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CROSS REFERENCE SEARCH ROOM

March 1, 1966 I. KAUFMAN ET AL 3,238,531

ELECTRONICALLY STEERABLE NARROW BEAM ANTENNA SYSTEM UTILIZING DIPOLAR RESONANT PLASMA COLUMNS

Filed March 12, 1963 5 Sheets-Sheet 1

Fig. 1

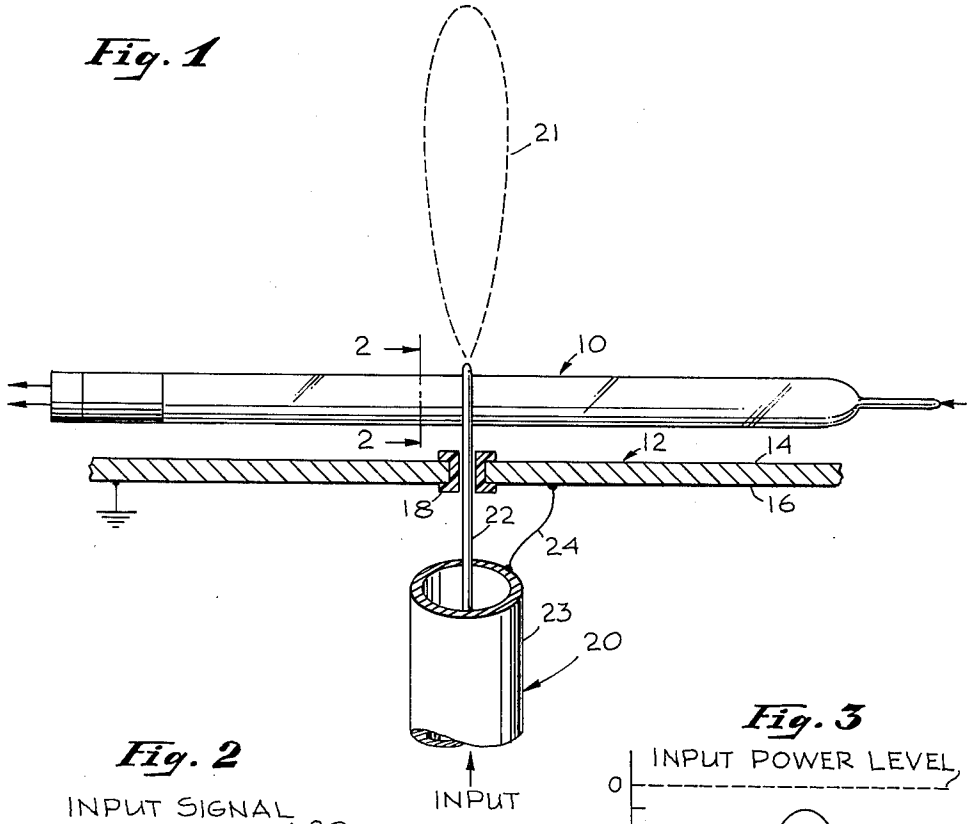


Fig. 2

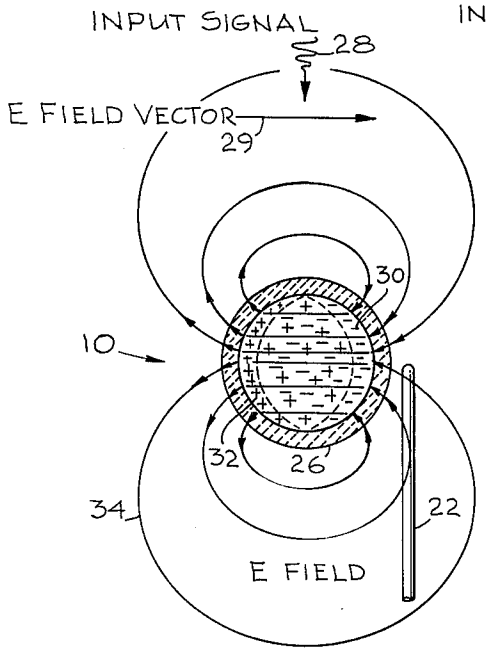
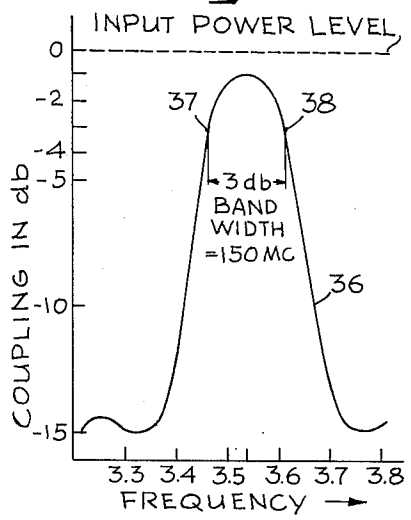


Fig. 3



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Fig. 4

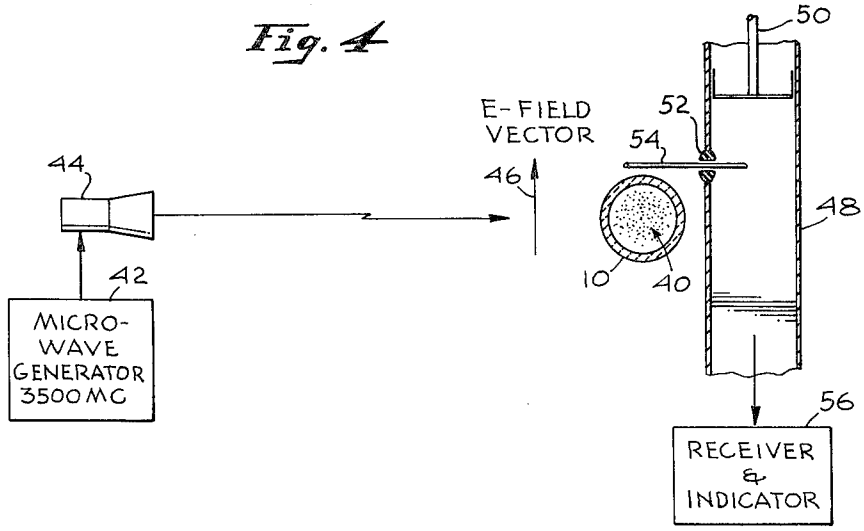


Fig. 5

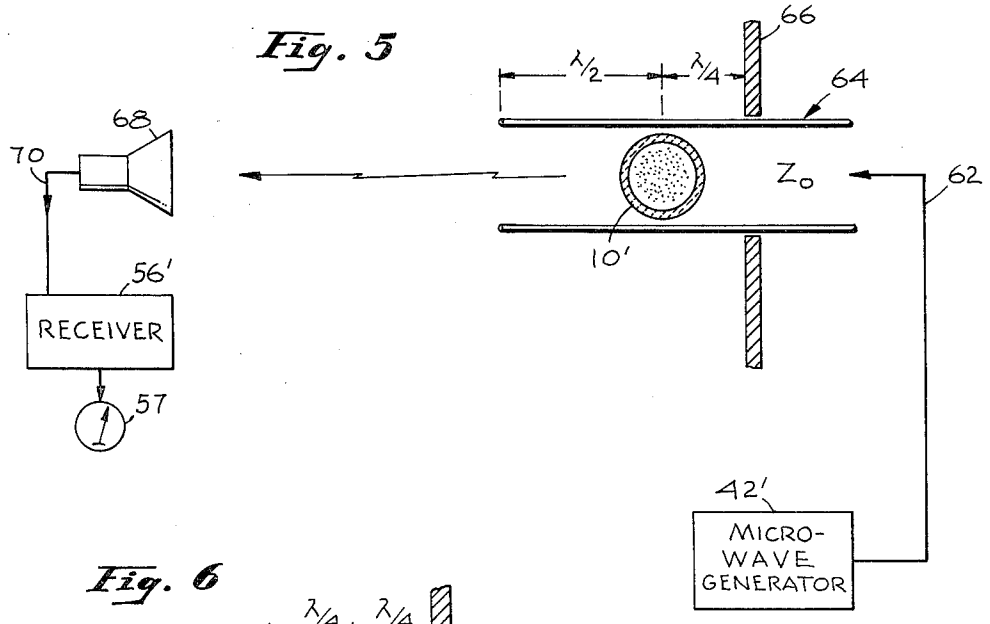
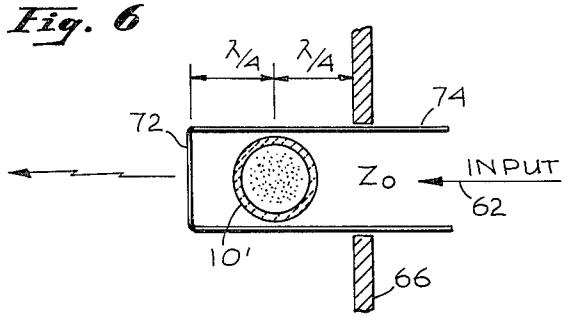


