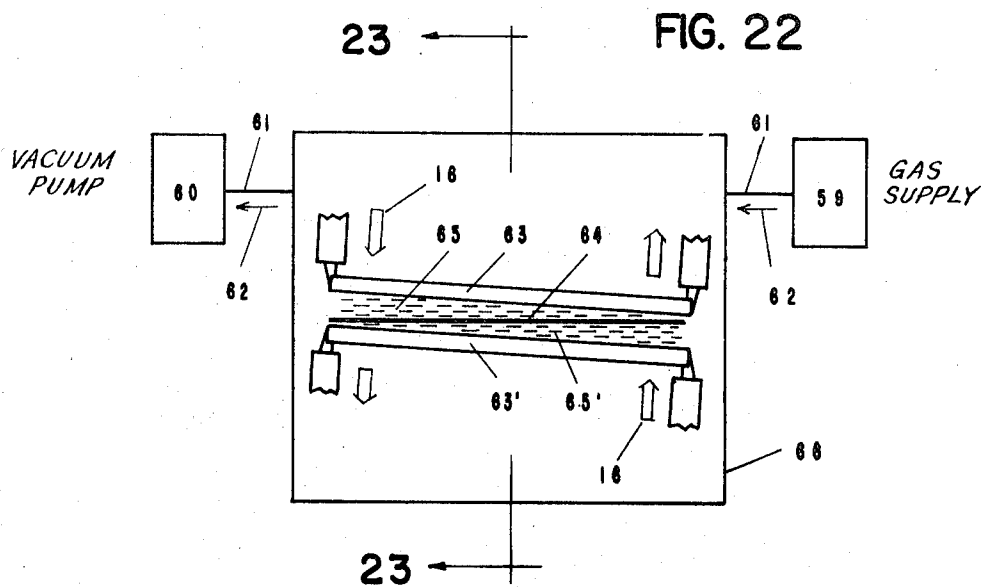


FIG. 24

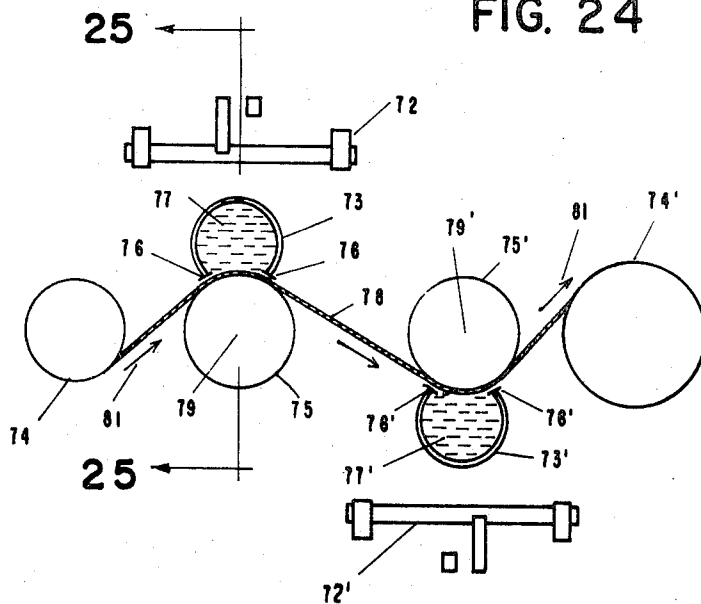
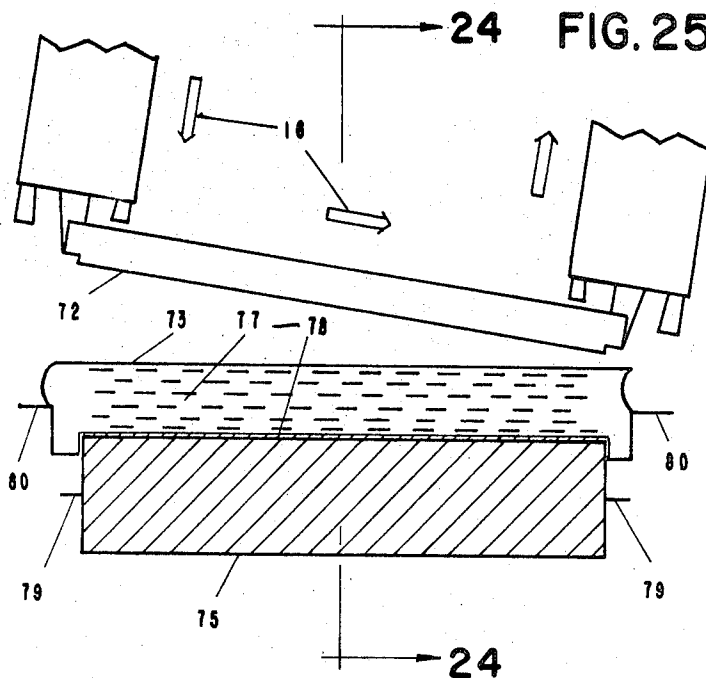


FIG. 25



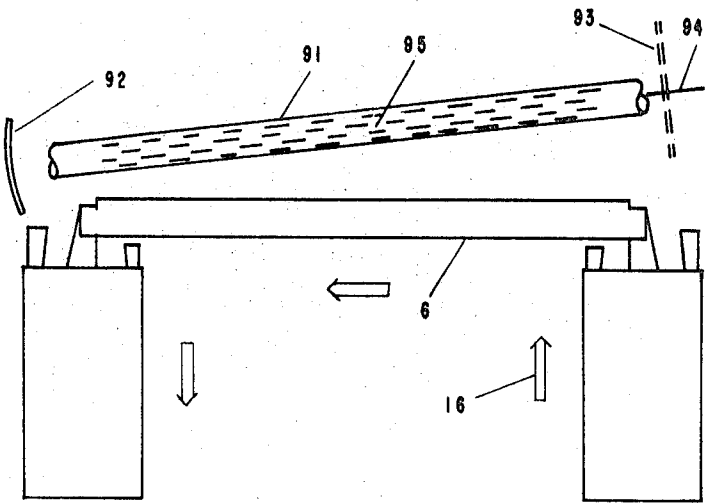
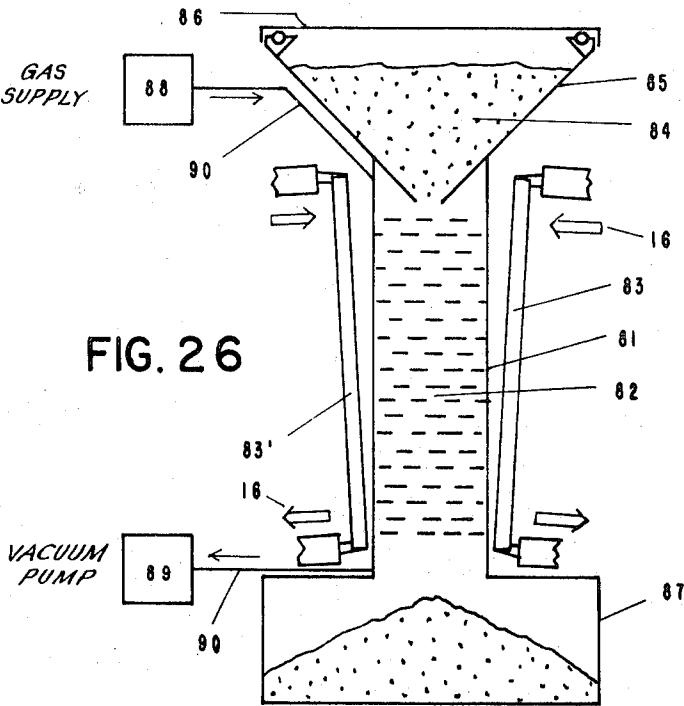


FIG. 27

APPARATUS AND METHOD FOR PLASMA GENERATION AND MATERIAL TREATMENT WITH ELECTROMAGNETIC RADIATION

This invention relates to a process for introducing high-frequency electromagnetic energy into a gaseous system so as to partially ionize the gas and to maintain a stable discharge or plasma. More particularly, this invention relates to an apparatus by means of which a large-volume plasma can be generated, and to numerous processes by which the large plasma volume can be used to impart desirable changes in properties to different materials treated by the plasma.

