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A. KARP

2,858,472

SLOW-WAVE CIRCUIT FOR A TRAVELING WAVE TUBE

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FIG. 1

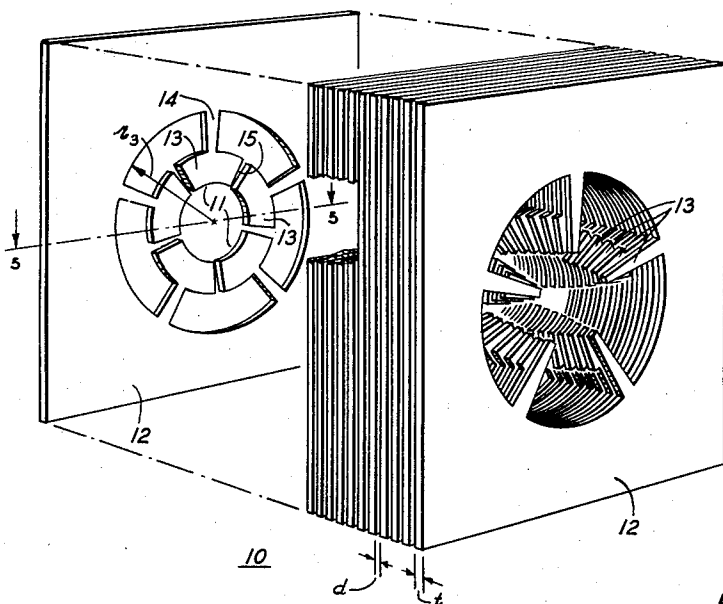


FIG. 2

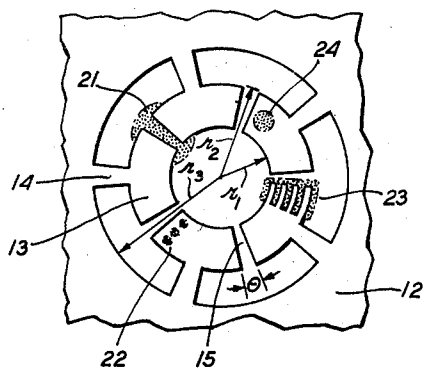
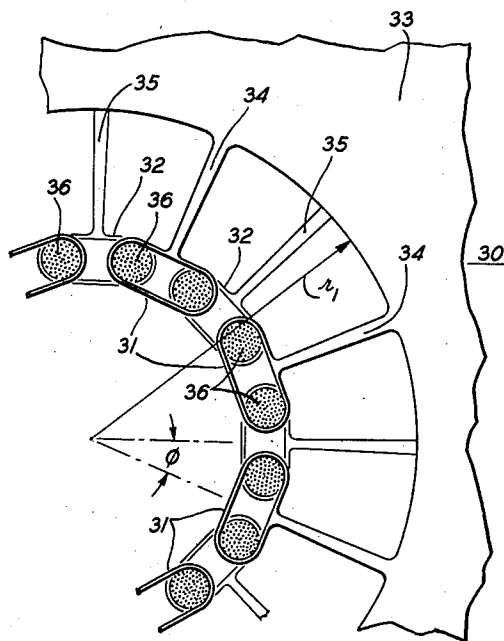