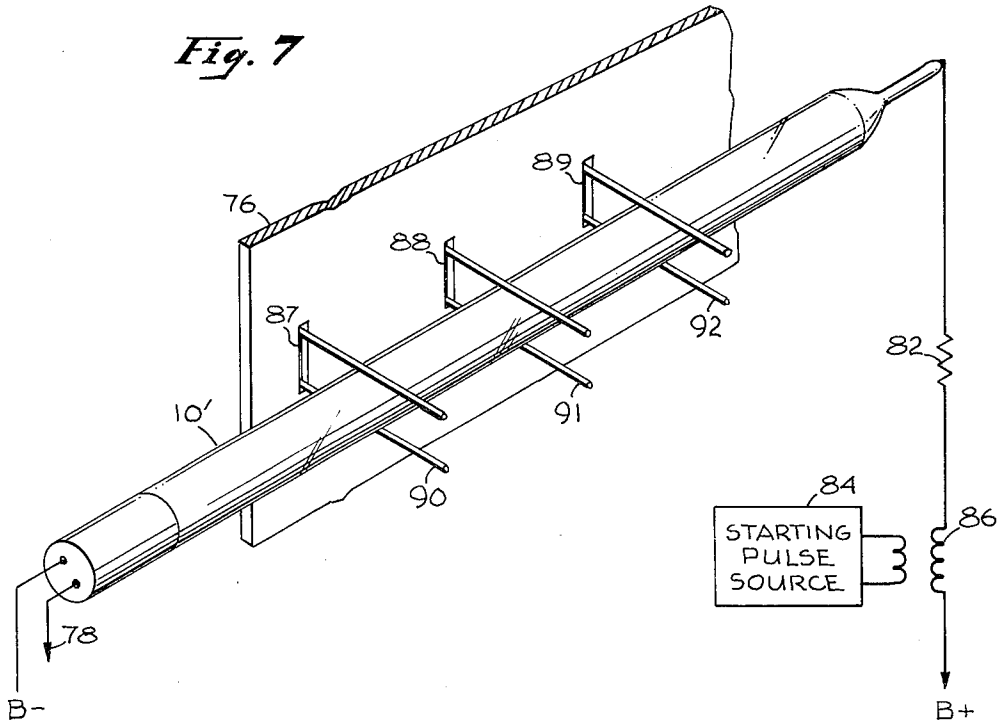
Fig. 6



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Fig. 7



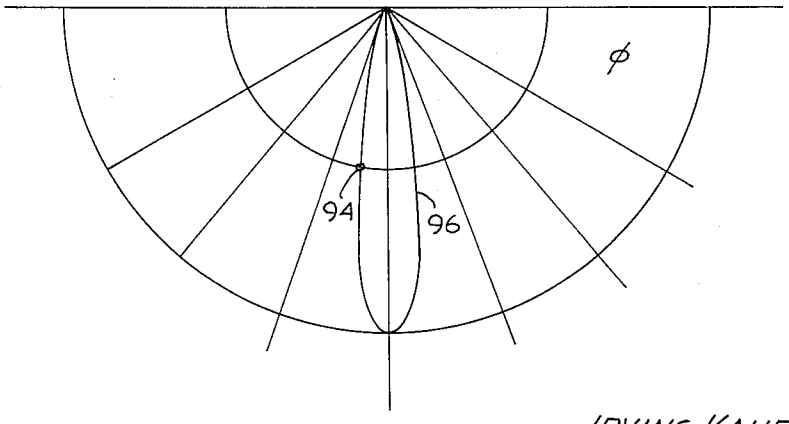


Fig. 8

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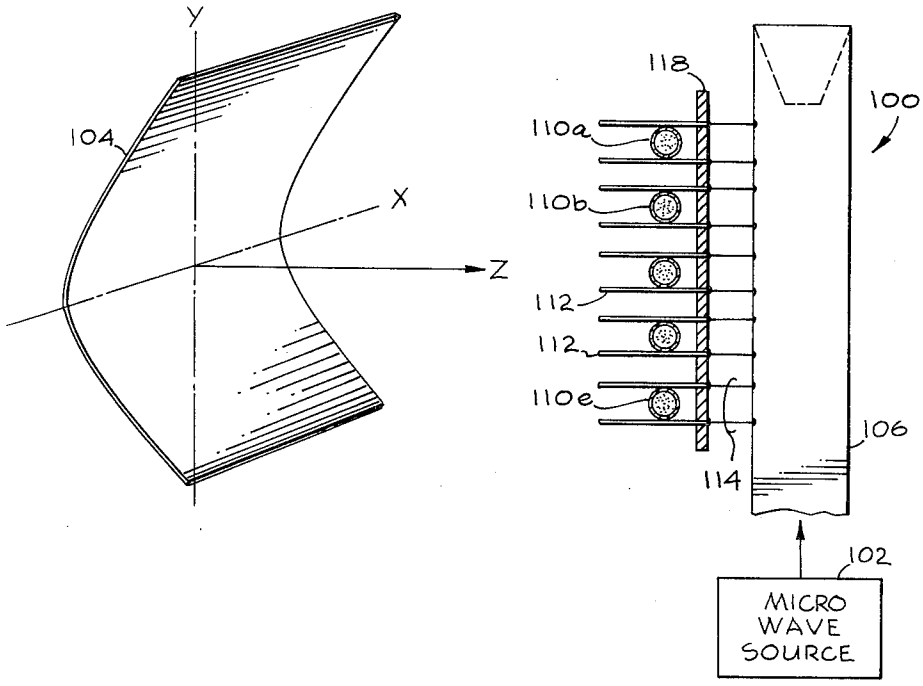
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ELECTRONICALLY STEERABLE NARROW BEAM ANTENNA SYSTEM UTILIZING DIPOLAR RESONANT PLASMA COLUMNS

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Fig. 9



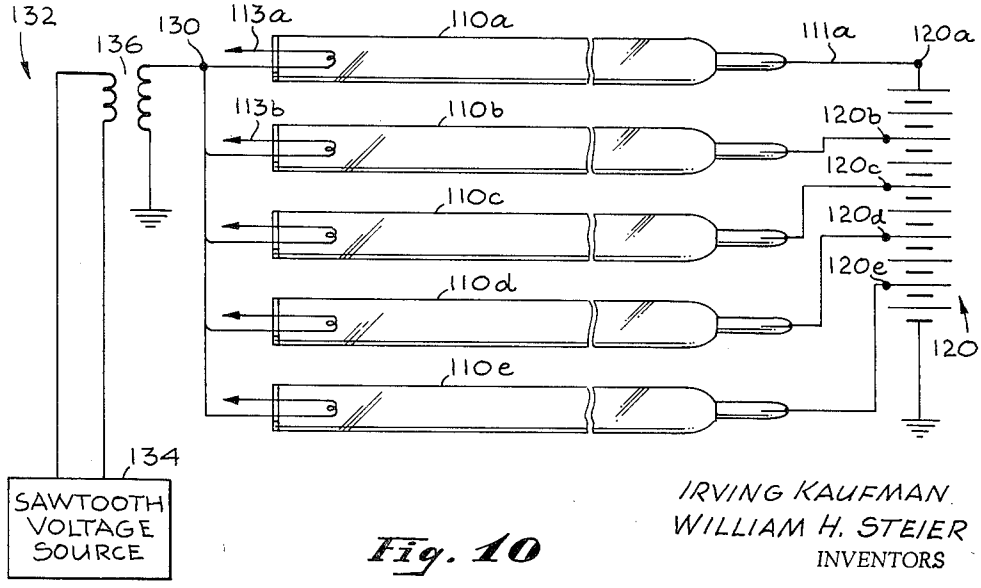
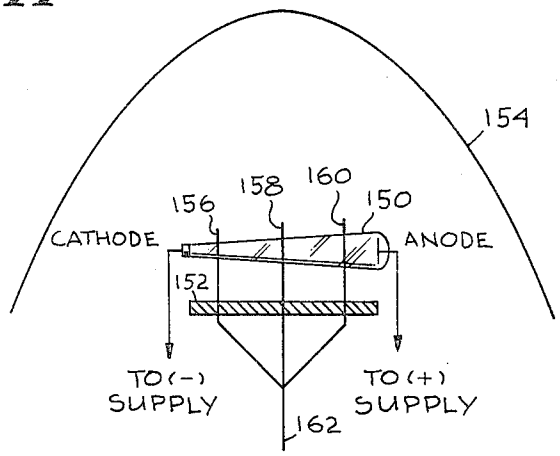