There exist many applications where it is desired to create a plasma, that is, to excite a gas to a higher level of internal energy or partial ionization. Some of these will be described further on in the present disclosure. A particularly convenient means for creating a plasma is by the use of electrical energy, and of the various forms of electrical energy which can be used, very high frequency energy, specifically in the microwave range, is particularly advantageous. The reason for this will become apparent from the present disclosure.

There has, however, so far existed a major obstacle to the wide-spread use of microwave energy for generating plasmas, namely the lack of suitable applicators. All previously available applicators of microwave energy which could be used to generate plasmas were limited to relatively very small plasma volumes, hence to the treatment of small amounts of material only.

One object of the present invention is to increase the volume of a microwave plasma so that it can be used for treating large quantities of material.

Another aspect of the invention is to use the large-volume microwave plasma to carry out certain specific treatments of materials, for example, to obtain efficient dissociation of molecular gases, such as oxygen, nitrogen, hydrogen, etc., to obtain increased bond strength of fibres and films of natural or synthetic polymer materials or combination thereof, and to effect chemical reaction of gaseous organic or inorganic compounds to form other compounds, either within the plasma zone or by combination with other material outside the plasma zone. Other applications for which an embodiment of the present invention, the so-called "Large Volume Microwave Plasma Generator" (LMP) is particularly well suited, and has certain unique advantages over other devices, are to "pump" a gas laser, and to generate electromagnetic radiation in certain parts of the spectrum, for example, in the ultraviolet, the visible or the infrared ranges of wavelengths.

One aspect of the invention common to all the features and applications already mentioned involves the use of a slow wave electromagnetic structure as the means for applying microwave energy to the gas plasma. Another aspect involves a convenient form of container for the gas and plasma (and other material to be treated), this container being made of a microwave-transparent material such as quartz or polytetrafluoroethylene, and means for maintaining the gas at a certain desired pressure inside the container and causing it to flow through the plasma zone at a desired rate, should this be required.

Still another aspect of the invention involves the use of a double walled, transparent plastic radiation shield where the space between the double walls is filled with a microwave-absorbing, transparent substance such as

water. This shield surrounds the microwave applicator and plasma container, and protects the operator from any stray microwave radiation while permitting him an unobstructed view of all parts of the apparatus for optimum control of the process.

More particularly, in accordance with one embodiment of the present invention, there is provided an apparatus for generating a plasma using electromagnetic energy in the microwave frequency range comprising a source of microwave energy, at least one slow wave structure having an input end for applying said microwave energy to a plasma, means for conveying said microwave energy from said source of said microwave energy to the input end of said slow wave structure, a plasma container and means for maintaining conditions of pressure and gas flow in said plasma container. Preferably, such apparatus includes a dummy load connected to an output end of said slow wave structure; as well as including means for measuring forward, reflected and transmitted microwave power. Still further, the apparatus also preferably includes means for adjusting the input of microwave energy into the plasma, as well as the transparent microwave radiation shield adapted for unobstructed observation of the plasma, said radiation shield surrounding said slow wave structure and said plasma container.

The source of microwave energy is preferably one which has a frequency in the range of 100 MHz to 30,000 MHz. In a preferred embodiment, the plasma container includes vacuum locks adapted to permit the continuous passage of material to be treated from the atmosphere into and through said plasma container; the plasma container may be vertically disposed to permit material to be treated to pass through the plasma under the force of gravity.

In accordance with a further embodiment of the present invention, there is also provided a slow-mode microwave applicator suitable for use for heating, drying, curing, ionization of gases, or other treatment by microwave energy of workpieces containing lossy dielectric material, in solid, liquid or gaseous form, comprising a slow wave microwave structure, and microwave energization means connected to the said structure adapted to energize said microwave structure whereby a region adjacent said structure will contain a predominance of degenerate $\pi/2$ mode or near degenerate $\pi/2$ mode electric field energy. This apparatus preferably includes a transparent microwave radiation shield adapted for unobstructed observation of a plasma or workpieces, said radiation shield surrounding said slow wave structure. A particularly preferred form of the last embodiment comprises

- a first set of parallel conducting rods in spaced relation,
- a second set of parallel conducting rods in spaced relation and interleaved alternately with the first set,
- a first strap-bar in the form of an extended conducting plate making contact with each of the first set of parallel conducting rods,
- a second strap-bar generally parallel to the first and in the form of an extended conducting plate making contact with each of the second set of parallel conducting rods,
- microwave energization means attached to said first and second strap-bars to energize said bars and engender an electric field region adjacent said bars,

said field containing a predominance of degenerate $\pi/2$ mode or near degenerate $\pi/2$ mode electric field energy.

In accordance with a still further embodiment of this invention, there is provided an apparatus suitable for generating a plasma, the improvement comprising a slow wave structure having an input end adapted to apply microwave energy to a plasma, means for conveying said microwave energy from a source thereof to the input end of said slow wave structure, and a source of microwave energy; preferably such apparatus also includes a transparent microwave radiation shield adapted to provide an unobstructed observation of a plasma, said shield surrounding said slow wave structure and being also adapted to surround a plasma container.

In a still further embodiment of this invention, there is provided a method of treating material to alter the properties of such material comprising providing an apparatus for generating a plasma using electromagnetic energy in the microwave frequency range, said apparatus having a source of microwave energy, at least one slow wave structure having an input end for applying said microwave energy to a plasma, means for conveying said microwave energy from said source of said microwave energy to the input end of said slow wave structure, a plasma container and means for maintaining conditions of pressure and gas flow in said plasma container, and exposing said material to said plasma.

The slow wave structure may be of the "semi-radiating" type, such as a strapped-bar structure, and may be terminated in a dummy load or other type of dissipative termination. In accordance with a preferred embodiment of the invention, the slow wave structure is placed in close proximity to the gas plasma container so that efficient "coupling," or transfer of power, can occur from the electromagnetic field of the structure to the plasma within the container. Under conditions where there is no plasma but a non-ionized gas of high electrical impedance, and where the slow wave structure is still being energized, this microwave energy will not be radiated from the structure, but will traverse it with little loss, and will be dissipated in the dummy load.

In accordance with a further feature of the invention, the slow wave structure may be arranged to provide substantially constant energy transfer along its length by increasing the coupling between the slow wave structure and the plasma at points farther from the source of microwave energy. This can be accomplished by mounting the slow wave structure at an angle e.g. between 1° and 30° , with respect to the plasma container, or by changing the electrical characteristics of the structure along its length. It can also be accomplished by "sandwiching" the plasma container between two slow wave structures which are energized from opposite ends.

