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MICROWAVE ELECTRON DISCHARGE DEVICE HAVING ANNULAR RESONANT CAVITY

Filed Sept. 1, 1961 | 2 Sheets-Sheet 1

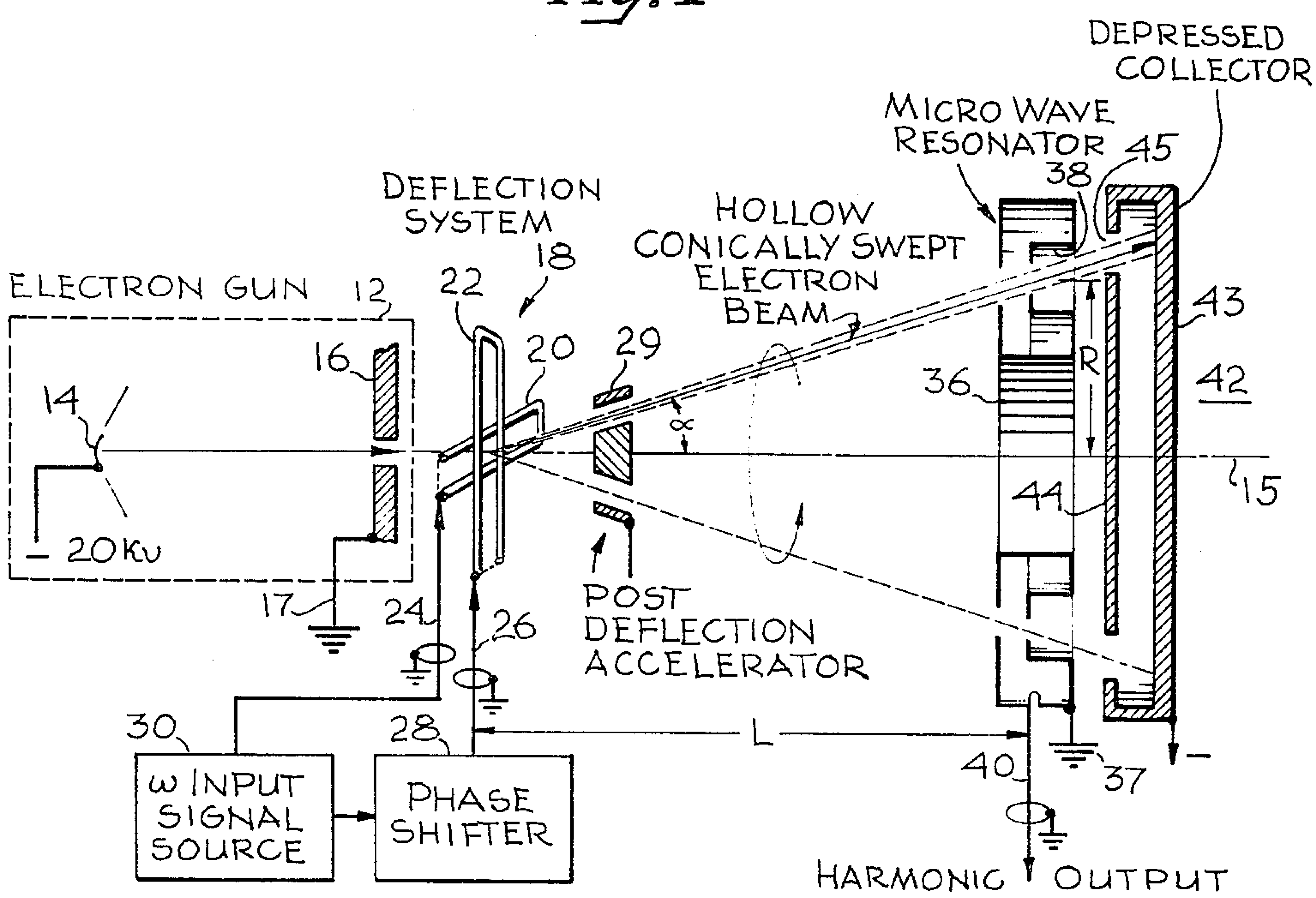

Fig. 1

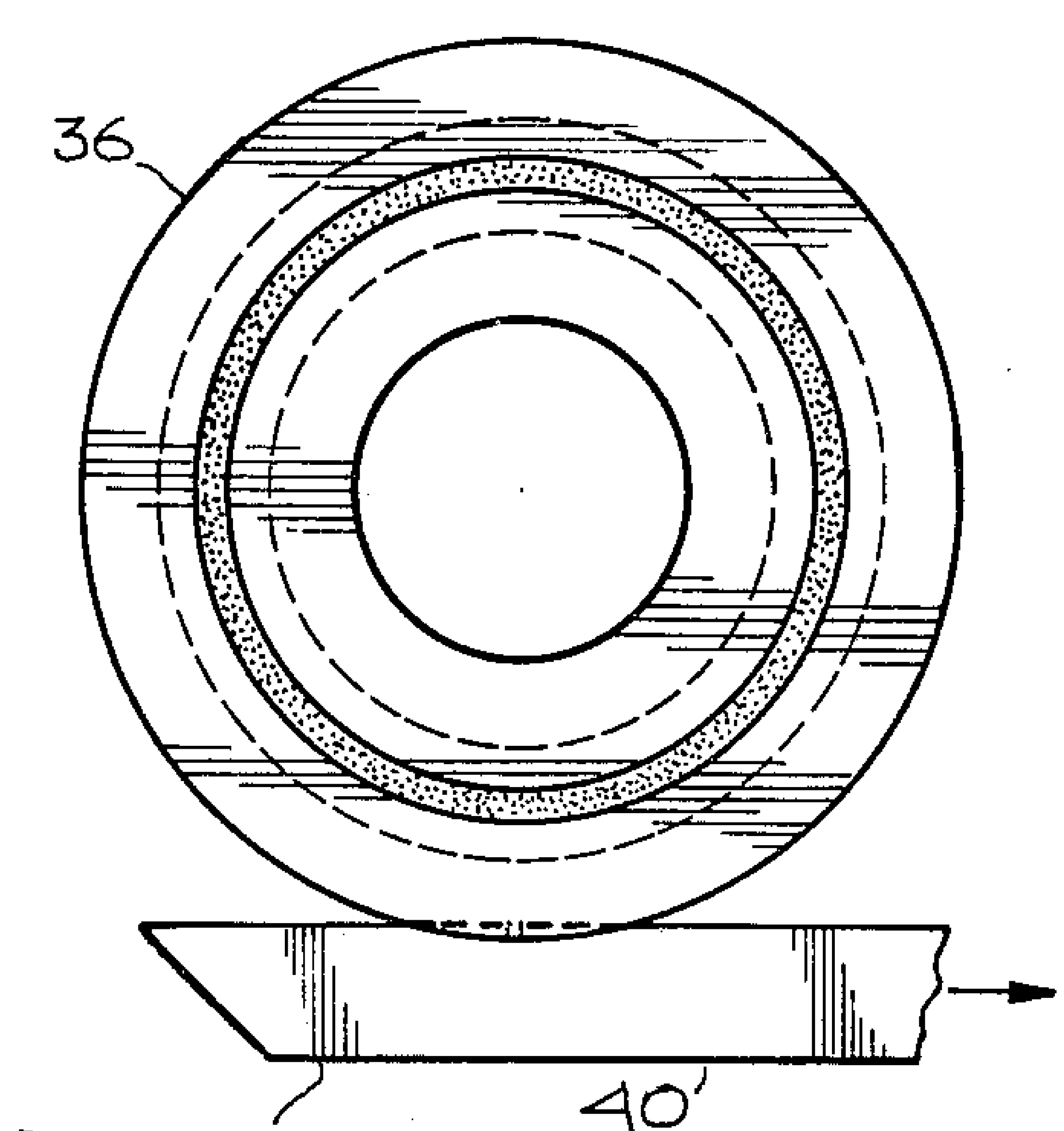

Fig. 2 (a)

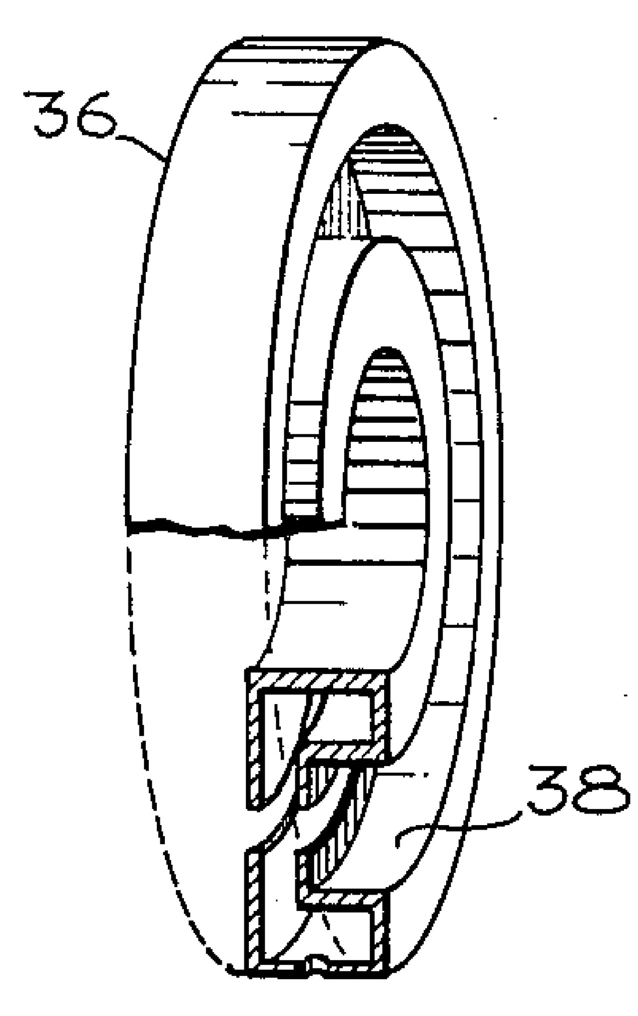

Fig. 2 (b)