Fig. 10

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Fig. 11



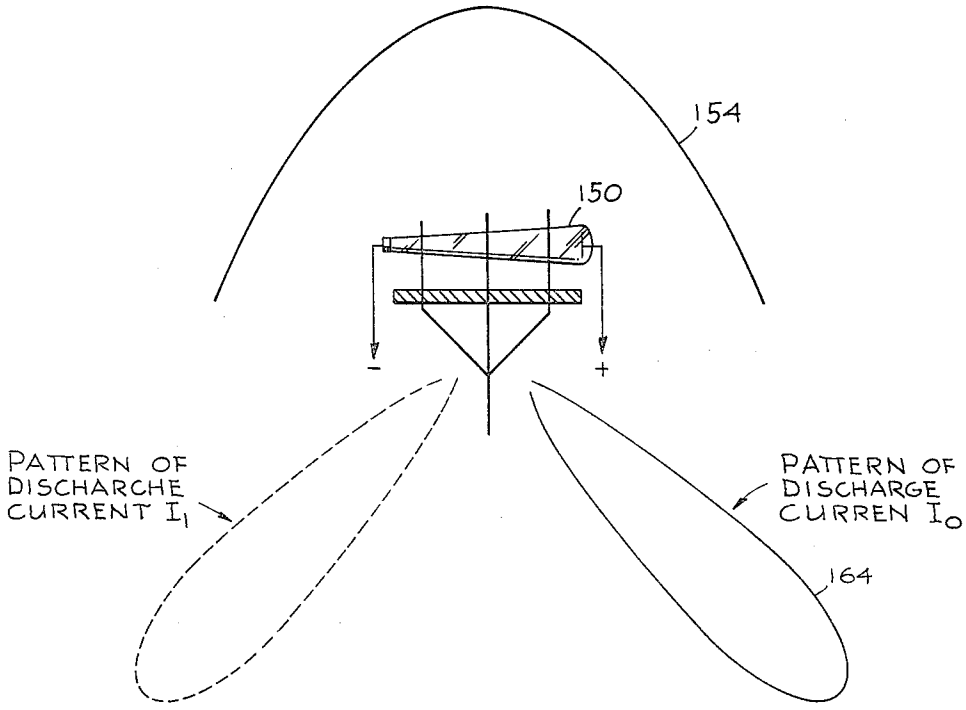


Fig. 12

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United States Patent Office 3,238,531 Patented Mar. 1, 1966

3,238,531

ELECTRONICALLY STEERABLE NARROW BEAM ANTENNA SYSTEM UTILIZING DIPOLAR RESONANT PLASMA COLUMNS

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Filed Mar. 12, 1963, Ser. No. 264,515
5 Claims. (Cl. 343—701)

This invention relates generally to electromagnetic wave systems in which an elongated column of ionized gas plasma is involved in the operation of the system, and more particularly to electromagnetic wave antenna systems which include dipolar resonant plasma columns.

As used in connection with the present invention, "plasma" may be defined as a region containing large quantities of free electrons and positive ions with the region being statically neutral or electrically neutral when considered as a whole, and being tolerant of high frequency fluctuations of the electron density in any elemental portion of the region.

In our copending United States patent application, Serial Number 181,531, filed on March 22, 1962, now Patent No. 3,212,034, there are disclosed and claimed certain arrangements for utilizing a resonant plasma column as a frequency selective apparatus functionally analogous to a microwave band-pass filter.

In the present invention, elongated plasma columns, essentially similar to those disclosed in the above mentioned copending application are used in a substantially different manner and in a different environment to provide electronically tunable and electronically steerable transmitting and receiving antennas for coherent electromagnetic wave energy.

The apparatus of our present invention has immediate utility in its application to any one of a variety of frequency selective beam-forming antenna systems for transimssion or reception or both. In addition, our invention finds one particularly advantageous application in the art of electronically scanned antennas. There is a need in the communications as well as the radar field for high gain, narrow beam antennas which provide for rapid angular scanning of the direction of the narrow beam. To meet this demand, workers in the antenna art have developed larger and larger antennas and have gone to higher frequencies where atmospheric attenuation and the difficulty of high power generation presents serious limitations. The desire for high gain arises from the need to communicate over increasingly greater distances. The narrow beam requirement stems from the demand for increasing precision of direction finding in radar systems. A prime difficulty in achieving the foregoing disiderata is the necessity, in any scanning system, of selectively repositioning the antenna beam direction. In systems where antenna structures are physically rotated or otherwise repositioned, the mechanical inertia of the structure and the magnitude of the angular accelerations required have presented practical limitations; that is, the desired angular repositioning rates frequently demand unrealizable driving torques and excessive mechanical stresses on the antenna structures and their supporting apparatus. The foregoing practical limitations are a strong incentive for developing systems which embody a stationary antenna structure and electrical arrangements for angularly readjusting the direction of the antenna beam relative to the antenna structure. In the prior art, various electronically scanning antennas have been developed which depend on signal phase shifting to control the direction of the antenna beam. In such systems the high mechanical inertia of a massive antenna structure is, of

course, avoided; however, it is replaced by the mechanical inertia or the electrical inductance of the electronic phase shifting mechanisms. Nevertheless, electronically scanning is extremely attractive in that the inductive "inertia" of an all-electronic system can be overcome by increased voltages rather than mechanical torques and because a greater latitude of beam positioning programs is possible.

In addition, electronically scanning antennas which depend on signal phase shifting networks suffer from the fact that they become quite complex in that they generally require at least one phase shift element for each radiating element of the antenna. The phase shifting elements must be driven either mechanically or electrically to establish the required phase front for a narrow antenna beam. Usually the phase shifting elements are controlled by a computer network which also serves as a means for indicating the instantaneous position of the antenna beam. In general, mechanical phase shifters are limited to a speed of beam repositioning equal to about five milliseconds per beam width. Likewise, all electronic phase shifting networks provide a maximum scan rate of about 0.1 millisecond per beam width. In addition, electronic scanning antenna systems frequently have undesirably high side lobes, lower gain and lower beam positioning accuracy than is frequently desired.

Accordingly, it is a primary object of the present invention to provide an improved narrow beam electronically steerable antenna system.

It is a different object of the invention to provide an improved system for using a dipolar resonant plasma column as a transmitting or receiving antenna for coherent electromagnetic wave energy.

It is another object of the invention to provide an improved antenna system employing narrow-band resonance characteristics of elongated plasma columns.

It is a further object to provide an improved antenna apparatus for selectively and individually radiating or receiving a plurality of electromagnetic wave signals which jointly occupy a common frequency band.

It is a still further object of the invention to provide an improved electrically tunable antenna which is tunable over a band of frequencies in the microwave region and which enables low-loss translation of signals within a selected relatively narrow band together with substantially complete exclusion of signals having frequencies outside that selected band.

It is still another object of the present invention to provide an antenna system embodying a resonant column of ionized gas plasma which has negligible losses at the microwave frequency which is to be relayed or received.