In an electrical discharge, electrons produced by partial ionization of the gas gain energy from the electric field, and transfer some of this energy to molecules via collisions, thereby creating more electrons and positive ions; the energetic electrons are also capable of dissociating molecules, or of raising them to higher states of excitation. The resulting species include, among others, neutral atoms, free radicals, rotationally or vibrationally excited molecules, etc. Many of these species are chemically highly reactive, and tend to recombine to

form the starting material, if only one kind of atom is present, or various compounds if several different kinds of atoms are present.

In addition to their usefulness for effecting chemical changes, the excited species which constitute a plasma also emit radiation which can be used for various purposes, for example, for laser action, for spectral sources, for identifying trace impurities in the gas, for generating light in various parts of the spectrum, etc. The physical principles involved are well known to those skilled in the art, and need not be discussed in detail here. Suffice it to say that an efficient plasma generator such as the one embodied by the present invention can have many and varied applications, some of which constitute a particular aspect of the present invention.

Of the various forms of electrical energy which can be used to generate gaseous plasmas (for example, d.c., low frequency a.c., "corona," radio frequency, microwave) microwave energy is particularly advantageous in many cases. Some of the advantages are the following:

- a. There are no electrodes, which frequently constitute a major source of contamination.
- b. The yield of active species is much higher (ten times or more) than in other forms of discharges, that is, the energy density is higher.
- c. Most of the energy in the plasma resides in the "electron gas," that is, the "electron temperature," T_e , is much higher than the gas temperature, T_g .
- d. It is possible to sustain a microwave plasma at higher pressures than most other forms of electrical discharges, at a given applied power level.
- e. Practically all the available microwave energy can be coupled into the plasma.
- f. The state of the art in the technology of generating microwave power is advanced.

In spite of these advantages, the use of microwave plasmas has been severely limited by the small size of plasma volumes achievable with conventional microwave applicators, namely antennas, waveguides, and cavity resonators. Such applicators are described, for example, by Fehsenfeld et al. (Review of Scientific Instruments, Volume 36, page 294, 1965), by Shaw (Formation and Trapping of Free Radicals, A.M. Bass and H.P. Broida, Eds., Academic Press 1960, page 57), and by McTaggart (Plasma Chemistry in Electrical Discharges, Elsevier, London, 1967, Chapter 4). Processing a large volume of gas as required, for example, in a chemical plant would require a multiplicity of such applicators which would render the capital outlay for equipment prohibitive. One object of this invention, namely the use of a slow wave structure for applying the microwave energy to the plasma, completely solves this problem: for example, by using a 36 inch-long "semi-radiant" slow wave applicator operating in the degenerate $\pi/2$ mode, as an object of the present invention, it is possible to generate microwave plasmas in a volume of 1,000 cubic centimeters or more; this is a factor of about 100 greater than that which can be achieved with a typical, commercially available cavity resonator. It should be emphasized that this ratio can easily be increased even more.

Slow wave structures as microwave applicators, well known to those skilled in the art, can be divided into two general types: resonant slow wave structures, and traveling slow wave structures. As examples of the former

and latter there may be mentioned, respectively, the disclosures of C.M. Loring (U.S. Pat. No. 3,532,848 issued Oct. 6, 1970), and J.E. Gerling (U.S. Pat. No. 3,472,200 issued Oct. 14, 1969).

In addition to slow wave applicators, there exists a "fast-wave" applicator, the so-called "zero-mode" applicator for which a patent application has been filed separately (U.S. Pat. Ser. No. 117,538). All the prior disclosures listed above deal specifically with the use of microwave energy for heating, drying or curing large areas or moving sheets of material; none specifically mention, or are suitable for, gaseous discharges as embodied by the present invention. On the other hand, the wide band, traveling slow wave structure operating at or near the degenerate $\pi/2$ mode, an object of the present invention, is particularly advantageous for generating large volume microwave plasmas in the context of the present invention. The particular reasons for this will become clear in the course of the present disclosure. It is to be expressly understood, however, that this slow wave structure, although very well suited for plasma generation, is used here by way of illustration only, and that it is not intended as a definition of the limits of the invention. It is also understood that the beneficial properties of this applicator make it very useful for applications other than plasma generation, such as drying, heating or curing as taught by the prior art referred to above.

The novel features which are believed to be characteristic of the invention, both as to its organization and method of operation, together with further objects and advantages thereof, will be better understood from the following description considered in connection with the accompanying drawings in which an illustrative system embodying the principles of the invention is illustrated by way of example. It is to be expressly understood, however, that the drawings are for the purpose of illustration and description only, and are not intended as a definition of the limits of the invention.

In the drawings:

FIG. 1 is a front view of a large volume microwave plasma generator (LMP) apparatus embodying several aspects of this invention.

FIG. 2 is a side view of said LMP apparatus.

FIG. 3 is a perspective view, partly in section, of the transparent radiation shield portion of the apparatus in FIG. 1.

FIG. 4 is a detailed frontal view of a part of the linear slow electromagnetic wave structure of the strapped bar type, as incorporated on the apparatus of FIG. 1.

FIG. 5 is a cross sectional view taken along the line 5—5 of FIG. 4.

FIG. 6 is a plan view of the slow wave structure taken along the line 6—6 of FIG. 4.

FIG. 7 is a sectional view, perpendicular to the axis, through a slow wave electromagnetic structure of the strapped bar type in circular geometry.

FIG. 8 is a cross sectional view taken along line 8—8 of FIG. 7.

FIG. 9 is a Brillouin diagram of a slow wave structure of the type shown in FIGS. 4 to 6.

FIG. 10 is a schematic frontal view of a slow wave structure and plasma container.

FIG. 11 is a schematic diagram depicting two graphs of average electric field strength squared measured lengthwise along a slow wave structure.

FIG. 12 is a cross sectional view taken through a slow wave structure of the type shown in FIGS. 4 to 6 and a plasma container, for the case where said plasma container is of the transverse flow type.

FIGS. 13 and 14 are plan views of particular types of transverse-flow plasma containers.

FIG. 15 is a schematic frontal view of a plasma container sandwiched between two slow wave structures to which microwave energy is applied from opposite directions.

FIG. 16 is a schematic plan view of a comb-type of slow wave structure.

FIG. 17 is a schematic plan view of a ladder-type of slow wave structure.

FIG. 18 is a schematic plan view of a zig-zag line type of slow wave structure.

FIG. 19 is a schematic plan view of a helix-type of slow wave structure.

FIG. 20 is a semi-logarithmic chart depicting the yield of oxygen atoms in a flow of oxygen gas which is ionized by different amounts of microwave power, where the latter is applied in one case by a cavity resonator and in the other case by a slow wave structure of the type shown in FIGS. 4 to 6.

FIG. 21 is a chart depicting the maximum yield of nitrogen atoms in a flow of nitrogen gas which is ionized by microwave power, in one case applied with a cavity resonator and in the other with a slow wave structure of the type shown in FIGS. 4 to 6.

FIG. 22 is a schematic frontal section through a microwave plasma apparatus for the treatment of material in web, sheet or plate form.

FIG. 23 is a sectional view taken along line 23—23 in FIG. 22.

FIG. 24 is a schematic sectional side view of an alternate microwave plasma apparatus for the treatment of material in web, sheet or plate form.

FIG. 25 is a sectional view taken along line 25—25 in FIG. 24.

FIG. 26 is a schematic frontal sectional view of a microwave plasma apparatus for the treatment of material in granular, fibrous, or other form.

FIG. 27 is a schematic frontal view of a laser apparatus pumped by microwave energy.