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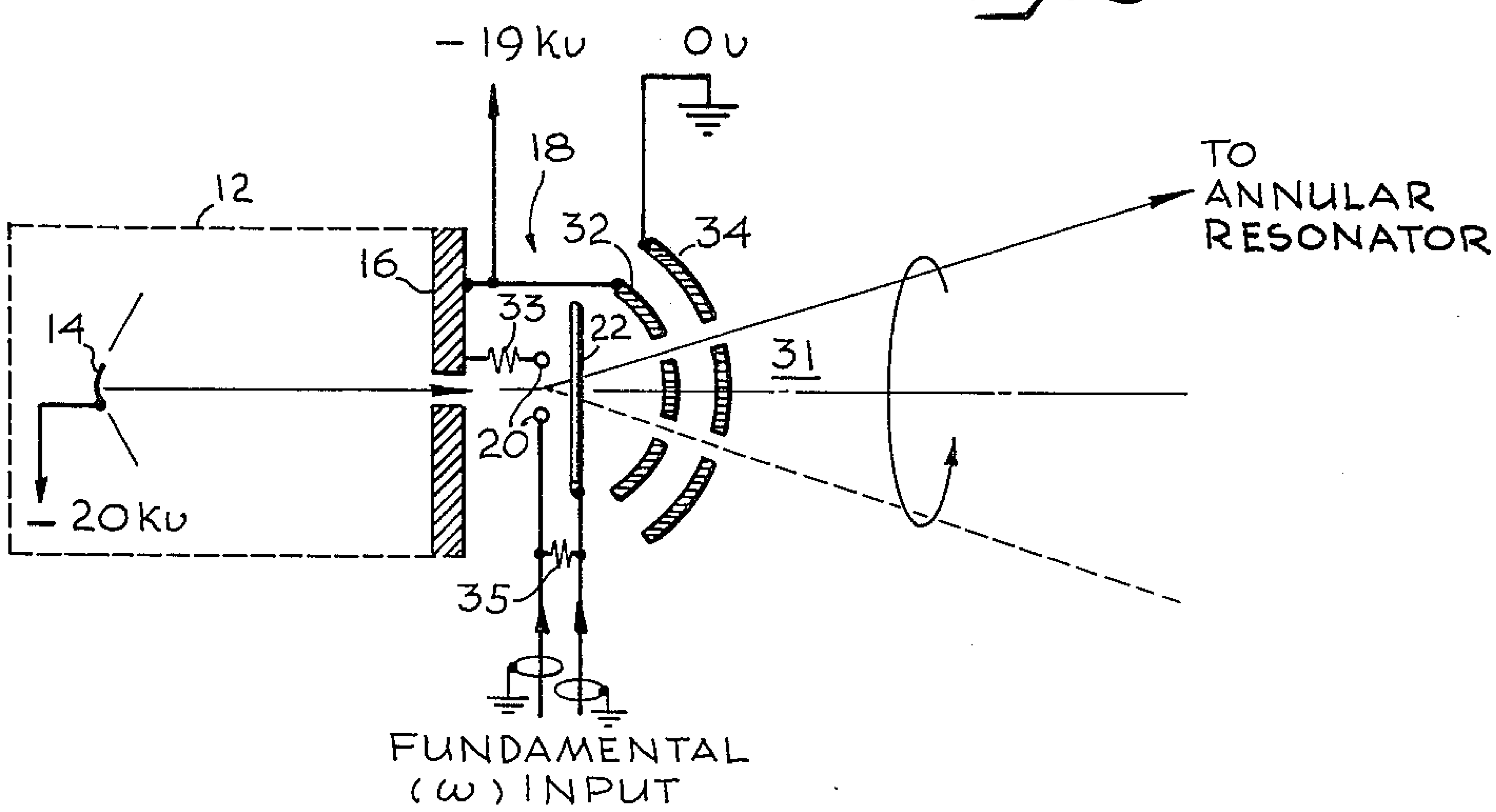
Fig. 3