FIG. 3



INVENTOR
A. KARP

BY

Hugh S. Wentz

ATTORNEY

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A. KARP

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FIG. 5

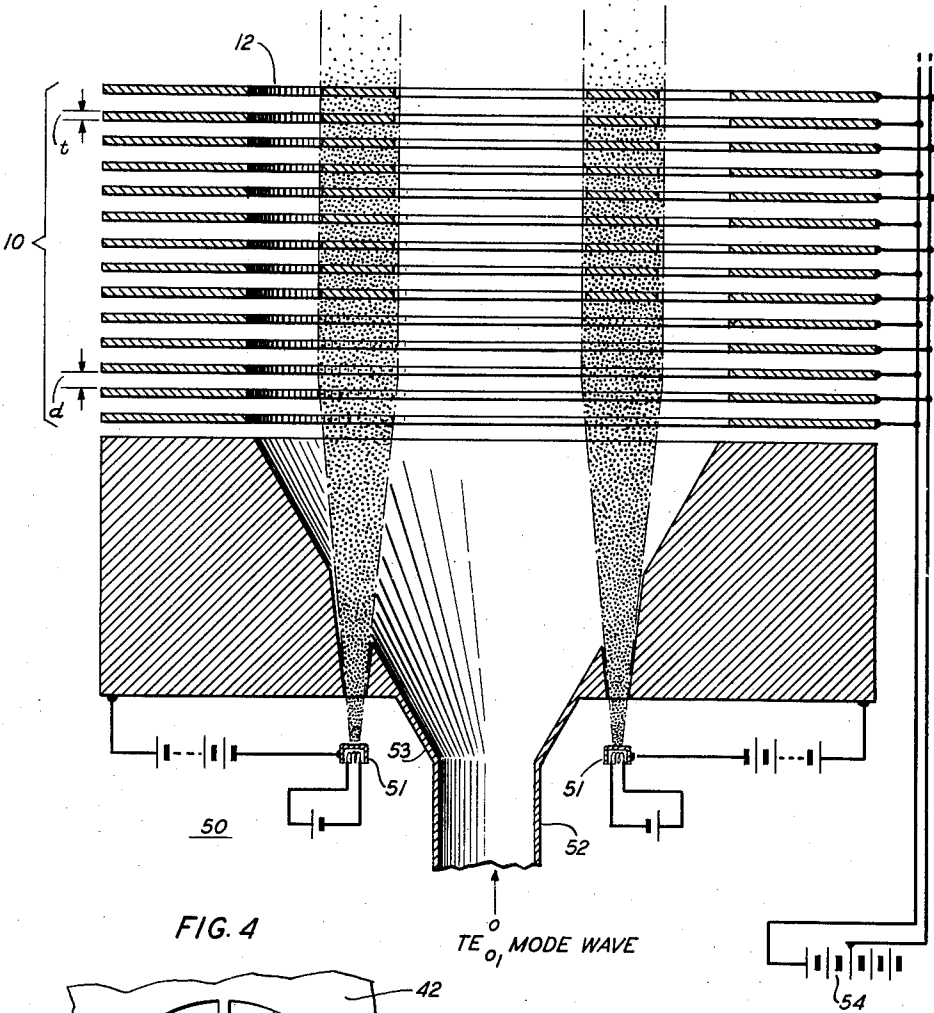
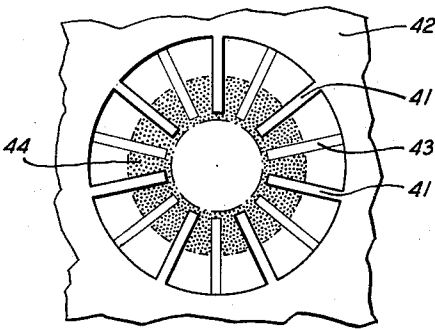


FIG. 4



INVENTOR
A. KARP
BY *Hugh S. Wentz*
ATTORNEY

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SLOW-WAVE CIRCUIT FOR A TRAVELING WAVE TUBE

Arthur Karp, Red Bank, N. J., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

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14 Claims. (Cl. 315-3.6)

This invention relates to electromagnetic wave phase retarding circuits and more particularly to slow wave circuits suitable for use in traveling wave tubes.

An object of this invention is to provide an improved wave propagation circuit especially suitable for use in high power millimeter wavelength traveling wave tubes. A more specific object is to provide such a circuit which is adapted for use with circular transverse electric mode waves.

The invention of the traveling wave tube was the first step in the development of many of the present day techniques in the generation and amplification of millimeter wavelength electromagnetic waves. Although the common type of traveling wave tube employing a wave propagating helix was limited by requirements of physical size to operation at wavelengths generally longer than one centimeter, recent discoveries, such as the spatial harmonic traveling wave tube disclosed in U. S. Patent 2,683,238, issued July 6, 1954, to S. Millman, have extended this range to less than one-half centimeter.

These advances in the art have aroused interest in the possibility of transcontinental transmission of millimeter waves via closed wave guides. A single wave guide can accommodate signal frequencies over a range of many thousands of megacycles and could theoretically replace most if not all existing transcontinental lines. Serious difficulties in long distance wave guide transmission, however, remain to be overcome before such transmission is practical. Among these, perhaps one of the more prominent is the lack of broad-band high-power tubes which are rugged and easy to manufacture. The present invention is intended to supply such a tube.