Referring more particularly to the drawings, the large volume microwave plasma generator apparatus of FIGS. 1 and 2 consists of a cabinet 19 which houses all the components. Microwave energy from a power source 1 is fed to the slow wave structure 6 via conventional rectangular waveguide 2, the two being coupled by a transition section 5. Power monitors 3 and 10 allow one to measure the forward, reflected, and transmitted microwave power, respectively. A triple-stub tuner 4 assures minimal reflection of power back to the source 1, and any transmitted power is absorbed in the dummy load 11. The direction of microwave energy flow is indicated by heavy arrows 16. Lengthwise and in close proximity to the slow wave structure 6 is a gas plasma container 8, typically made of microwave-transparent material such as quartz; it contains the ionized gas plasma 7 which is created when the gas inside the container absorbs microwave power. Desired conditions of gas flow rate and pressure are maintained by adjusting the gas feed rate from the storage vessel 14, by means of a flow and pressure regulator 15, and by means of the pumping rate of the vacuum pump 13. Details of the plasma and the gas flow system depend

upon the particular application, so that the latter is merely indicated schematically by the gas flow conduit 12 and arrows 17 which depict the direction of gas flow. The plasma container 8 is cooled from the outside by a forced flow of air from a fan 18.

The radiation shield 9, shown in detail in FIG. 3, permits an operator to observe the microwave plasma zone at close range, and in the absence of exposure from any stray microwave radiation. The shield consists of a rectangular box, open at the bottom, which is made for example of 1/8 inch to 1/4 inch thick plexiglass plate 23. Double walls enclose a leak-tight space, typically 1/2 inch wide, filled via a filler or drainage plug 21 with a water solution 22 which strongly absorbs microwave radiation. Oval openings 20 provide a passage for the gas plasma container; the bottom of the shield rests on the cabinet 19, which completes the radiation-tight enclosure.

In the context of this invention, the strapped bar type of slow wave structure depicted in FIGS. 4 to 6 is a particularly advantageous applicator of microwave energy, as will be seen below. The transition from the rectangular waveguide 2 to the slow wave structure consists of a doubly tapered inner conductor 24 suitably situated at a length L₁ from the end of the rectangular transmission line section. The inner conductor 24 is followed by a tapered parallel plane transmission line 25 whose length L₂, best determined experimentally, is about μ/4 where μ is the free space wavelength at the operating frequency. The angle α, also determined by experiment, is about 30°.

A number of metal conducting bars or tubes 26 are placed in a plane and electrically connected near their midplane by parallel straps 27 and 28 in an alternating manner as shown in FIG. 4, and the bars 26 which form the periodic structure are terminated at each end by a shorting plane 29. The separation L₃ between the strap-conductors 27 and 28, and the distance L₄ between the end shorting planes determine the operating frequency of the structure. As will be shown, it is advantageous to operate the present structure in the so-called π/2 mode in which case L₃ and L₄, best determined experimentally, are typically μ/10 and μ/2 in length, respectively. When operated in this manner, the region occupied by the plasma container contains the strong electric field 30 of the π/2 mode, which couples into the plasma, leading to a transfer of the microwave energy to the plasma. Any unused microwave energy propagates along the slow wave structure to the outlet transition, which is identical to that at the inlet, and is transmitted via a rectangular waveguide to a dummy load where it is converted to heat energy.

FIGS. 7 and 8 show two views of a strapped bartype of slow wave structure having a cylindrical geometry, which is electrically identical to the linear structure depicted in FIGS. 4 to 6. Here again the conducting bars 31, arranged around the perimeter of a circle, are connected alternately by the strap conductors 32 and 33, and are shorted on both ends by shorting planes 34. The strong electric fields inside the cylinder may couple with a plasma, when a plasma container is placed along the axis of the energized structure.

A periodic structure is sometimes best described by a Brillouin diagram such as the one shown in FIG. 9. Information regarding its pass bands, stop bands, phase velocity and group velocity are contained in such a diagram, and the frequencies at which the degenerate π/2

mode occurs can be identified. The frequency separation f₁ - f₀ of the two degenerate π/2 modes 35 and 36 is dependent on the uniformity of the cells composing the structure: theoretically the narrow stop band f₁ - f₀ is completely removed when the cells are identical, and the modes lying on the two branches indicated by dashed lines 37 and 38 are no longer existant. In actual practice an absolute symmetry is not desirable if one wishes to operate at or near the degenerate π/2 mode.

It is known to those versed in periodic microwave structures that operation near a band edge, that is, either in the degenerate π/2 or in the π mode, leads to particularly strong electric fields near the slow wave structure; the reason for this is that the electric field strength is inversely proportional to V_g, the group wave velocity, which is very small near a band edge. Furthermore, as the electric field drops off as e - β_ny with distance y normal to the plane of the slow wave structure, it extends out particularly far in the case of the degenerate π/2 mode (for which β_n is a factor of 2 smaller than that of the π mode, for example). In order to create a gaseous plasma, the applied electric field strength must exceed the dielectric breakdown strength of the gas; as the breakdown strength increases with increasing gas pressure, strong electric fields are necessary for plasmas at elevated pressures. Clearly then, the main features associated with operating the strapped bar structure of FIGS. 4 to 6 in the π/2 mode, namely high field strength extending over a considerable distance from the slow wave structure, are very advantageous for the production of large volume microwave plasmas at elevated pressures.

For example, the experimental data shown in Table I below were obtained with a 36 inch long strapped bar slow wave structure as shown in FIGS. 4 to 6, operating in the π/2 mode at 2,450 MHz frequency. Some further characteristics of this device were as follows: the dimensions L₃ and L₄ were, respectively, 1/4 inch and 2.5 inches, and during normal operation substantially 90 percent or more of the microwave power was coupled into the plasma. At elevated gas pressures there was a limit as to how much power could be coupled into the plasma, the excess power being transmitted to the dummy load. (Or, conversely, at a given power level, there was a maximum pressure at which substantially all this power would couple into the plasma). Further increases in pressure eventually resulted in extinction of the plasma as shown in Table I.

TABLE I

Approximate GAS	Pressure for Maximum Power Absorption po (torr)	Extinction Pressure pe (torr)	Maximum Power Wm (watts)	Typical Gas Flow Rate (l./min)
Argon	250	495	750	1 to 20
	300	580	1500	Do.
	500	980	2500	Do.
Nitrogen	40	80	750	1 to 15
	60	110	1500	Do.
	160	310	2500	Do.

The plasma container in this case was a quartz tube having an inside diameter of 19 millimeters and a total volume of 260 cubic centimeters which was completely filled by the plasma. Similar experiments have been carried out in substantially larger plasma volumes.

Other important features of the invention can be seen from FIG. 10: in order to obtain a uniform field intensity, hence a plasma of uniform power density along the full length L of the slow wave structure 6, it is necessary to incline the plasma container 8 at a slight angle θ with respect to the former. The electromagnetic wave propagating down the length of the slow wave structure 6 may be expressed, for small values of θ , by

$$E = E_0 e^{-\beta_n y} e^{-(\beta_L + \beta_g)z} + i \beta_e z e^{j \omega t} \quad (1)$$

where β_n is the normal attenuation constant of the electric field strength, β_L is the longitudinal attenuation constant of the slow wave structure, and β_g is the linear attenuation constant of the electromagnetic wave inside the plasma container. Under optimum conditions, the electric field vector of the electromagnetic wave should be constant. From (1) this signifies that

$$\beta_n y - \beta_L z - \beta_g z = \text{constant} \quad (2)$$

Differentiating equation (2) with respect to y ,

$$dz/dy = -(\beta_n/\beta_L + \beta_g) \approx \theta \quad (3)$$

It is seen that a uniform power transfer, hence plasma density, can be maintained throughout the full length of the plasma container 8, by inclining the latter at an angle θ with respect to the plane of the slow wave applicator 6 without in any way restricting the length L of the applicator. This is shown graphically in FIG. 11 where the time-averaged relative electric field intensity squared (E^2), which is proportional to power transfer, is plotted against longitudinal distance z along the slow wave structure. Curve 39 shows the exponentially decreasing profile for the case where the plasma tube is maintained at a constant distance y from the plane of the slow wave structure; curve 40 shows the constant power transfer profile obtained by proper choice of the angle θ . In the case of a 36 inch long structure operating at 2,450 MHz frequency, θ is found to be about 3° to 10° .