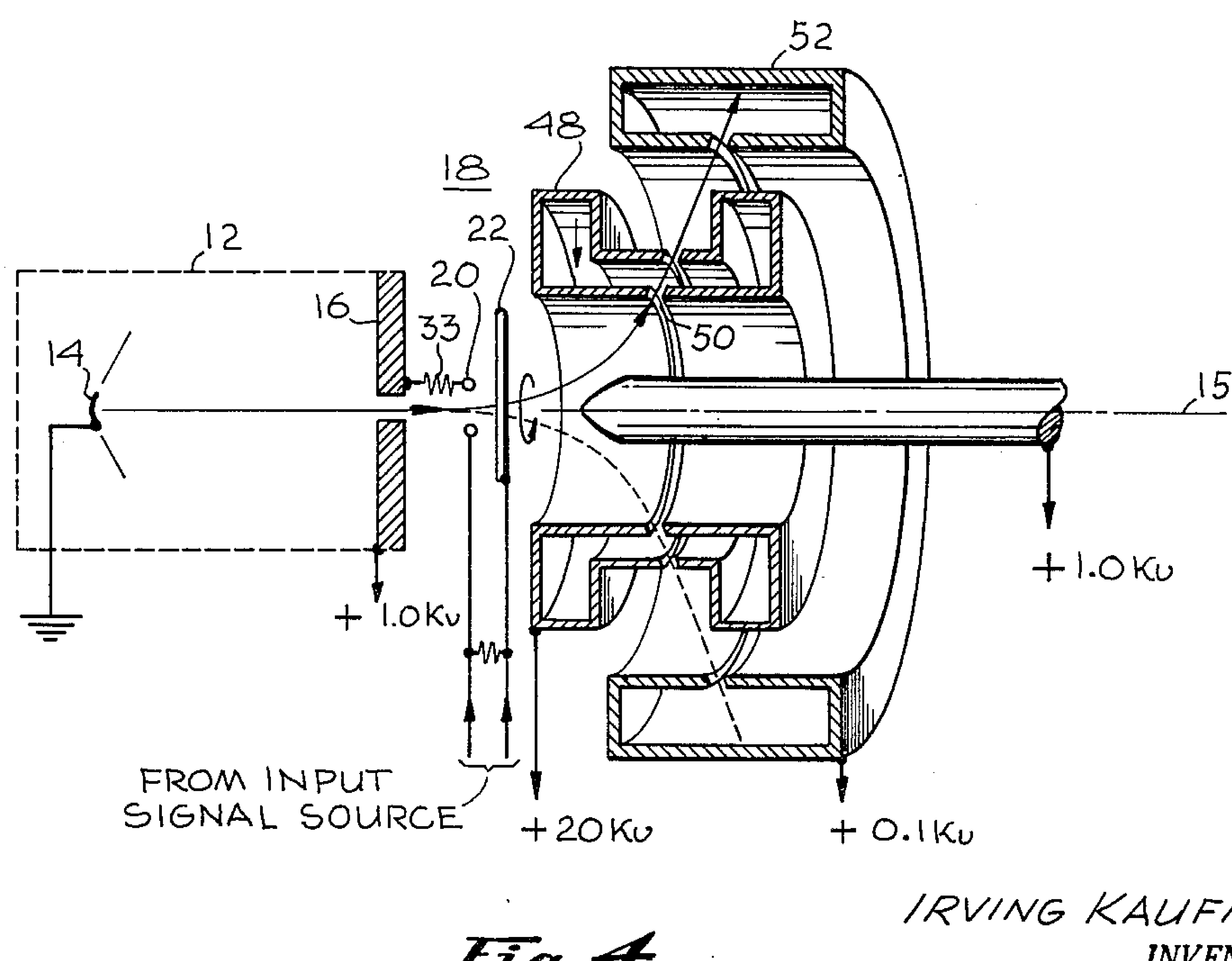


Fig. 4

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MICROWAVE ELECTRON DISCHARGE DEVICE HAVING ANNULAR RESONANT CAVITY

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1 Claim. (Cl. 315—5.25)

The present invention relates generally to the art of generating, amplifying, and frequency multiplying microwave signals, and is especially adapted and useful for converting direct current power to radio frequency power in the millimeter and submillimeter wavelength regions. More particularly, this invention has reference to frequency multipliers, oscillators, and amplifiers employing microwave cavity resonators excited by controlled electron beams.

It is a general object of the present invention to provide improved apparatus for efficiently producing electric waves in the millimeter and sub-millimeter wavelengths.

It is a primary object to overcome the high frequency limitations of known microwave generators and amplifiers by providing apparatus which is inherently independent of certain basic handicaps of the commonly used prior art techniques and devices.

It is a further object to facilitate the manufacture and reduce the cost and complexity of microwave active systems.

Various devices are known for generating radio frequency power at wavelengths of a few millimeters. Such devices which have utilized linear electron beams are divisible operationally into two general classes: (1) devices employing longitudinal compression "bunching" of the electron beam, and (2) devices using radio frequency deflection of an electron beam in conjunction with a slotted or apertured target for chopping the beam.

In systems of the first type above mentioned, such as klystrons and traveling wave tubes employing beam density modulation or beam velocity modulation, the electron bunches created necessarily must be shorter than the wavelength to be generated. It has been difficult to fulfill that requirement with appreciable electron densities at millimeter wavelengths. Extremely low efficiencies have resulted. Moreover, even if sufficiently short electron bunches are created in such devices, the bunches are quickly distended or stretched by longitudinal space charge forces within the beam.

Referring to the second class of devices mentioned above, it is a very simple matter to produce electron bunches by the beam chopping technique. However, such systems have the extreme disadvantage that, as the frequency is increased, the electron bunch is shortened without being increased in density and therefore contains proportionally fewer electrons. Accordingly, the amount of microwave output power which can be produced from the reduced energy bunches becomes prohibtively small as the frequency is increased.

The present invention overcomes the foregoing handicaps of previous systems by continuously utilizing substantially all of the beam current produced by the electron gun. In addition, the present invention increases the useful kinetic energy of the beam electrons without increasing the load imposed on the controlling microwave input signal source. Even more important, the present invention reduces, by an order of magnitude, the deleterious effects of aberrations in the longitudinal velocity of the cathode ray beam electrons.

The foregoing desirable effects are accomplished by using a cathode ray generating system in which the electron beam is circularly or elliptically deflected under the control of and in synchronism with an input microwave signal. The beam thereby describes a conical helix, with the electrons of the beam respectively traversing successive portions of a microwave resonator device which is adapted to derive energy from the electron beam. In a preferred embodiment of the invention, the microwave resonator comprises an annular waveguide member positioned in a plane substantially perpendicular to the axis of the conical beam and arranged to internally receive the electrons of the beam.

The microwave resonator is constructed and arranged to provide a decelerating electric field in the region where each electron is internally traversing the structure. By decelerating the beam electrons, the electromagnetic waves within the microwave resonator absorb kinetic energy from the rapidly moving electrons and thereby regenerate the microwave oscillations within the resonator. Further, in accordance with preferred embodiments of the invention, the electron beam is conically deflected by the input microwave signal at a point in the system where the beam electrons have a relatively low velocity. The conical beam is thereafter increased in energy by a direct current energized accelerating system so that the total microwave energy which may be derived from the conical beam is finally several orders of magnitude greater than the microwave input power required for deflecting the beam.