Preferably described, we overcome the aforementioned difficulties and limitations of the prior art and achieve the foregoing objects utilizing the known phenomenon of dipolar resonance in an elongated plasma column and employing that resonance in a novel antenna apparatus for transmitting or receiving coherent electromagnetic radiation. In accordance with one exemplary embodiment of our invention, a plasma column enclosed in an insulative envelope is positioned to extend transversely through a region subjected to microwave radiation which has its electric field polarized substantially perpendicular to the longitudinal axis of the plasma column. When so arranged, and with the plasma column energized by a longitudinal discharge current passing therethrough, transverse electric fields of the microwave radiation produce oscillatory transverse displacement of the electron cloud of the plasma relative to the comparatively stationary positive ion cloud. Substantially all the electrons in an elemental cross sectional portion of the plasma column move transversely to the axis of the column in a coherent or common time phase manner. At the

instant of time when the electron cloud has maximum transverse displacement relative to the ion cloud, energy is stored in the form of electrostatic field potential both internally and externally of the column. At another instant of time when the electron cloud is minimally displaced, the electrons have a maximum transverse velocity representing a maximum kinetic energy. The natural frequency of the transverse electronic oscillation is dependent upon a number of physical factors including, primarily, the free electron density or degree of ionization of the plasma. Accordingly, the natural resonant frequency of the plasma may be tuned over a wide frequency range by controlling the magnitude of the longitudinal discharge current passing through the plasma. Thus the resonant frequency of the column may be adjusted to the frequency of a communication signal which is desired to be received or to the frequency of the magnetron or other microwave oscillator, in the case of a system wherein the plasma column is used as a transmitting antenna. Where the column acts as a receiving antenna, a received signal utilization circuit or system is coupled to the oscillating "near" electric field of the plasma in a way such that the signal utilization coupling is substantially non-responsive or immune to the primary radiation to which the region is subjected. By that arrangement our invention enables reception of selected signals which are within the narrow band-pass characteristic of the resonant plasma column and provide for substantially complete rejection of extraneous signals such as wide band noise, and jamming.

The various forms of apparatus which our invention may take are all dependent for their operation on the principle of plasma resonance or dipolar resonance of a column of ionized gas plasma. It can be shown that a column of plasma located away from dielectrics or conductors acts as an electrical resonator having a resonant frequency $\omega_r=\omega_p/\sqrt{2}$. The basic concept and theory of dipolar resonance in a plasma is not, per se, a new discovery but has been considered by a number of workers in the art. For example, in an article entitled "Plasma Resonance in Ionospheric Irregularities", Arkiv f. Fysik, 1951, volume 3, page 247, by N. Herlofson, it was shown that a plasma column suspended in free space and illuminated by electromagnetic energy would produce energy reflection and absorption at certain frequencies dependent on the plasma density. That phenomenon was of interest in the investigation of radar reflections from meteor trails. It was shown that a long column of ionized gas could produce a much larger reflection when excited by a wave whose electric vector was transverse to the column rather than by one whose electric vector was parallel. Thus, while the phenomenon of plasma resonance has been investigated in the prior art, applicants are unaware of any prior art teaching our suggestion of practical application of the phenomenon to antenna apparatus or the like.

In another field of prior art there has been a fairly complete investigation of the use of gas discharge phenomena in microwave systems. In this branch of the prior art the gas discharge has generally been utilized for functions and purposes not requiring plasma resonance. A fairly complete survey of this particular branch of the prior art appears in an article entitled "Microwave Applications of Gas Discharges" by F. R. Arams, Electronics, November 1954, pp. 168–172. In that article it is noted that ionized gas plasmae have been suggested as microwave noise sources, t–r and atr switch devices, attenuators, phase shifters, electronic switches, tunable resonant cavities and non-reciprocal gyrators. Moreover, the "Electronics" article seems to recognize that a plasma characteristically has a critical value of the electron density N at which the electrons will oscillate in phase with an exciting electromagnetic field, and suggests the possibility of using such oscillation as a mechanism for "bunching" or velocity modulating an electron beam.

The prior art, known to the applicants and as exemplified by the above mentioned "Electronics" article, has completely failed to appreciate that a quantity of plasma can serve as a high frequency resonator of extended dimensions similar to a line of dipole elements or that such a resonator could be excited at a single local region to produce coherent oscillation over a much larger portion of the plasma. That general concept is utilized in each of the hereinafter described embodiments of apparatus in accordance with our present invention. None of the various devices disclosed by the prior art employ transverse or dipolar resonant oscillation of a plasma column to provide an extended line source of radiation in response to excitation of the plasma by a localized field.

These and other objects of this invention will be apparent from the following description taken with the accompanying drawing, throughout which like reference characters indicate like parts, which drawing forms a part of this application and in which:

FIG. 1 is a simplified diagrammatic illustration of one embodiment of an antenna system in accordance with our invention;

FIG. 2 is a cross-section along lines 2—2 of FIG. 1;

FIG. 3 is a graph of the frequency response of the apparatus illustrated in FIGS. 1 and 2;

FIG. 4 is a diagrammatic illustration of an arrangement in accordance with our invention utilized as a receiving antenna;

FIG. 5 is a diagrammatic illustration of another embodiment of our invention operating in the transmitting antenna mode;

FIG. 6 is a diagrammatic illustration of a variant form of a portion of the system of FIG. 5;

FIG. 7 is a perspective view of an arrangement similar to that of FIG. 5 but including multiple primary feed lines;

FIG. 8 is a polar graph of the power density characteristic of the apparatus of FIG. 7;

FIG. 9 is a diagrammatic illustration of an electronically scanned antenna system in accordance with our invention;

FIG. 10 is a schematic diagram of the direct current or low frequency circuits for energizing the plasma columns of the apparatus illustrated in FIG. 9.

FIG. 11 is a diagrammatic illustration of a further embodiment of an electronically scanned antenna system; and

FIG. 12 is a schematic diagram illustrating the beam patterns produced by the apparatus of FIG. 11.

In FIG. 1 there is shown in diagrammatic form one example of a microwave antenna system in accordance with the present invention. This system will be discussed in terms of its use as a transmitting system. However, it should be understood that the system is reciprocal; that is, it can be used with equal effectiveness either as a transmitting or receiving antenna or in the case of a radar apparatus as both. Specifically, microwave signals are applied to the apparatus of FIG. 1 by way of coaxial waveguide **20** which includes a center conductor **22** and an outer conductor **23** which is connected to a conductive reflector plate **12**, as indicated by the numeral **24**. The conductive reflector **12**, which may be a solid or perforated metal plate or a conductive screen, has a central aperture which supports an insulative bushing **18** through which the center conductor **22** of the coaxial waveguide projects. An elongated gas discharge device **10** which constitutes a means for providing a resonant plasma column adjacent the plate **12** is positioned with its longitudinal axis about one-quarter wavelength at the frequency to be transmitted from the front surface **14** of the conductive reflector. Preferably the outer end of the center conductor **22** extends closely adjacent one side of the discharge tube **10** to a position

at least slightly past the longitudinal axis of the discharge tube so that microwave electric fields generated along the center conductor 22 will be efficiently coupled to the plasma column contained within the discharge tube. In accordance with the operation of the present invention, as described in further detail hereinafter, the plasma column responds to the energy fed thereto by way of the center conductor 22 and oscillates at its natural dipolar resonant frequency to reradiate the microwave energy and provide a beam or antenna pattern 21.

In a preferred embodiment of the present invention we have used a mercury vapor discharge tube about 45 centimeters long and having an inside diameter of about 0.7 centimeter. One such discharge tube for providing an elongated plasma column has a cylindrical quartz envelope, a thyratron-type cathode, and a starting electrode located near the cathode (not shown). It should be understood, however, that various other types of discharge tubes may be utilized within the scope of the present invention to provide the results hereinafter noted. For example, we have on occasion used cylindrical Pyrex discharge tubes having an outside diameter of about 11 mm., an inside diameter of about 9 mm., and enclosing a mercury vapor at about 0.1 mm. pressure. With such a tube, dipolar resonance of the plasma column can be obtained at a frequency of about 3350 mc. with a longitudinal plasma discharge current of about 1 ampere. We have found that for best operation the plasma column provided by the discharge tube 10 should be long in relation to its diameter, a preferable length being a factor of about 20. However, if a long discharge tube is used, large voltages are necessary to initiate and maintain the plasma discharge. We contemplate that a discharge tube of perhaps four or five inches in length can be satisfactorily utilized, providing that it has an inside diameter at least an order of magnitude smaller than its length. Obviously, for some other applications it may be desirable to provide much longer plasma columns to provide a function similar to an extended array of dipoles. While the present invention is not restricted to any particular form of discharge device or the above noted relative dimensions, it will be apparent that the use of the shortest practical discharge device which fits the requirements of the particular application will have the immediate advantage of a lower voltage drop during operation.