FIG. 12, a sectional view perpendicular to the z axis of a linear strapped bar slow wave structure and adjacent plasma container 41, depicts a transverse flow modification of the gas flow geometry, which can be convenient under certain circumstances, notably where short average residence time of a gas molecule in the plasma zone is desired. FIGS. 13 and 14 show plan views of two possible transverse flow plasma containers, where 42 is the plasma container proper, 43 and 43' are the gas inlet and exit ports, respectively, 44 is the gas distribution manifold, and 45 is a porous diffuser type of manifold. Arrows 17 show the overall gas flow direction and arrows 46 show particular examples of gas flow paths.

FIG. 15 schematically depicts another possible variation of the invention, namely one in which microwave power is simultaneously applied to the plasma 7 in the plasma container 8 from two slow wave structures 6 and 6' between which the plasma container is "sandwiched." The plasma container makes an angle θ with each of the slow wave structures 6 and 6', but the direction of flow of the microwave power 16 in the case of 6' is opposite to that of 6. The advantage of this arrangement is that a plasma can be maintained in an even greater volume, that is, in a plasma container of

greater diameter, than in the case where microwave power is applied from a single slow wave structure. Clearly, it would be possible, if desired, to apply microwave power from more than two slow wave structures by placing them around the plasma container in a suitable manner.

Although the wide band, strapped bar type of slow wave structure discussed so far is well suited for applying microwave power to a plasma, it is possible to use other types of geometries, well known to those familiar with slow wave structures, for the same purpose. FIGS. 16 to 19 show schematically some examples of slow wave structure geometries which could be suitably adapted to the purposes of the present invention. FIG. 16 represents a plan view of a comb-type of slow wave structure in which microwave energy follows the direction of arrows 47 between the conductive side walls 48 and the vanes 49. FIG. 17 is a plan view of a ladder-type of slow wave structure consisting of conductive side walls 50 and bars 51; FIG. 18 is a plan view of a zig-zag line type of slow wave structure composed of a conductor 52, and FIG. 19 is a helical type of slow wave structure consisting of a conductor 53. It is understood that these or other types of slow wave structures not mentioned here could be suitably adapted for the requirements of the present invention, and that this is included in the spirit of the present invention.

In FIGS. 20 and 21 experimental results obtained when two different kinds of microwave applicators are compared; in one case an LMP apparatus of the type depicted in FIGS. 1 and 2 was used, and in the other case microwave power was applied by means of a cavity resonator, the frequency in both cases being 2,450 MHz. In the case of FIG. 20, a flow of oxygen gas was ionized by microwave power, leading to partial dissociation of the molecules to atoms. The flow rate of atoms is plotted against absorbed microwave power; it is seen from curves 55 and 56 that the atom concentration reaches a limiting value when power is applied with a cavity resonator, but from curve 54 it is clear that much larger atom yields are possible using a slow wave structure for applying the microwave power. In FIG. 21 a similar comparison is made, this time for the case of dissociation of nitrogen gas. The chart shows maximum yield of nitrogen atoms plotted against nitrogen gas flow rate. Again the percentage dissociation obtained with the LMP (curve 58) is seen to be substantially higher than that obtained with a cavity resonator (curve 57). It is well known that atoms are extremely reactive chemically; there are numerous processes of industrial interest in which high yields of atomic oxygen, nitrogen, or atoms of other molecular gases can be put to good use. For example, it is possible to form protective oxide or nitride layers on the surfaces of metals or semiconductors; to synthesize useful organic or inorganic molecules, and even to obtain laser action by so-called "chemical pumping." Details of these processes, familiar to those skilled in the art, need not be given here; suffice it to state that the LMP's efficiency for producing atoms and other chemically active species can be highly advantageous in these processes.

The remaining figures represent various possible industrial applications using the principles of the present invention. It is well known to persons familiar with plasma chemistry that desirable characteristics can be imparted to various materials via a plasma treatment: for example "cross-linking" can be achieved on the

surface of plastics when exposed to a gaseous plasma; plastic films, e.g. polyethylene and the like treated in this way have greatly improved bonding and printing characteristics. It is also possible to graft various molecules to free radical sites created by plasma treatment; in this manner the dyeability and washability characteristics of certain textiles, e.g. polyester and other synthetic materials can be greatly improved. Exposure to a plasma also has been found to substantially reduce shrinkage of natural fibres such as wool. Certain organic vapours can be made to form solid polymer films in a plasma; when a substrate is passed through the plasma, a layer of polymer which can be made very thin and free of defects will tend to deposit on it. Such layers are very useful for various industrial purposes such as encapsulation of electronic components, protection of surfaces against corrosion, etc.

A most important application of plasmas, however, is to improve the bonding characteristics of films or fibres of natural or synthetic polymeric materials or combination thereof. Some experiments have been carried out in which batches of various such materials were exposed to microwave plasmas in an LMP apparatus of the type illustrated in FIGS. 1 and 2. Some typical results of these experiments are shown in Tables II to IV.

TABLE II

Increase in the water-induced bonding of cellulose strips after treatment in a microwave plasma

Gas	Pressure (torr)	Treatment time (sec)	Power (watts)	Bond strength (kg/cm ²)
Control	—	—	—	1
Argon	45	120	100	113
Argon + 5% Oxygen	20	30	200	80
Air	20	120	200	16

TABLE III

Increase in the autohesion of polyethylene strips after treatment in a microwave plasma

Gas	Pressure (torr)	Treatment time (sec)	Power (watts)	Bond strength (kg/cm ²)
Control	—	—	—	0.9
Argon	75	5	1500	1.6
Air	5	10	1500	1.6
Argon + 5% Oxygen	50	20	1500	1.3
Helium	15	50	1500	1.4
Helium + 5% Oxygen	17	90	2500	2.0

TABLE IV

Increase in the strength of kraft pulp after treatment in a microwave plasma

Gas	Pressure (torr)	Treatment time (sec)	Power (watts)	Breaking length (m)
Control	—	—	—	880
Argon + 10% Oxygen	20	100	600	1720
Helium + 5% Oxygen	17	90	25	1490
Air	20	120	200	950
Argon	45	120	100	950

Clearly, the treatment of cellulose or polyethylene in the microwave discharge of an LMP apparatus can produce marked increases in the bonding ability of the surfaces. FIGS. 22 to 26 illustrate apparatus which can be used to carry out such treatments on an industrial scale.