The present invention, together with further objects and advantages thereof, may be best understood by reference to the following description taken in accordance with the accompanying drawings, in which like reference characters indicate like parts and in which:

FIGURE 1 is a schematic illustration of a microwave power conversion system of the general type to which the invention relates;

FIGS. 2*a* and 2*b* are respectively a front view and a side view of the annular microwave resonator used in the system of FIG. 1;

FIG. 3 is a fragmentary sectional view representing a structural modification of the embodiment of FIG. 1; and

FIG. 4 is a schematic diagram of a further embodiment in accordance with the invention.

Referring now to FIG. 1, numeral **12** designates a cathode ray producing electron gun including a cathode **14** and a beam forming accelerating electrode **16**. The electron beam generating means or electron gun **12** may take any one of various forms well known in the art. The only requirements of the present invention are that the electron gun **12** should produce a well defined pencil beam of electrons which is initially projected along the horizontal axis **15**. Along the electron beam axis **15** immediately subsequent to the beam forming electrode **16** is positioned a deflection system **18** comprising a pair of Lecher-wires or resonant transmission line sections **20** and **22**.

As shown in FIG. 1, the Lecher-wire pair **20** is disposed in a plane transverse to the beam axis and extending perpendicularly to the plane of the paper. The second Lecher-wire pair **22** is disposed in a plane substantially parallel to that of the first Lecher-wire pair, but with the second pair **22** at right angles to the first pair. Thus, the deflection system comprises two crossed pairs of shorted Lecher-wires, preferably resonant at the frequency of the microwave input signal. The intersection of the two line pairs **20** and **22** is preferably located one-quarter wavelength away from the shorted ends of the line pairs so that voltage maxima occurring on the lines **20** and **22** will be located at the center of the small square window which is framed by the two wire pairs. Thus, the electron beam which passes through the center of the window is subjected to the maximum electrodynamic forces provided by the voltage standing waves on the two line pairs. The first line pair 20 deflects the electron beam in the Y direction, that is, vertically up and down in the plane of the paper. The second line pair 22 operates to deflect the beam in the X direction, or perpendicularly to the paper.

Microwave input signals are applied to the deflection system 18 through a pair of transmission lines or coaxial cables 24 and 26 which are respectively connected to the first and second line pairs 20 and 22. The input signal is applied directly to the transmission line 24 from the signal source 30. The input signal is applied from the source 30 through a phase shifting device 28 and thence to the line 26. The phase shifting device 28, which may be of conventional construction, provides approximately a 90° phase differential between the electromagnetic waves at the transmission lines 24 and 26. It will be appreciated that the beam transit time between the planes of lines 24 and 26 must be taken into account in providing the optimum phase differential between the two signals; that is, if the phase differential were exactly 90°, the deflection effect obtained would be different from that which is desired by the amount of the beam transit time. Thus, in actual practice, a phase differential slightly exceeding 90° is to be desired. The phase difference between the signals applied to the line pair 20 and the line pair 22 causes the deflection system to circularly deflect the electron beam. Thus the electron beam, after passing through the deflection system 18, describes a conical rotating trace. More exactly, since the period of the input microwave signal is considerably shorter than the transit time of the beam electrons between the deflector and resonator, the beam electrons are distributed in a helical array along the surface of an imaginary right circular cone extending from the deflection system 18 to the microwave resonator device 36.

The deflection system 18 comprising the crossed Lecher-wires 20 and 22 may be constructed generally in accordance with the teachings of an article entitled "UHF Beam Analyzer," by L. R. Bloom and H. M. Von Foester, Review of Scientific Instruments, vol. 25, July 1954, pages 649–653. Complete information as to optimum designs of such microwave deflection systems is there provided and is incorporated herein by reference.

Referring to FIGS. 2*a* and 2*b*, the microwave resonator 36 preferably comprises a length of rectangular waveguide, conventionally designed of highly conductive material, and bent into a circular or elliptical shape, with the ends joined together to form a toroid. The cross-sectional dimensions of the waveguide are chosen in accordance with conventional theory to make the device resonant at a frequency corresponding to an integral multiple of the frequency of the input signal provided by source 30. The mean circumferential length of the annular resonator 36 is preferably made equal to an integral number of wave guide wavelengths at the harmonic frequency which is to be produced. An output signal transmission line 40, comprising a waveguide section conductively attached to one peripheral portion of the annular resonator 36, enables extraction of microwave power at the harmonic frequency for utilization in any desired load system. Microwave energy communication from the annular resonator 36 to the output coupler 40 is enabled by an aperture communicating interiorly between the two. The output signal coupling from resonator 36 to coupler 40 may take any one of various known forms, such as, for example, a crossed-slot coupling.

The annular resonator 36 may be designed to have either the usual standing wave excitation or a traveling wave moving circularly around the resonator. In order to minimize the transit time of electrons traversing the waveguide resonator from front to back, the resonator 36 is preferably provided with a reentrant portion 38 providing an interior ridge or shoulder in the fashion of waveguide structures of the so-called "ridged" type. The details of structure of the resonator 36 are not belabored here, since the same are well known to those skilled in the art. For example, the dimensional details of the annular waveguide resonator 36 of the present invention may be generally in accordance with the teachings of an article entitled "Resonance Properties of Ring Circuits," by F. J. Tischer, IRE Transactions on Microwave Theory and Techniques, vol. MTT–5, January 1957, pages 51–56.