Full appreciation of the presnet invention in all its aspects requires a brief consideration of the principles of plasma resonance. Electronic oscillation in a volume of ionized gas plasma was recognized and reported as early as 1931 by L. Tonks in an article entitled "Plasma-Electron Resonance, Plasma Resonance and Plasma Shape," in Phys. Rev. 1931, vol. 38, pp. 1219–1223, and has since been further investigated by others. It has been demonstrated heretofore that a cylindrical plasma column suspended in free space or arranged generally as illustrated in FIG. 1, when illuminated by a beam of electromagnetic wave energy having its electric field vector substantially normal to the column, will produce wave energy reflection and absorption at certain frequencies dependent upon the plasma density. The resonant plasma response to the incoming E-field is essentially a coherent oscillation of the plasma electrons in a direction parallel to the E-field and transverse to the plasma column. Physical visualization of the plasma electronic oscillation is illustrated in FIG. 2 as transverse oscillatory displacement of an electron cloud 30 oscillating in the horizontal direction relative to the comparatively stationary ioin cloud 32. FIG. 2, of course, represents an elementary cross-section of the plasma column which is contained within the discharge tube 22 of FIG. 1.

The electric fields produced externally of the plasma column are the same as those of a line of electric dipoles.

Thus, the plasma behavior appropriately can be regarded as "dipolar resonance."

In oscillations at resonance, the stored energy in the system of the plasma column oscillates between the forms of electrostatic energy of surface charges and of kinetic energy of the transversely moving plasma electrons.

It has been determined that a very long plasma column in free space will exhibit dipolar resonance at a resonant frequency given by

$$\omega_r=\frac{\omega_p}{\sqrt{2}} \tag{1}$$

where

ω_r is the resonant angular frequency; and

ω_p is the plasma angular frequency$=(5.6\times10^4\times\sqrt{N})$.

Other modes of resonances, such as the quadruple mode, are also possible. These modes of resonance of higher angular order are generally not excited by an impinging electromagnetic wave. They will not be considered any further herein.

Returning to the dipole mode, we have found that dipolar resonance is also possible if the plasma column is surrounded by a dielectric tube. The relation corresponding to (1) is now

$$\omega_r=\frac{\omega_p}{\sqrt{1+K_{eff}}} \tag{2}$$

where K_{eff} is an effective relative dielectric constant that depends on the dielectric constant of the tube and its inner and outer dimensions.

Equations 1 and 2 relate to the very long plasma column. It is found that the use of a column of finite length L "splits" the dipolar resonance into an infinite set of dipole resonances, each of slightly different frequency. For a column of radius *a* and length L (in free space), this set of resonant frequencies is given by

$$\omega_r=\frac{\omega_p}{\sqrt{1+K_{e_m}}} \tag{3}$$

where

$$K_{e_m}=\left[\frac{\left(\frac{m\pi a}{L}\right)K_0\left(\frac{m\pi a}{L}\right)+K_1\left(\frac{m\pi a}{L}\right)}{\left(\frac{m\pi a}{L}\right)I_0\left(\frac{m\pi a}{L}\right)-I_1\left(\frac{m\pi a}{L}\right)}\right]\left[\frac{I_1\left(\frac{m\pi a}{L}\right)}{K_1\left(\frac{m\pi a}{L}\right)}\right]$$

$m=1, 2, \ldots$; and

I_0, I_1, K_0, K_1 are modified Bessel functions of the first and second kind, respectively.

Although, by Equation 3, the resonant frequencies differ for the various values of *m*, it is found that for a ratio of L/a equal to or greater than 20 (as used in various systems which we have constructed), the lower order modes coalesce to the resonance given by Equation 1.

The column is excited into resonance by an impinging electromagnetic wave of the proper frequency and polarization, or by a coupling mechanism to the "near" field. An example of the latter is the "near" field probe 22, shown located near the plasma column.

When the apparatus of FIG. 1 operates as a receiving antenna, the incoming electromagnetic waves, as designated by the numeral 28 in FIG. 2, cut across the discharge tube 10 and thereby induce transverse oscillatory movement of the electron cloud 30 relative to the ion cloud 32. As described heretofore, the transverse oscillatory movement of the electron cloud produces an external "near" electric field as indicated by the field lines 34. This oscillatory electric field cuts across the near field probe 22 and induces therein a microwave signal corresponding in frequency and amplitude to the dipolar resonant oscillation of the plasma column. The signal thus developed in the probe 22 is coupled directly to the coaxial waveguide 20 and may be applied therefrom to an

appropriate receiver or other signal utilization load means (not shown).

If the frequency of the incoming microwave radiation **28**, as shown in FIG. 2, is not related to the plasma density in the discharge tube in a manner to satisfy Equation 1, dipolar resonance of the plasma is not excited, no signal will be generated in the probe **22**, and no power will be coupled to the coaxial line **20**. If the plasma density is related to at least one frequency component of the incoming microwave radiation **28** in the manner specified by Equation 1, that particular frequency component of the input radiation will strongly excite the plasma column and the column will therefore couple power to the waveguide **20**. Thus the system of FIG. 1 provides a narrow bandpass, for discriminating against noise and the like, and for receiving a specific signal to which the plasma column is tuned by adjustment of the longitudinal discharge current. By variably cotrolling the longitudinal discharge current applied to the discharge tube from a direct current source (not shown), the plasma density N may be controlled to any desired value within a fairly wide range. Thus the selected frequency at which the antenna system of FIG. 1 will respond to impinging radiation can be varied over a wide frequency range. Moreover, if desired, an electronic amplifier or the like may be connected in series relationship with the direct current source which supplies longitudinal discharge current so that the amplifier will serve to modulate the discharge current amplitude to provide scanning of a wide frequency band by the antenna system.

FIG. 3 illustrates the band pass characteristic of the antenna system of FIG. 1. In FIG. 3 frequency is plotted as the abscissa and the ordinate axis represent the power output in decibels relative to an arbitrary input power level. On curve **36** of FIG. 3, points **37** and **38** indicate the half-power points or the frequency at which the output power is down 3 decibels from the input power level. With a center frequency of about 3,540 mc. as indicated in FIG. 3, the antenna of FIG. 1 provides a bandwidth of about 150 mc. between the half-power point; that is, if the microwave radiation impinging on the antenna system of FIG. 1 includes frequency components between about 3,460 mc. and 3,620 mc., those components will be received and translated by way of coaxial waveguide **20** to the receiver circuitry while noise signals, jamming signals, or other undesired signals below 3,460 mc. or above 3,620 mc. will be comparatively attenuated by the antenna system. The relatively narrow bandpass characteristic of the antenna apparatus of the present invention is particularly advantageous in pulsed radar systems where it is frequently desirable to provide maximum rejection of noise and jamming signals.