FIGS. 22 and 23 show schematically two views of an apparatus utilizing the principles of the present invention, in which material in web, film, foil, or plate form can be treated by any one of the plasma processes mentioned above. FIG. 22 is a frontal section and FIG. 23 a transverse section through the apparatus, respectively taken along lines 22—22 and 23—23. Material in the form of a film 64, say, unrolls continuously from discharge roll 69 to take-up roll 69', as indicated by arrows 71. The incoming material first passes through a vacuum seal 68 into a lock which is maintained at reduced pressure by continuous pumping through a tube 70. From the lock the film passes through another seal 68 into the treatment chamber 66, where a uniform microwave plasma 65 and 65' is maintained on both sides of the film by slow wave structures 63 and 63', respectively; these are inclined with respect to the plane of the film, the direction of microwave power flow being indicated by arrows 16. The linear speed with which the film travels through the plasma zone is chosen in such a way that the time of exposure to the plasma is sufficient to give the desired effect. After treatment the film exits via vacuum seals 68' and another lock 67' to atmosphere where it is received on roll 69'. The desired gas purity and pressure inside the treatment chamber 66 is maintained by a gas supply 59 and a vacuum pump 60 via gas feed lines 61, the gas flow direction being indicated by arrows 62.

In FIGS. 24 and 25 a similar apparatus is illustrated, except that here the costly vacuum treatment chamber has been replaced by suitable plasma containers 73 and 73', of which the film to be treated 78 makes up part of the vacuum-tight wall. As shown in FIG. 24, which represents a transverse section through the apparatus, this is accomplished in the following manner: the film 78 is pressed firmly against vacuum seals 76, which are part of the plasma container 73, by a cylinder 75 rotating about an axis 79. Thus the plasma 77 can impinge directly upon one side of the film surface, which is continuously renewed as the film travels from discharge roll 74 to take-up roll 74' in the direction indicated by arrows 81. The other side of the film is treated by a similar unit also shown. FIG. 25 represents a section along line 25—25 in FIG. 24, in which the film 78 is seen to be in contact with the plasma 77 over its entire width. As before, the plasma is maintained uniformly by microwave power from the slow wave applicator 72, and gas flow and pressure conditions in the plasma container can be maintained as desired via gas flow conduits 80.

FIG. 26 represents an apparatus for the microwave plasma treatment of material which is not in web or film form, hence not conducive to treatment by apparatus of the type illustrated in FIGS. 22 to 25. Granular, fibrous, and other types of materials may be treated in this apparatus which consists of a wide plasma container section 81, in this case mounted vertically, in which a uniform microwave plasma 82 is maintained by two (or more) slow wave structures 83 and 83'. Again, the direction of microwave energy flow is indicated by

heavy arrows 16. The material to be treated 84 is placed inside a hopper-vessel 85 which can be closed vacuum-tight by means of a lid 86. During a treatment cycle, the material passes through the plasma zone under the action of gravity, and is collected in the vacuum-tight storage bin 87. Again the desired gas purity and pressure is maintained in the apparatus by means of a gas supply 88, gas conduits 90, and a vacuum pump 89.

Another possible application of the present invention of industrial interest is illustrated schematically in FIG. 27: the use of microwave power for pumping a gas laser. As is well known to those skilled in the art, numerous gases or mixtures of gases such as nitrogen, argon, carbon dioxide, carbon monoxide and others, when excited to a higher state of internal energy, for example by an electrical discharge, can be made to emit coherent radiation at particular wave-lengths. The CO₂ system was given particular attention while adapting the present invention to pumping a gas laser; the reason was that the infrared emission at 10.6 microns wave-length of the CO₂ molecule is very useful industrially, as is well known to those familiar with lasers. Several features of the present invention are very advantageous from the point of view of laser technology, particularly in the case of CO₂ lasers:

1. The long length of the plasma column permits a high degree of amplification.
2. The large plasma volume permits a considerable amount of energy to be stored and released, and facilitates effective heat exchange.
3. The high electron temperature to gas temperature ratio improves the efficiency of the laser by minimizing losses from the system in the form of low-grade thermal energy.
4. The absence of electrodes, hence absence of erosion problems and contamination.
5. High stability and uniformity of the microwave plasma.
6. Relatively high operating pressure.
7. Choice of continuous or pulsed mode of operation.

Referring to FIG. 27, a plasma 95 is created inside the plasma container 91, which is of the transverse flow variety as shown in FIGS. 12 to 14, by applying microwave energy from a slow wave structure 6, or from a multiplicity of slow wave structures, for example as shown in FIG. 15. A suitable transverse flow of gas or gas mixture is maintained through the plasma container so as to minimize heating effects. (In the experiments which have been carried out, a mixture consisting substantially of 80 percent helium, 10 percent nitrogen and 10 percent carbon dioxide was used). Laser action is brought about when properly aligned mirrors are placed at either end of the plasma container: 92 is a fully reflecting spherical mirror (polished stainless steel, in the present case), and 93 is a partly reflecting, partly transmitting plane mirror (coated germanium in the present case), through which part of the radiation escapes in the form of a narrow laser beam 94. In the present case a forced flow of air was used to cool the plasma container 91, but circulation of a suitable cooling fluid could be used as well.

Further features and advantages of the present invention can be pointed out by referring to the preceding drawings and their descriptions.

- a. The primary advantage of this invention is, of course, the large plasma volume which allows one to treat materials in industrial quantities. Although all the examples presented so far pertained to the 2,450 MHz ISM band (Government-approved frequency for industrial microwave applications) larger plasma volumes could be achieved by operating at the 915 MHz ISM band. At this lower frequency, the characteristic dimensions of the slow wave structure are greater, and the electric field extends still further out from the plane of the structure.

There may be other advantages to operating at the next higher ISM band, 5,800 MHz, such as the use of higher operating pressures. It is understood, then, that the invention is in no way limited to a particular microwave frequency range, except as governed by practical considerations of size of the slow wave structure, which becomes too large and cumbersome at frequencies substantially lower than about 500 MHz, and too small at frequencies substantially above the 5,800 MHz ISM band. Returning to the large volume feature of the invention, in most chemical applications of microwave plasmas, an important parameter is the average time, t , which it takes for a gas molecule to pass through the plasma zone. This "residence time" is given by

$$t = AL/F = V/F \quad (4)$$

where A, L, and V are, respectively, the cross sectional area, length and volume of the plasma zone, and F is the gas flow rate. For a given value of t , it is seen that an increase in V permits a corresponding increase in F, the amount of gas that can be processed per unit of time.

- b. In certain types of chemical syntheses, for example, in the synthesis of unstable molecules such as hydrazine or acetylene, it is important that t be kept as small as possible in order to prevent decomposition by the plasma of the product formed; in such cases it is preferable to use the transverse flow configuration illustrated in FIG. 12. An additional advantage of the invention, then, is the ability to control the residence time for a given gas throughput.

- c. As mentioned earlier, large uniform plasma volumes can be obtained by operating the slow wave structure in the $\pi/2$ mode, and by inclining the plasma tube at an angle θ with respect to the structure, as shown in FIG. 10. Another advantage of this arrangement is that standing wave patterns which normally arise due to points of discontinuity along the transmission line are not likely to be important on account of the efficient coupling.

- d. The uniform electric field characteristic discussed in connection with FIGS. 10 and 11, is not generally a property of resonant cavity type applicators. In fact, the latter usually have very inhomogeneous electric field distributions. A uniform field, however, can be very important, for example, in chemical synthesis reactions such as chemical conversion (cracking) of hydrocarbon molecules where many reaction schemes are possible, each requiring a different energy of activation. Now, the energy distribution of free electrons, which are primarily responsible for effecting chemical changes by rupturing chemical bonds, depends very strongly upon

the electric field intensity; if the latter is uniform, the energy distribution of electrons tends to be uniform, hence the type of reaction taking place will tend to be more specific, and conditions can be chosen so as to give a greater yield of a desired product.