This invention is based upon the spatial harmonic principle of wave amplification disclosed in the above-mentioned patent. Briefly explained, spatial harmonic amplification takes place when a stream of electrons is beamed with the proper velocity in coupling proximity with a wave propagating circuit of the iterative filter type having a non-zero distance between sections. Neglecting losses, such a circuit, by virtue of its periodic nature, causes the maximum, as distinguished from the instantaneous, amplitude of the electric field to be a periodic function of distance along the circuit. Thus at a given instant of time the peak electric intensities along the circuit are not all the same value, contrary to the condition along a uniform structure, such as a lossless wave propagating coaxial cable, where the peak intensities are equal. As a result of this nonuniformity, the over-all electric field appears to be composed of a doubly infinite series of spatial harmonic components each having the same frequency but each having a phase velocity of propagation different from that of any other component in the series. By matching the velocity of the electron stream with the phase velocity of one of these components, it is possible to extract kinetic energy from the electrons, which is a condition for wave amplification, even though the phase velocity of the fundamental

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component of the electromagnetic wave is much greater than the velocity of the electron stream.

In accordance with the present invention, a number of spatial harmonic circuits are disposed circularly within a conductively bounded wave guiding passage in such a way that they can be used in conjunction with an electromagnetic wave propagating within the guide in the fundamental transverse electric circular mode. (This mode is commonly designated TE_{01} and its field configuration is shown in "Fields and Waves in Modern Radio" by Ramo and Whinnery, John Wiley, 1946, pages 338 and 339.) One or more electron streams can then be beamed in coupling relation to these circuits in order to produce wave amplification. Among the advantages of such an arrangement are structural ruggedness, increased power handling capacity, and ease of manufacture.

A more complete understanding of the general nature of the invention, together with a better appreciation of its numerous advantages, will best be gained from a study of the following detailed description given in connection with the accompanying drawings in which:

Fig. 1 is a perspective view of a first illustrative embodiment of the invention;

Fig. 2 is a cross section view of the embodiment of Fig. 1;

Fig. 3 is a fragmentary cross section view of a second illustrative embodiment of the invention;

Fig. 4 shows a modification of the embodiment of Fig. 3; and

Fig. 5 illustrates in longitudinal cross section an arrangement for beaming electrons past the embodiments of Fig. 1 of the invention and, in addition, shows one way of impedance matching into and out of this embodiment.

Referring now in detail to the drawings, Fig. 1 shows by way of illustration of the present invention a slow wave structure 10 comprising a number of spatial harmonic circuits 11 arranged circularly about the axis of a conductively bounded wave guiding passage of radius r_0 . This passage, together with the spatial harmonic circuits 11, is in this embodiment formed by a plurality of metal stampings or plates 12 having a thickness t and spaced a distance d between opposing surfaces. Plates 12 may be formed in any convenient way such as by photographic etching of a suitable conductor such as copper or gold plated molybdenum. The openings in them are made so that crescent shaped wedges or segments 13 are positioned in the region where, in the absence of the wedges, there would exist the maximum field intensity of a wave propagating in the fundamental circular transverse electric mode. Segments 13 are supported in place by struts 14 which connect them to the main body of the plates. Gaps 15 each having an angle θ between segments form an essential part of circuits 11 and it is in and around these gaps that the electric field of a wave propagating down structure 10 can have a relatively strong electric field component parallel to the direction of wave propagation. It is this component which is able to interact with one or more electron streams beamed in these regions. Any suitable means (not shown) may be used for generating the electron streams and for focusing them along paths in the vicinity of gaps 15. A suitable means is shown in the above-mentioned Millman application.

It should be noted that, while spatial harmonic circuits 11 are formed, in the embodiment shown in Fig. 1, by groups of segments 13 supported around openings in longitudinally spaced plates 12, these circuits may be formed by longitudinally spacing similar groups of segments of the same general configuration along the inside of a circular conducting wave guide. The spaced-plate

arrangement of Fig. 1, however, helps to maintain the purity of the TE_{01} mode by suppressing unwanted modes. In either structure though the number of longitudinally spaced segments used depends upon the amplification or gain required in the traveling wave tube utilizing them.

At each end of the embodiment of Fig. 1 some form of impedance matching to and from a cylindrical wave guide should generally be used. The way shown at the right end of structure 10 consists of tapering the area of segments 13 gradually from full size down to roughly zero size over a distance several guide wavelengths long. It should be understood, however, that this is not the only possible arrangement since others equally effective may be used instead. The left end of structure 10 has been shown for simplicity in Fig. 1 without any form of impedance matching.