In FIG. 4 there is illustrated another embodiment in accordance with the present invention wherein the selected signal received by the plasma column antenna is coupled to a receiver or signal utilization load means **56** by way of an arrangement including a rectangular waveguide **48**. In this embodiment the waveguide **48** serves substantially the same general function as the coaxial line **20** of the apparatus illustrated in FIG. 1. Specifically, in FIG. 4 the antenna structure comprising the discharge tube **10** enclosing the ionized gas plasma column **40** serves as the receiving antenna of a communication system. The communication system additionally includes a transmitter which is illustrated as comprising a microwave generator **42** from which power is coupled to a transmitting horn **44** and is thereby radiated generally toward the plasma column **40** with the transmitted radiation being oriented so that the electric field vector **46** is substantially perpendicular to the direction of propagation and perpendicular to the longitudinal axis of the plasma column. The radiation impinging on the plasma column causes transverse dipolar oscillation in the plasma in the same manner as described heretofore in connection with the apparatus of FIG. 1. The near electric fields generated by the oscillating plasma cut across a pickup probe **54** which is supported by an insulative bushing **52** in one side wall of the waveguide **48** and is positioned transversely adjacent the envelope of the discharge tube **10**. Voltages generated in the probe **54** by the near electric fields of the plasma column are coupled along the probe **54** to the interior of the waveguide and generate waves therein for propagation downwardly along the waveguide and by way of any conventional coupling arrangement to a receiver **56**. The receiver **56**, of course, may comprise a traveling wave tube amplifier and a conventional crystal detector or any of various other well known arrangements for utilizing small amplitude microwave signals. To provide maximum coupling from the plasma column to the waveguide, the waveguide **48** is provided at its upper end with a conventional tuning plunger or piston **50** for adjusting or tuning the waveguide for maximum response to the resonant frequency of the plasma column.

The embodiment of FIG. 4 is normally operated with the input wave energy being propagated from the transmitting horn **44** to the plasma column **40**. However, since the plasma column is a reciprocally operative element it will be understood that the apparatus can operate reversely, with the microwave power to be transmitted being applied from an appropriate generator through the waveguide **48** and being coupled to and radiated by the plasma column **40**.

In FIG. 5 there is illustrated a further embodiment in accordance with the invention which is similar to the arrangement just mentioned in that the plasma column is utilized as part of the transmitting antenna. Specifically, a microwave generator **42'** feeds microwave energy to the input end of a parallel wire transmission line **64**. Coupling from the generator **42'** to the input end of the transmission line **64** may be had by any of various conventional means such as, for example, a conventional Balun coupler. Accordingly, such coupling is designated diagrammatically by the numeral **62**. From its input end the parallel wire transmission line **64** extends through an aperture in a metallic reflector plate **66** and straddles the elongated discharge device **10'**. In a preferred embodiment, the axis of the discharge device **10'** is spaced one-quarter wavelength from the front surface of the reflector **66** and the parallel wire transmission line **64** extends beyond the axis of the discharge device **10'** a distance of one-half wavelength at the resonant frequency so that a voltage maximum along the transmission line occurs approximately at the discharge device **10'**, thereby providing maximum coupling of microwave energy from the transmission line **64** ot the plasma column. The use of the parallel wire transmission line **64** has the advantages that direct radiation from the parallel wire line is considerably less than that which would be radiated from the single probe **54** of the arrangement illustrated in FIG. 4. Accordingly, when the parallel wire line is used, the plasma column itself is the principal radiator and a negligible amount of energy is radiated directly by the transmission line **64**. In addition, the parallel wire transmission line arrangement has the advantages that it provides a balanced system for driving the plasma column and prevents distortion of the antenna pattern of the oscillating plasma column. As shown in FIG. 5, microwave energy at the plasma resonant frequency is radiated by the plasma column in a narrow beam directed toward a receiving system comprising receiving horn **68**, a conventional receiver **56'**, and an indicating means **57** coupled to the output of the receiver. Thus the apparatus of FIG. 5, considered as a whole, constitutes a communication system in which the resonant plasma column forms the essential element of a highly directional transmitting antenna.

In FIG. 6 there is illustrated a variant form of a transmitting antenna which may be utilized in a system of the type illustrated in FIG. 5. Specifically, in the apparatus of FIG. 6 the parallel wire transmission line **74** which

projects through the reflector 66 and straddles the elongated discharge device 10' is terminated at its outer end by a shorting member 72. The short circuiting member 72 is preferably spaced about one-quarter wavelength from the longitudinal axis of the discharge tube 10' and the discharge tube is one-quarter wavelength from the front surface of the reflector 66. It will be appreciated that the antenna arrangement of FIG. 6 operates substantially the same as described heretofore with reference to FIG. 5. Specifically, microwave energy is applied to the right hand end of the two wire transmission line 74 and is coupled from the line 74 to the plasma column wherein it generates or induces transverse oscillation of the electron cloud of the plasma so that the plasma column radiates substantially like a long line of electric dipoles and provides a fan beam which is fairly wide in the plane of the paper but which is quite narrow in the horizontal plane which includes the axis of the discharge tube 10'. The antenna pattern which is provided by an apparatus in accordance with FIGS. 4, 5, 6 or 7 is illustrated in FIG. 8 wherein the solid line curve is a polar graph of the power density versus the horizontal angle ϕ with the electric field vertically polarized.

In apparatus which we have constructed in accordance with FIGS. 5 and 6, the lengths of the parallel wire transmission line extending past the plasma column were optimized in each case by receiving the radiated microwave power by means of a horn 68 and measuring the power during adjustment of the lengths of the parallel wire transmission lines 64 and 74. It has been found that for maximum radiation the optimum lengths of the lines 64 and 74 extending past the axis of the discharge tube 10' were slightly larger than $\lambda/2$ and $\lambda/4$, respectively. This need for a little excess length in the transmission lines indicates that the coupling line desirably should provide a small amount of shunt capacity at the position of the plasma column.

In FIG. 7 there is illustrated in perspective a further embodiment of apparatus in accordance with the present invention which is generally similar to the antenna arrangement described heretofore with reference to FIG. 5 but which differs in that the plasma column contained within the elongated discharge device 10' is excited by a plurality of longitudinally spaced two wire transmission lines 90, 91 and 92. Preferably the transmission lines 90, 91 and 92 project outwardly through apertures 87, 88 and 89 in a reflector plate 76 which may be substantially identical to reflector plate 66 of the apparatus of FIG. 5. The two wire transmission line 90 straddles the discharge tube 10' precisely as described heretofore. The discharge tube 10 is spaced from the reflector 76 a distance of about one-quarter wavelength. The three parallel transmission lines 90, 91 and 92 are preferably fed in phase by appropriately coupling to a coaxial line or waveguide source of microwave energy. Such coupling (not shown) is normally disposed behind the reflector 76 and may include high frequency time delay elements for assuring that the excitation applied to the plasma column by the different parallel wire lines is precisely in phase. As shown in FIG. 7, the elongated discharge device 10' is provided with a conventional cathode structure having cathode in-leads 78 which may be connected to the negative terminal of the direct current voltage source indicated as B—. The anode of the discharge device 10' is preferably connected through a ballast resistance 82 and a pulse transformer 86 to the positive terminal B+ of the direct current voltage source. The primary winding of the pulse transformer 86 is connected to a pulse source 84 which provides high frequency and high voltage energy for starting or igniting the discharge tube 10'.

In certain applications the apparatus illustrated in FIG. 7 has the advantage that excitation of the plasma at spaced points along the column provides coherent oscillation of the plasma column along a substantially greater portion of its length so that the plasma provides an output radiation pattern or antenna pattern which has a stronger, narrower center lobe and considerably smaller side lobes; that is, the plasma oscillates with its dipoles aligned parallel to the reflector 76 and with the oscillation extending over a length of the plasma column many times longer than the diameter of one of the conductors of the parallel wire line 90. If the entire length of the plasma column were to oscillate with equal amplitude and phase in response to excitation at one point, then an extremely narrow fan beam pattern would be produced. In some cases we have found that only a fraction of the column length is caused to radiate by excitation at a single point. In such cases the antenna pattern or output radiation pattern may be considerably narrowed by the arrangement of FIG. 7 wherein the parallel wire line is split into three branches (90, 91 and 92) which, respectively, project through different apertures in the reflector 76 and which excite the plasma column at different spaced points along its length. By that arrangement, the plasma column is simultaneously excited in phase at several points along its length so that it functions as a line of dipoles somewhat longer than the dimension between the outermost parallel wire lines 90 and 92. The multiple "pitchfork" excita- arrangement of FIG. 7 has been successfully used to provide a fan beam radiation pattern in which the half-power points 94 and 96 are separated by about 30 degrees, as indicated in FIG. 8.