- e. Another important advantage of the traveling slow-wave structure as opposed to resonant type applicators, described for example in U.S. Pat. No. 3,532,848, is that changes in the dielectric constant of the work load affect only the total phase change between the input and the output points, but have little or no effect on the field amplitude, due to the loose coupling between the slow-wave structure and the work load (the plasma). In the case of the above mentioned resonant-cavity applicators, however, where a tight coupling is necessary between the applicator and the work load, changes in the dielectric constant can cause considerable amounts of microwave power to be reflected back to the generator.
- f. On the other hand, a traveling wave type slow wave structure such as the one described in U.S. Pat. No. 3,472,200 is a "non-radiative," narrow band periodic structure which is normally non-propagating; the reason for this is that adjacent cells of the structure are not strongly coupled to each other, for example, by irises or other coupling means known to those familiar with microwave slow wave structures. In theory this periodic structure only propagates energy when a conducting surface is placed close by, where this surface increases the fringing field capacitance between the cells; this, in turn, increases the pass-band of the circuit sufficiently to allow propagation, hence energy transfer to the work piece. These limitations do not exist in the case of the broad band, "semi-radiant" traveling wave structure of the present invention.
- g. It is also well known to those versed in periodic structures that correct functioning of narrow band structures such as the one described in U.S. Pat. No. 3,472,200 depends very critically on dimensions: each cell must have exactly the same cut-off resonant frequency which must lie well within the narrow pass-band of the structure. As a result, such structures can only conveniently be manufactured in relatively short lengths, 2 feet or less. This drawback does not exist in the case of the broad-band travelling wave structure depicted in FIGS. 4 to 6, which can easily be manufactured in lengths of 60 inches or more with conventional machine tools and without the need for highly accurate machining operations.
- h. An inherent advantage of the present invention, embodiments of which are shown in FIGS. 1 and 2, is the accessibility of the plasma container 8 for cooling purposes: particularly at higher pressures, and in the case of exothermic chemical reactions, the plasma may create sufficient heat to necessitate cooling the plasma container. This can be accomplished simply by a forced flow of air from any direction. Usually a longitudinal air flow provided by a fan or blower 18 is preferred, as the radiation shield 9 acts so as to guide the flow of cooling air along the plasma container 8. An alternate method of cooling could be the flow of a liquid having low dielectric losses, such as Dow Corning Type 200

Dielectric Fluid, or of a petroleum product known as BAYOL 35, through a concentric enclosure around the plasma container.

- i. A further advantage of the accessibility of the plasma container 8 is that it can be viewed from all sides. This is particularly important when the plasma is used as a source of electromagnetic radiation, another industrial use of the present invention which has many possible applications.

As is well known to those skilled in the art, short lifetimes, particularly at power levels in the kilowatt range, are a standard feature of arc lamps, such as high pressure xenon arcs. The reason for early failure resides in the presence of electrodes: not only do the electrode seals with the quartz envelope tend to rupture, but metal sputters off the electrode, darkens the envelope which in turn increases heat absorption by the latter, leading to rapid degradative failure. The present invention, illustrated schematically by FIG. 10, can be used as an electrodeless source of radiation; the absence of electrodes removes the problems mentioned above, lending to this design a practically unlimited life.

Depending on the desired application, several parameters can be changed: the size and shape of the plasma container (and of the accompanying slow wave structure), and the gas in the plasma container. For example, if a small, very bright source of "white" light is required, one could choose a small slow wave structure designed to give a very intense electric field, and a filling of xenon gas in the plasma container. Other requirements could be for sources having large surface areas and yielding relatively high amounts of ultraviolet radiation in their spectrum; such sources could be useful, for example, in photochemistry, for activating large photo-emitting surfaces, or for other uses. In this case one might prefer to operate at a lower frequency, for example 915 MHz, so as to have the largest practically sized slow wave structure; one might also want to choose a configuration of plasma container having the largest possible useful surface area, for example a flat, wide configuration; and one might select a gas, such as carbon monoxide, or a mixture of gases, whose emission spectrum is known to consist, to a substantial degree, of wavelengths in the ultraviolet portion of the spectrum.

Yet another requirement for an electrodeless radiation source, as embodied by the present invention, may exist in the field of analytical chemistry. It is well known to those familiar with spectroscopy that all substances, when excited to a high state of internal energy as in a plasma, emit radiation of characteristic wavelengths, by which they may be identified. This can be particularly useful, for example, in the detection and identification of trace amounts of impurities in gases, vapours, or gas mixtures where the absence of possible contamination from electrodes is particularly important.

It will be understood that various modifications can be made to the above-described preferred embodiments without departing from the spirit and scope of the invention.

We claim:

1. An apparatus for generating a plasma using electromagnetic energy in the microwave frequency range comprising a source of microwave energy, at least one slow wave structure having an input end for receiving microwave energy from the source thereof, means for

conveying said microwave energy from said source of said microwave energy to the input end of said slow wave structure to create a region adjacent said slow wave structure containing electromagnetic energy, a plasma container spaced from and located in proximity to said slow wave structure in the region containing electromagnetic energy, said plasma container being adapted to receive an ionizable gaseous fluid so that the microwave energy is applied to said gaseous fluid to generate a plasma therefrom, means for maintaining conditions of pressure and flow of said ionizable gaseous fluid in said plasma container, and said slow wave structure having an output end for discharging certain of the microwave energy traveling along said slow wave structure.

2. An apparatus, as defined in claim 1, said apparatus including a dummy load connected to the output end of said slow wave structure.

3. An apparatus, as defined in claim 1, said apparatus including means for measuring forward, reflected and transmitted microwave power.

4. An apparatus, as defined in claim 1, said apparatus including a transparent microwave radiation shield adapted for unobstructed observation of a plasma, said radiation shield surrounding said slow wave structure and said plasma container.

5. An apparatus, as defined in claim 1, wherein said slow wave structure is a non-resonant semi-radiant strapped bar type.

6. An apparatus, as defined in claim 4, wherein said radiation shield comprises an inner wall made of a transparent dielectric material, an outer wall made of a transparent dielectric material, and a transparent liquid which absorbs microwave energy filling the space between said inner and outer walls.

7. A slow-wave microwave applicator apparatus suitable for use for heating, drying, curing, ionization of gases, or other treatment of workpieces by microwave energy, and which gases or workpieces contain lossy dielectric material, in solid, liquid or gaseous form, said apparatus comprising a slow wave microwave structure, and microwave energization means connected to the said microwave structure adapted to energize said microwave structure so that a region adjacent said structure will contain a predominance of degenerate $\pi/2$ mode or near degenerate $\pi/2$ mode primarily backward wave electric field energy to enable band edge operation at the $\pi/2$ mode, the backward waves of said electric field energy housing, a phase velocity approaching zero and propagating their energy in one direction and their phase fronts in an opposite direction, the operation bandpass of said slow wave structure being defined by a frequency spectrum F_1-F_0 near the mode bandedge.

8. A slow-wave microwave applicator apparatus suitable for use for heating, drying, curing, ionization of gases, or other treatment of workpieces by microwave energy, and which gases or workpieces contain lossy dielectric material, in solid, liquid or gaseous form, said apparatus comprising:

- a. a slow wave microwave structure,
- b. said slow wave microwave structure comprising:
 1. a first set of parallel conducting rods in spaced relation,
 2. a second set of parallel conducting rods in spaced relation and interleaved alternately with the first set,

3. a first strap-bar in the form of an extended conducting plate making contact with each of the first set of parallel conducting rods,

4. a second strap-bar generally parallel to the first strap-bar and in the form of an extended conducting plate making contact with each of the second set of parallel conducting rods,

c. and microwave energization means operatively attached to said first and second strap-bars of said microwave structure adapted to energize said microwave structure so that a region adjacent said structure will contain a predominance of degenerate $\pi/2$ mode or near degenerate $\pi/2$ mode electric field energy.