The one essential departure from conventional structure which characterizes the annular resonator of the present invention is that the resonator 36 is circularly slotted in the side facing the electron gun and along a line substantially coinciding with the mean radius of the annulus and exactly coinciding with the circular intersection of the conical electron beam and the front surface of the resonator. The back surface of the waveguide may be similarly slotted along the path of the traversing electrons, or, more exactly, the inner portion of the reentrant ridge 38 is so slotted. Provision of the circular slots or apertures in the waveguide resonator permits the high velocity electrons to travel through the resonator and subsequently impinge upon a target or collector, thereby avoiding the generation of deleterious secondary electrons within the resonator itself.

If the electrons, after traversing the resonator 36, were allowed to strike a target or anode at the same direct current potential as the resonator, a considerable amount of heat loss would occur at the collector. Accordingly, in the preferred embodiment a Faraday cup collector 42 is provided. The Faraday collector 42 may be a circular hollow cup-like structure having rear and front walls 43 and 44, respectively, with the front wall 44 circularly slotted as at 45, with the circular slot being coincident with the conical line of flight of the electron beam so that the electrons are collected interiorly of the Faraday collector 42 to avoid generation of secondary electrons.

For simplicity in the embodiment shown schematically in FIG. 1, the accelerating electrode 16 is shown as being grounded at 17, and the microwave resonator 36 is grounded at 37. With this arrangement, the cathode 14 is preferably connected to a direct current potenetial source of 20 kv. negative with respect to ground. To minimize collector heat loss, the Faraday collector cup 42 is operated at a potential only slightly positive with respect to the cathode potential and therefore at a potential of about −19 kv. with respect to ground.

Interposed in the conical beam drift space between the deflection system 18 and the microwave resonator 36, there is provided an accelerating anode 29 comprising inner and outer concentric rings which may serve as electro-optical lenses to accelerate the conical beam and to concentrate the beam electrons on the circular slot in the front wall of the resonator 36. Accelerating anode 29 is preferably operated at a potential which is substantially positive with respect to the deflection system 18 and the first accelerating electrode 16.

To clarify the operation of the system of FIG. 1, it is advantageous to first consider that the resonator 36 supports a traveling electromagnetic wave at the harmonic frequency which is to be generated. It may be seen that if the waveguide wavelength in the resonator 36 is λ_g, then any wave traveling around the resonator will arrive at the starting point in phase with another wave starting from that same point. Thus, the physical requirement for a distributed resonator is fulfilled if the mean circumferential length of the resonator 36 is an integral multiple of λ_g. An electron which traverses the resonator 36 from the front wall to the back and in a retarding electric field will deliver energy to that field. The motion of the peak of the electron retarding phase of the radio frequency electric field within the resonator 36 is circular at the phase velocity of the harmonic traveling wave, and the electric field is perpendicular to the plane of the resonator annulus and therefore substantially parallel to the path of the electrons traversing the resonator. By causing the electron beam to circularly scan the resonator at a phase velocity coinciding with the phase velocity of the traveling wave within the resonator, the individual electrons traverse successive peripheral portions of the resonator in synchronism with the existence of the peak electron retarding electric field in the successive portions of the resonator. Thus, the beam electrons successively and continuously deliver energy to the electric field within the resonator. In this manner, electromagnetic oscillations are built up within the resonator until a level is reached at which the average power derived from the electron beam equals that delivered to the output load plus the resistive power losses in the resonator walls. Since the deflection system **18** produces a circular or rotating electron beam at the frequency of the input signal from source **30**, the effective linear sweep at the resonator **36** is:

$$v_e=\frac{n\lambda g}{\frac{1}{f}}=nf\lambda g$$

Because the frequencies and the dimensions of the resonator **36** have been chosen so that the resonator **36** supports a harmonic of the input frequency f, the circular phase velocity of the electron beam is in synchronism with the radio frequency traveling wave inside the resonator **36**. Accordingly, the frequency of the wave generated in the resonator **36** is:

$$f_{\text{wave}}=\frac{v_e}{\lambda_g}=nf$$

Accordingly, the output microwave signals produced by resonator **36** and extracted through coupler **40** will be the nth harmonic of the microwave input signal provided by source **30**.

It is important to note that it is not necessary for the circular phase velocity of the scanning beam to be less than the velocity of light. Each electron of the beam moves in a straight line along a polar element of the cone at a speed determined by the electron gun accelerating potential and the deflection system. The electron velocities are obviously less than the velocity of light. The circular sweep, however, rotates at the frequency of the input signal source **30** so that the effective linear scan speed of the beam at the cone surface increases with the distance from the deflection system **18**. The linear scan speed of the beam at the resonator **36** is thus a phase velocity, not an actual electron velocity, and therefore the scan speed can approach and even exceed the speed of light. This is an extremely important consideration because it permits the resonator **36** to be a hollow metal waveguide structure not loaded by dielectric or other slow wave materials and having electromagnetic fields which extend throughout the interior volume of the resonator.