In FIG. 9 there is illustrated an electronically steerable antenna system comprising a plurality of dipolar resonant plasma columns positioned in parallel with one another in an array. The steerable antenna system includes a metallic reflector means 104 which preferably takes the form of a parabolic cylinder which is a parabolic curve in the YZ plane and which appears as a substantially rectangular metal sheet when viewed along the Z axis. Directly in front of the parabolic reflector there is positioned a primary feed antenna 100 for illuminating the parabolic reflector 104 with energy from a microwave energy source 102. The feed antenna comprises a waveguide 106 for conducting microwaves from the source 102 to a plurality of parallel wire transmission lines 112 which are conventionally coupled to the waveguide in a manner to feed energy from the waveguide to the lines 112. From the waveguide each line 112 passes through an appropriate aperture in a metallic reflector plate 118 and straddles an elongated gas discharge device which is positioned about one-quarter wavelength from, and parallel to, the plate 118. The elongated plasma discharge devices 110*a*–110*e* are preferably positioned so that their longitudinal axes are parallel to the X axis of the parabolic reflector 104. The coupling 114 of each parallel wire transmission line 112 to the waveguide is shown only diagrammatically in FIG. 9 to facilitate clarity of understanding. It will be appreciated that any of various well known coupling devices commonly used in the waveguide arts may be provided for coupling energy out of the waveguide 106 and onto each of the parallel wire transmission lines 112.

The arrangement of FIG. 9 provides for establishing multiple antenna beams. That is, the single antenna reflector 104 receives primary feeding of microwave energy from the resonant plasma discharge tubes 110*a*–110*e*. Only one of the dischrage tubes is resonant at any one time; that is, when the plasma tube 110*a* has a free electron density such that it resonates at the frequency of the microwave energy from source 102, the other discharge devices 110*b*–110*e* have their electron densities adjusted to values such that they are not responsive to the applied microwave energy at that particular time. At a slightly later time the second discharge device 110*b* reaches an electron density such that it resonates and efficiently couples energy from its transmission line 112 and radiates that energy to the reflector 104. The time sequential resonant operation of the discharge devices

110*a*–110*e* is achieved by means of the direct current energizing system which is illustrated schematically in FIG. 10. Specifically, as shown in FIG. 10, the discharge devices 110*a*, 110*b*, 110*c*, 110*d* and 110*e* have their cathodes 113*a*–113*e* connected to a common terminal 130 which is connected to ground through the secondary winding of a transformer 136. A sawtooth waveform modulating voltage is applied to the primary winding of the transformer 136 from a sawtooth voltage source 134. The anodes 111 of the five discharge devices are separately and individually connected to spaced voltage points 120*a*–120*e* provided by a direct current voltage source 120 which is shown schematically as a battery. Under static conditions, that is when no modulating voltage is provided from the source 134, all the discharge devices 110*a*–110*e* will be energized with substantially different longitudinal discharge currents flowing therethrough so that the plasma densities are substantially different with the first discharge device 110*a* having the greatest free electron density N and with the other discharge devices having substantially lower electron densities. When a negative going sawtooth voltage is applied to terminal 130 by the plasma density modulation means 132, the longitudinal discharge current through each and every one of the discharge devices 110*a*–110*e* will be progressively increased in accordance with the shape of the sawtooth wave. Assuming that under the static conditions 110*a* had an electron density N such that was resonant at the frequency of the applied microwave energy, then, as the voltage applied thereto is increased, that particular tube passes out of resonance and the next discharge tube 110*b* passes through resonance as its electron density increases. In a similar manner, the successive discharge devices 110*c*, 110*d* and 110*e* sequentially pass through the electron density values which enable them to resonate with the microwave energy which is being applied thereto from the source 102. Now, referring again to FIG. 9, the discharge tubes 110*a*–110*e* function as a number of primary feed sources which are physically displaced or spaced along a plane which is normal to the Z axis of the parabolic reflector 104. Each one of the discharge devices 110*a*–110*e*, when resonant, has all the characteristics of a broadside array of short dipoles. Accordingly, each one of the discharge devices produces a fan beam, the peak intensity of which is in a direction normal to or nearly normal to the axis of the discharge device. That is, the peak intensity of the beam produced by the discharge tube 110*a* is directed toward the parabolic reflector 104 along a line parallel to the Z axis of the reflector 104. Since the tubes 110*a*–110*e* are sequentially operative the secondary radiation beam which is reflected from the reflector 104 and extends outwardly in the direction of the Z axis is scanned angularly back and forth in the YZ plane. The scanning rate or scanning frequency, of course, is dependent upon the rise time and frequency of the sawtooth waveform provided by the source 132. The system illustrated in FIGS. 9 and 10 is intended to represent merely one preferred example of an arrangement by which a plurality of dipolar resonant plasma columns may be utilized to achieve electronic scanning or electronic steering of the secondary beam of an antenna system. Various arrangements will occur to persons skilled in the art for adapting the concept of elongated resonant plasma columns to both simple and complex antenna reflector arrangements. For example, it is contemplated that the present invention may be adapted for use in complex antenna configurations of the general type described in an article entitled "The Parabolic Dome Antenna; A Large Aperture, 360 Degrees, Rapid Scan Antenna," I.R.E. Wescon Record, 1958, Part I, pp. 272–293. In general it is considered that all such arrangements in which resonant plasma column "dipole arrays" are used as line sources for illuminating cylindrical reflectors to provide primary feed thereto are within the spirit and scope of the present invention.

Moreover, it will be appreciated that the arrangement shown in FIG. 9 does not necessarily have to be operated by means of a modulation sawtooth votlage applied to the discharge devices 110*a*–110*e*. It is contemplated that the five discharge devices may be statically energized from different direct current voltages so that they statically and continually have individually fixed but slightly different "free electron" densities. In such an arrangement the frequency of the microwave source 102 may be swept across a frequency band or frequency range which is sufficiently wide so that the plasma columns of the discharge devices 110*a*–110*e* are time sequentially resonant with the microwave energy supplied from the source 102. That is, a microwave signal to be transmitted is continually applied to all of the parallel wire lines 112 but is instantaneously coupled from a line 112 to, for example, the elongated discharge device 110*b* only when the frequency of the microwave signal is such that the specific electron density of the discharge device 110*b* satisfies the foregoing Equation 1. Thus, by causing the frequency of the microwave signal to scan across the frequency band occupied by the resonant frequency of the five plasma columns, the signal will be successively coupled to and radiated by the different columns. Since the five different columns are differently located relative to the parabolic reflector 104, the secondary beams developed by the reflector 104 are scanned across a sector of space in the YZ plane of the system.

Another exemplary embodiment of a plasma resonance antenna in accordance with our invention is shown in FIG. 11. Here a discharge tube 150 whose diameter is tapered along its length is placed in front of a plane reflector 152. The whole assembly is located in front of a substantially parabolic reflector 154. The discharge tube 150 is fed by sections of parallel wire line 156, 158, 160 at three axially spaced points. These sections of line 156–160 are joined to and fed from a common feed line 162.

Since the discharge tube is tapered, at a given value of discharge current the plasma electron density is a function of the axial distance. As a rough approximation, this density varies along the axis inversely as the square of the diameter of the discharge tube.

The operation of the system shown in FIGS. 11 and 12 can best be understood by considering the system as a transmitting antenna with constant frequency input energy.

The gas, pressure, and voltage of the discharge tube 150 are chosen so that at value I_1 the center portion of the tube adjacent feed line 158 is in plasma resonance. Accordingly, at some lower current I_0, the portion adjacent line section 156 is in resonance; while at some higher discharge current I_2, the portion of the tube 150 adjacent to line section 160 is in resonance. Whenever a given position of the plasma column is in resonance, it acts to couple energy from its associated parallel wire line section and radiate toward the parabolic reflector 154 from which it is radiated downwardly as shown in FIG. 12, and into space.

Since the three axially successive portions of the discharge tube are located differently with respect to the focal point of the parabolic reflector 154 the direction of beam radiated from reflector 154 is determined by which of the three portions of the plasma column is in resonance.