9. An apparatus, as defined in claim 1, wherein said source of microwave energy is designed so that said apparatus is capable of providing radiation in the wave length ranging from the vacuum ultraviolet to the far infrared.

10. An apparatus for generating a plasma as defined in Claim 1, wherein said apparatus includes a transparent microwave radiation shield surrounding said slow wave structure and said plasma container and being adapted to provide an unobstructed observation of a plasma generated from said ionizable gaseous fluid, said radiation shield comprising:

- a. an inner wall made of a transparent dielectric material,
- b. an outer wall made of a transparent dielectric material,
- c. and a transparent liquid which absorbs microwave energy filling the space between said inner and outer walls.

11. An apparatus for generating a plasma using electromagnetic energy in the microwave frequency range comprising a source of microwave energy, at least one slow wave structure having an input end for receiving microwave energy from the source thereof and forming a region adjacent to said slow wave structure which contains a predominance of degenerate $\pi/2$ or near-degenerate $\pi/2$ mode primarily backward wave electromagnetic energy to enable band edge operation at the $\pi/2$ mode, the backward waves of said electromagnetic field energy housing a phase velocity approaching zero and propagating their energy in one direction and their phase fronts in the opposite direction, the operation bandpass of said slow wave structure being defined by a frequency spectrum F_1-F_0 near the $\pi/2$ mode bandedge, said electromagnetic energy having a normal attenuation constant β_n , and said slow wave structure having a longitudinal attenuation constant β_L , and the electromagnetic wave inside of the plasma container having a linear attenuation constant β_p which are relatively constant, such that the electric field vector of the backward wave electromagnetic energy is relatively constant, means for conveying said microwave energy from said source of said microwave energy to the input end of said slow wave structure, a plasma container located with respect to said region and adapted to contain a ionizable gaseous fluid for receiving and applying said microwave energy to said ionizable gaseous fluid to generate a plasma therefrom.

12. An apparatus, as defined in claim 11, wherein said source of microwave energy has a frequency in the range of from about 100 MHz to about 30,000 MHz.

13. An apparatus, as defined in claim 11, wherein said source of microwave energy has a frequency in the range of from about 915 MHz to about 5,800 MHz.

14. An apparatus, as defined in claim 11, wherein said slow wave structure is a non-resonant, semi-radiant strapped bar type.

15. An apparatus for generating a plasma using electromagnetic energy in the microwave frequency range, said apparatus comprising a plasma container capable of having an ionizable gaseous fluid introducible thereinto, said container being formed with a wall capable of permitting microwave energy to be coupled into the gaseous fluid, at least one slow wave structure having an input end for applying microwave energy to said ionizable gaseous fluid to generate a plasma therefrom, means for conveying said microwave energy from said microwave energy generating means to the input end of said slow wave structure, the longitudinal axis of said plasma container being angularly located with respect to the longitudinal axis of said slow wave structure at an angle θ so that electromagnetic waves propagating along the length of said slow wave structure will provide a relatively constant energy transfer profile along the length of the plasma container.

16. An apparatus, as defined in claim 15, wherein said angle θ is between about 1° to about 30° .

17. An apparatus, as defined in claim 15, wherein the angle θ is established to obtain a constant energy density transfer through the plasma container based on the normal attenuation constant of the electric field strength which produces the electromagnetic energy, the longitudinal attenuation constant of the slow wave structure, and the linear attenuation constant of the electromagnetic waves in the plasma container.

18. An apparatus, as defined in claim 15, wherein the angle θ is established to obtain a constant energy density transfer through the plasma container based on the ratio of the normal attenuation constant of the electric field strength, which produces the electromagnetic energy, divided by the longitudinal attenuation constant of the slow wave structure, plus the linear attenuation constant of the electromagnetic waves in the plasma container.

19. An apparatus, as defined in claim 15, wherein said slow wave structure is a non-resonant, semi-radiant strapped bar type of structure.

20. An apparatus, as defined in claim 15, wherein said slow wave structure is a wide-band, semi-radiant strapped bar type of structure, and said apparatus is adapted to be operated so that the region adjacent to said slow wave structure contains a predominance of degenerate $\pi/2$, or near-degenerate $\pi/2$ mode electromagnetic energy.

21. An apparatus for generating a plasma using electromagnetic energy in the microwave frequency range, said apparatus comprising a plasma container capable of having an ionizable gaseous fluid introducible thereinto, said container being formed of a wall relatively transparent to microwave energy and capable of permitting microwave energy to be coupled into the gaseous fluid, microwave energy generating means for generating a source of microwave energy, a transmission line adapted to transmit microwave energy and being operatively connected to said microwave energy generating means for receiving and transmitting the microwave energy thus generated, tuning means operatively connected to said transmission line to obtain minimum

energy-return reflection to said generating means, a slow wave structure having an input end for applying microwave energy to an ionizable gaseous fluid in said plasma container to generate a plasma therefrom, transition means operatively connected to said tuning means and said input end of said slow wave structure for delivering the microwave energy to said slow wave structure, said plasma container being located proximate to said slow wave structure to receive the microwave energy carried by said slow wave structure, means for providing a source of ionizable gaseous fluid to the plasma container, and means operatively interposed between said last-named means and said plasma container.

22. An apparatus, as defined in claim 21, said apparatus comprising a dummy load operatively connected to an output end of said slow wave structure.

23. An apparatus, as defined in claim 21, said apparatus comprising monitoring means for measuring forward, reflected and transmitted microwave power.

24. A slow-mode microwave applicator suitable for heating, drying, curing, ionization of gases, or other treatment by microwave energy of workpieces containing lossy dielectric material, and which dielectric material may be in solid, liquid or gaseous form, said microwave applicator comprising:

a. a slow wave microwave structure, and said slow wave microwave structure comprising:

1. a transmission line member having at least one open end,

2. a pair of spaced-apart microwave energy conductors located within said transmission line member and having terminal end portions spaced inwardly from said one open end of said transmission line member,

3. a pair of transmission members extending into said one open end of said transmission line member and each one of said pair of transmission members being connected at one of their ends thereof to a respective one of said pair of spaced-apart conductors,

4. each of said conductors being tapered inwardly from one of their ends to the other of their ends which are spaced inwardly from said one open end of said transmission line member and which ends are connected to said transmission members,

5. strapped bar conductive means operatively connected to each of said transmission members at the other ends thereof,

b. and microwave energy generating means operatively connected to said slow wave microwave structure for applying microwave energy to said slow wave structure, said energy generating means applying energy of such frequency and said conductors being constructed to generate a region adjacent said structure which will contain a predominance of degenerate $\pi/2$ or near degenerate $\pi/2$ mode electric field energy.

25. A slow-mode microwave applicator, as defined in claim 24, wherein said strapped bar conductive means comprises:

a. a first set of parallel conducting rods in spaced relation,

b. a second set of parallel conducting rods in spaced relation and interleaved alternately with the first set,

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- c. a first strap-bar in the form of an extended conducting plate making contact with each of the first set of parallel conducting rods and one of said transmission members, and
- d. a second strap-bar generally parallel to the first 5

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strap bar and in the form of an extended conducting plate making contact with each of the second set of parallel conducting rods and the other of said transmission members.

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