In FIG. 3 is shown an alternative embodiment or modification of the beam generation system, the beam deflection system, and accelerating system of the apparatus in accordance with the invention. The electron gun **12**, cathode **14**, and collimating electrode **16** of FIG. 3 are structurally identical to the same elements of FIG. 1, and accordingly are indicated by the same reference numerals. Likewise, the deflection system is shown in FIG. 3 as comprising a pair of crossed Lecher-wires **20** and **22** identical to the same elements of FIG. 1. The system of FIG. 3 differs from that of FIG. 1 in that it includes a post-deflection beam acceleration system comprised of first and second semispherical electrodes **32** and **34**. The electrodes **32** and **34** are circularly slotted along the conical beam path to permit the conical beam to project outwardly to the right beyond the electrode **34**. In the apparatus of FIG. 3, the collimating electrode **16** is connected to a point of −19 kv. with respect to ground. Similarly, the

cathode **14** is connected to −20 kv. The first semispherical lens electrode **32** is connected commonly with collimating electrode **16** to the −19 kv. source, and the second semispherical lens electrode **34** is connected to ground or the point of reference potential. The two shorted Lecher-wire deflection elements **20** and **22** are connected together by a first radio frequency choke **35** and are connected to the collimating electrode **16** by means of a second radio frequency choke **33**. It is to be noted that in the arrangement of FIG. 3 the beam electrons, upon arrival at the deflection system, have been accelerated by only 1000 volts, i.e., the potential between the cathode **14** and the collimating electrode **16**. Thus the electron beam, as it traverses the deflection system **20** and **22**, is a relatively "soft" and easily deflected beam which requires very substantially less deflection system input energy than would be required by the corresponding deflection system of FIG. 1.

The first semispherical electrode **32**, being connected to the same potential as the collimating electrode **16**, shields the deflection system from high potential gradients and thereby minimizes deflection distortion which might otherwise occur. Between the two semispherical electrodes **32** and **34** there exists an intense potential gradient of approximately 19 kv. This potential gradient operates to accelerate the conical deflected beam so as to increase the kinetic energy of each beam electron by several orders of magnitude. It is emphasized here that the final kinetic energy of the conical beam, as it emerges from the electrode **34**, is provided primarily by the direct current voltage source and not by the microwave energy fed to the deflection system. As stated heretofore, this is an extremely important consideration because of the low powers available from practical sources of microwave input power.

For simplicity in describing the systems shown in FIGS. 1 and 3, the deflection system has been set forth as comprising a pair of shorted Lecher-wires disposed at right angles to provide a small square window through which the electron beam is projected. The use of Lecher-wires for deflection is not intended to be an essential characteristic of the present invention. The Lecher-wire system has been set forth by way of example as one completely satisfactory and operative arrangement. Other systems, such as a waveguide cavity or a ridged waveguide cavity, or parallel plate lines, would be acceptable as a deflection means in the system of the present invention and are considered to be within the broad scope of the invention. In all of the above-mentioned alternative deflection systems, each electron leaving the deflection system would travel in a straight line along an element of the cone, thereby satisfying the requirements for properly exciting the annular microwave resonator **36**. The above-mentioned alternative deflection systems may be advantageous as compared to the Lecher-wire system in that they are self-shielding systems, whereas the Lecher-wires are open radiators and would expend a considerable amount of input deflection power by radiation to the surroundings, with only a relatively small portion of the power being used for actual deflection of the electron beam. One advantage of the Lecher-wire pair deflection system in that it can be fitted into a relatively small space as compared to waveguide cavities which might be used for deflection.

In the embodiments set forth in FIGS. 1 and 3, the deflection systems are followed by a long drift distance necessary to provide a beam cone diameter corresponding to that of the annular resonator **36**. A relatively long drift distance in the embodiment of FIG. 1 is necessary to minimize the deflection angle and the deflection input power. However, the use of a long drift distance is disadvantageous in that (1) it limits operation of the system to relatively low beam currents and therefore relatively low magnitudes of harmonic power output; and (2) with long drift distance, aberrations in longitudinal electron velocity introduced by the deflection system produce an undesirably large spread in the arrival time of the electrons at the annular resonator. That is true because aberrations in longitudinal velocity produce uncertainties in arrival time which are directly proportional to the transit time as determined by the drift distance. Since each electron must arrive at a particular angular portion of the resonator simultaneously with the arrival of the peak of the electric field at that portion of the resonator, the spread in arrival time caused by long drift distance tends to limit the maximum frequency (minimum wavelength) for which the annular resonator may be designed. Further, aberrations in the deflection system may distort the circular sweep into a slightly elliptical sweep. Because of the necessarily small width of the circular slot in the front wall of the resonator **36**, such ellipticity is undesirable. The dimensional ellipticity, of course, can be minimized by reducing the beam drift distance.

FIG. 4 illustrates a further embodiment in accordance with the present invention which avoids the foregoing possible disadvantages of the earlier embodiments by providing for an extremely short drift distance. As shown in FIG. 4, the beam forming electron gun **12** may be identical to the electron gun of FIG. 1, and the deflection system **18** comprising Lecher-wires **20** and **22** is similar in structure and function to the same elements of FIG. 1. The apparatus of FIG. 4 differs from the preceding embodiments in the structure of the annular waveguide resonator and in the structure and arrangement of the post-deflection acceleration system. The waveguide resonator **48**, as shown in FIG. 4, is generally cylindrical in shape and is designed to support an annularly propagating electromagnetic wave at the desired harmonic frequency, with the electric field of the wave extending radially within the annulus and therefore at right angles to the axis of symmetry of the system. The waveguide annulus **48** is shown as being a ridged waveguide, with the internal ridge being formed by a reentrant portion extending inwardly from the outer diameter of the cylinder.