Consequently, by changing the discharge current continuously from I_0 to I_2, the main lobe 164 of the radiated beam may be rotated in azimuth. The angular patterns of the radiated beam for currents I_0 and I_2 are shown in FIG. 12. Thus, the apparatus of FIGS. 11 and 12 provides for electronically lobing or scanning the output beam pattern 164 in response to and as a function of controlled variation of the longitudinal discharge current in the gas discharge device 150. It will be appreciated that the apparatus of FIGS. 11 and 12, being reciprocal

in all respects, is similarly operable as a scannable receiving antenna system.

While the present invention has been described with reference to certain specific embodiments only, it will be obvious to those skilled in the art that it is not so limited but is susceptible of various changes and modifications without departing from the spirit and scope thereof.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. In an electronically steerable beam antenna system for selectively propagating a beam of microwave energy in a first direction during a first time interval and in a second direction during a second time interval:

a microwave reflector having a concave reflecting surface and having a principal axis of symmetry which lies angularly between said first and second directions;

an array including at least first and second elongated gas discharge devices positioned in a spaced-apart parallel alignment in a plane substantially normal to said principal axis and adjacent said concave surface;

time variable circuit means, connected to continuously pass ionizing currents longitudinally through both said discharge devices, for maintaining an elongated plasma column within each said device and for selectively and alternatively establishing a critical free electron density in said first discharge device during said first time interval and in said second discharge device during said second time interval;

said selectively established free electron density being the critical density which satisfies the relation:

$$\omega_r = \frac{5.6 \cdot 10^4 \sqrt{N}}{\sqrt{1+K}}$$

wherein:

ω_r is the angular frequency of the microwave radiation which is to be propagated,

K is the composite effective dielectric constant of said discharge devices, and

N is said critical free electron density in electrons per cubic centimeter;

coupling means, including portions positioned closely adjacent each of said discharge devices, for coupling microwave energy to each of said plasma columns;

said microwave energy causing coherent and resonant oscillatory displacement of the plasma electron cloud in said first and second devices during said first and second time intervals respectively, with said displacement being in a direction substantially parallel to the plane of said array and normal to the axes of said discharge devices;

said oscillatory displacement of the electron cloud causing emission of plasma resonance radiation along a substantial portion of the length of said first and second devices during said first and second time intervals respectively, whereby substantially planar radiation waves are propagated in said first and second directions respectively during said first and second time intervals.

2. In a system for selectively propagating a beam of microwave energy in a first direction during a first time interval and in a second direction during a second time interval:

reflector means having a concave reflecting surface and having a principal axis of symmetry which lies angularly between said first and second directions;

an array including at least first and second elongated gas discharge devices positioned in a spaced-apart parallel alignment in a plane substantially normal to said principal axis and adjacent said concave surface;

time variable circuit means, connected to pass ionizing currents longitudinally through both said discharge devices, for maintaining an elongated plasma column within each said device and for selectively establishing a critical free electron density in said first discharge device during said first time interval and in said second discharge device during said second time interval;

said selectively established free electron density being the critical density for enabling resonant oscillatory displacement of the electron cloud of the plasma column at the frequency of the microwave energy which is to be propagated;

coupling means, including portions positioned closely adjacent each of said discharge devices, for coupling microwave energy to each of said plasma columns;

said microwave energy causing coherent and resonant oscillatory displacement of the electron cloud in said first and second devices during said first and second time intervals respectively, with said displacement being in a direction substantially parallel to the plane of said array and normal to the axes of said discharge devices;

said oscillatory displacement of the electron cloud causing emission of plasma resonance radiation along a substantial portion of the length of said first and second devices during said first and second time intervals respectively;

said reflector means being operative to form the plasma resonance radiation emanating from said first device into a beam having said first direction, and to form the radiation from said second device into a beam having said second direction.

3. In apparatus for propagating a beam of microwave energy in a first beam direction during a first time interval and in a second beam direction during a second time interval:

an array including at least first and second elongated gas discharge devices positioned in spaced-apart parallel alignment in a predetermined plane;

current supplying circuit means for energizing both said devices in a manner to maintain first and second elongated plasma columns respectively within said first and second devices;

current controlling means for selectively and alternatively adjusting the free electron density in said first and second plasma columns to a critical density value satisfying the relation:

$$\omega_r = \frac{5.6 \cdot 10^4 \sqrt{N}}{\sqrt{1+K}}$$

wherein:

ω_r is the angular frequency of the microwave radiation which is to be propagated,

K is the composite effective dielectric constant of said discharge devices, and

N is said critical free electron density in electrons per cubic centimeter;

means for continuously coupling input microwave energy to each of said plasma columns with said microwave energy being primarily absorbed and reradiated by said first plsama column during said first time interval and by said second plasma column during said second time interval,

said microwave energy causing in each case coherent oscillatory displacement of the electron cloud of the plasma along a substantial length of the plasma column with said displacement being in a direction substantially parallel to the plane of said array,

said displacement producing, in each case, plasma resonance radiation emanating coherently from a substantial length of the plasma column;

and microwave beam forming reflector means, positioned adjacent said array, for forming the plasma resonance radiation which emanates from said first plasma column into a beam having said first direc-

tion and forming the radiation from said second column into a beam having said second direction.

4. In apparatus for propagating a beam of microwave energy in a first beam direction during a first time interval and in a second beam direction during a second time interval:

an array including at least first and second elongated gas discharge devices positioned in spaced-apart parallel alignment in a predetermined plane;

discharge current supplying circuit means, connected to pass ionizing currents longitudinally through each of said discharge devices, for energizing the same to provide an elongated ionized-gas plasma column within each of said discharge devices;

means to control the magnitudes of said ionizing currents for selectively and alternatively establishing, in said discharge devices, a critical free electron density satisfying the relation;

$$\omega_r = \frac{5.6 \cdot 10^4 \sqrt{N}}{\sqrt{1+K}}$$

wherein:

ω_r is the angular frequency of the microwave radiation which is to be propagated,

K is the composite effective dielectric constant of said discharge devices, and

N is said critical free electron density in electrons per cubic centimeter;

said critical density being established in said first discharge device during said first time interval and in said second discharge device during said second time interval;

a microwave signal transmission line for providing microwave energy to said array;

coupling means, including portions positioned closely adjacent each of said discharge devices, for applying microwave energy from said line to each of said plasma columns;

said microwave energy being primarily absorbed by said first discharge device during said first time interval and by said second discharge device during said second time interval and causing in each case coherent oscillatory displacement of the electron cloud of the corresponding plasma column with said displacement being in a direction substantially parallel to said predetermined plane and normal to the axes of said discharge devices;

said coherent oscillatory displacement producing coherently phased plasma resonance radiation emanating externally of a substantial portion of the length of said first and second discharge devices respectively during said first and second time intervals;

and beam forming radiation reflecting means for forming the plasma resonance radiation which emanates respectively from said first and second discharge devices into first and second beams having substantially said first and second directions respectively.

5. In a system for selectively propagating a beam of ultra-high frequency radiation in first and second angularly spaced directions respectively during first and second time intervals:

an array including at least first and second elongated gas discharge devices positioned in substantial parallelism in a predetermined plane;

ionization means for maintaining an elongated ionized-gas plasma column within each of said devices and for adjustably establishing a predetermined degree of ionization in said first device during said first time interval and in said second device during said second time interval;

said predetermined degree of ionization being selected to satisfy the relation

$$\omega_r = \frac{5.6 \cdot 10^4 \sqrt{N}}{\sqrt{1+K}}$$

wherein:

ω_r is the angular frequency of the ultra-high frequency radiation which is to be propagated,

K is the composite effective dielectric constant of one of said discharge devices, and

N is the free electron density in electrons per cubic centimeter which corresponds to said predetermined degree of ionization;

ultra-high frequency circuit means for coupling energy of said frequency ω_r to each of said discharge devices, said energy being coupled in a manner to cause resonant oscillatory displacement of the plasma electron cloud in said first and second devices during said first and second time intervals respectively, with said displacement being in a direction substantially parallel to the plane of said array and normal to the axes of said discharge devices;

said oscillatory displacement of the electron clouds causing emission of plasma resonance radiation along a substantial portion of the length of said first and second devices during said first and second time intervals respectively;

and beam forming radiation reflecting means positioned adjacent said array for forming the plasma resonance radiation emitted from said first device into a beam having said first direction and forming the plasma resonance radiation emitted from said second device into a beam having said second direction.

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