Since the electric field extends radially within the waveguide annulus, it is necessary that the electron beam traverse the annulus more or less radially from the inner diameter to the outer diameter of the ridge. To that end there is provided within the annular waveguide resonator **48** an electrostatic post-deflection acceleration system and beam bending system. This system is comprised of a cylindrical conductive rod **54** disposed on the axis of symmetry of the system and connected to a positive potential of about 1 kv., which is the same as the potential of the collimating electrode **16** in the electrode gun **12**. The annular waveguide resonator **48** is connected to a point of about 20 kv. positive with respect to the cathode, thereby providing an intense electrostatic field between the rod **54** and the resonator **48**. This intense electrostatic field acts on the slightly deflected beam to bend it outwardly and project it more or less radially through the slot **50** of the annular resonator **48**. It will be seen that this arrangement shortens the effective drift distance of the beam by as much as an order of magnitude. Since the final direction of electron motion here is nearly perpendicular to the axis of symmetry of the system, the electrons traverse the annular resonator radially and therefore in the proper direction for energy transfer interaction with the retarding electric field within the resonator.

In the arrangement of FIG. 4, the radio frequency deflection system **18** produces a consecutive time circular sweep identical to that produced by the deflection system of FIG. 1. However, the circular sweep in the apparatus of FIG. 4 not only provides a slight angular deflection of the beam, but it also selects the proper azimuth or proper radial direction for each successive electron. Since each segment of the beam moves along a ray of the same polar angle, its path may be bent outwardly by the axially symmetrical electrostatic field without changing the radial direction of the beam segment. The important consideration in the system of FIG. 4 is that the beam bending, and hence most of the radial velocity of the electrons, is provided by energy from the direct current voltage source so that the fundamental frequency power which must be fed into the deflection system **18** is minimized. In addition, it is important to note that the time aberrations, which become serious when long drift distances are employed, are avoided, thereby making it possible to use a considerably narrower slot **50** in the inner and outer walls of the resonator **48** and making it possible to design the resonator **48** for operation at shorter wavelengths than would be possible for the system of FIG. 1.

As shown in FIG. 4, the Faraday cup collector **52** takes the form of a hollow annulus which is slotted on its inner diameter to receive the beam electrons after they exit from the resonator **48**.

A basic advantage of the system in accordance with FIG. 4 is that the electron beam, as it traverses the deflection system **18**, is a relatively low velocity beam which requires much less power for a given angular deflection than would be required in the system of FIG. 1. Furthermore, because of the beam bending arrangement employed in the apparatus of FIG. 4, the angle of deflection which must be provided by the deflection system **18** is very small, thereby further decreasing the load imposed on the source **30** of microwave fundamental frequency energy which supplies the deflection system **18**. Beam acceleration is provided primarily by the electric field between elements **48** and **54**. The deflection system is required to provide only a relatively small amount of transverse velocity to the beam electrons. Most of the radial velocity of the electrons is furnished by the direct current voltage source, and not by the deflection system. Reducing the deflection system power consumption is important because of the low power output levels which are available from practical microwave sources. If a reasonably practical amount of harmonic frequency power were to be extracted from a system such as that of FIG. 1, but not employing post-deflection acceleration, it would be necessary to supply fundamental frequency input power to the deflection system in amounts approaching 1 watt. That much input power at millimeter and sub-millimeter wavelengths is not readily and economically available. The present invention overcomes that difficulty by furnishing most of the radial kinetic energy of the beam electrons, not from the radio frequency deflection system, but rather from the direct current energizing source as applied to the post-deflection accelerating means.

In addition to reducing the required radio frequency input power, post-deflection acceleration also proportionally reduces the amount of aberration introduced by the deflection system. Reduction of such aberration is of great value because it reduces the spread in electron arrival times at a given angular point on the output resonator and thereby enables use of the system at higher frequencies. In addition, a shorter drift distance has the advantage that for a given resonator slot width appreciably greater beam currents may be used. The output power is, of course, increased by increased beam current.

While there have been described what are at present considered to be preferred embodiments of the invention, it will be obvious to those skilled in the art that various changes and modifications may be made therein without departing from the invention, and it is aimed in the appended claim to cover all such changes and modifications as fall within the true spirit and scope of the invention.

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

In a microwave frequency converter comprising a discharge device having beam forming means for providing an axially directed beam of charged particles:

deflection means for imparting conical rotation to said beam in response to deflection signals of a first frequency;

a generally cylindrical microwave resonator positioned in symmetrical and axial alignment with the central axis of said conically rotating beam;

said resonator comprising a hollow annulus of conductive material internally dimensioned to support annularly traveling electromagnetic waves of a second frequency having their electric field vectors extending substantially radially with respect to said axis;

means for positively biasing said annulus relative to said beam forming means;

and post-deflection acceleration means, comprising a substantially cylindrical dynode member having a relatively negative direct current potential, positioned symmetrically with respect to said beam axis adjacent the lines of flight of said charged particles for accelerating and outwardly deflecting said particles so that the same traverse said annulus in a direction to impart kinetic energy to the second frequency electric fields within said annulus.

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