When slow wave structure 10 is operated as a traveling wave tube, one or more electron streams can be beamed within an evacuated envelope lengthwise through the spaces provided by gaps 15 so that the electrons interact with an electromagnetic wave of proper configuration applied to the structure by such means as a hollow circular wave guide. The phase velocities of propagation of the spatial harmonic components of this wave along circuits 11 are determined principally by the physical dimensions of segments 13, gaps 15, distance d , and thickness t , and these velocities can be computed if desired by the method, now well known to the art, described in the above-mentioned patent. Alternatively, these velocities may be determined from the plot of the phase propagation constant β measured as a function of the frequency of the wave applied to circuits 11. As explained previously by matching one of these velocities with the velocity of an electron stream, energy can be transferred from the electrons to the traveling electromagnetic wave.

Electrons traveling longitudinally down circuits 11 in or near gaps 15 "see" substantially no longitudinal field as they pass directly over the conductive surfaces of segments 13 (since there can be no electric field tangential to a metal surface) while when passing between plates 12 they "see" a strong longitudinal electric field. This alternate passage from drift space to interaction space is analogous to a stroboscopic light flashing on a patterned wheel, the duration of each flash corresponding to the time the electrons are in the reaction space between plates 12, the interval between flashes corresponding to the time it takes an electron to go from the beginning of one plane surface of a plate 12 to the beginning of the next plane surface, i. e. the distance $t+d$, and the angular velocity of the wheel corresponding to the phase velocity of the fundamental spatial harmonic component of the traveling wave. For a given wheel velocity there will be several discrete stroboscopic frequencies at which the wheel appears stationary and each of these apparent non-rotations of the wheel corresponds to synchronism between a spatial harmonic component of the wave propagating along circuits 11 and the electrons. In this synchronous condition a single electron "sees" the same electric field vector as it passes through each region between plates 12. Thus the requirement for electromagnetic-wave electron-stream interaction is met by, in effect, "fooling the electrons."

By assuming that the group velocity of the wave propagating down the structure is opposite to the velocity of electron flow, it can be seen, following the above analogy, that the electrons can be synchronized with the spatial harmonic component of the wave having a negative phase velocity relative to the group velocity. When such conditions actually exist in a spatial harmonic tube, electromagnetic power flows from the collector end to the gun end of the tube. This mode of operation, useful for amplification up to a critical value of beam current, is likewise useful for obtaining oscillations beyond this critical value since the necessary feedback path for sustaining

the oscillations is then automatically provided by the electron stream.

Fig. 2 is a cross sectional view of structure 10. Members 13 and 14 are disposed symmetrically around the circular opening of radius r_3 in plate 12. The number of segments 13 in each plate group depends upon a number of factors such as the power handling capacity desired or the over-all diameter ($2r_3$) required. In general, it is probably desirable to use a prime number, such as the five shown, in order to minimize the danger of individual circuits working together in sub-groups and producing outputs at the end of the tube that differ in phase or frequency. The physical and electrical relations of these circuits to each other in the arrangement shown, however, are by themselves important factors in reducing this danger since all parts of the circuit are tied together by virtue of the existence of a single mode wave.

Area 21 in Fig. 2 indicates the cross section and position of an electron stream which can be beamed through and around gaps 15. Areas 22, 23, and 24 indicate the cross sections and positions of alternative electron streams which can be accommodated by properly slotting or aperturing wedges 13 as shown here but not shown in Fig. 1.

In an experimental model substantially the same as that illustrated in Figs. 1 and 2, in which $r_3=1$ inch, r_2 , r_1 , and θ bear the same relation to r_3 as shown in Fig. 2, $t=0.075$ inch and $d=0.034$ inch, an electron stream accelerating voltage of approximately 1200 volts was found to be sufficient to synchronize the electrons with a 9000 megacycle wave propagating down the structure.

Fig. 3 is a second illustrative embodiment of the invention shown in partial cross section in which a slow wave structure 30, substantially the same in principles of construction and in operation as the embodiment in Fig. 1, is formed by a plurality of wire loops 31 and 32 supported symmetrically by struts 34 and 35, respectively, around circular openings of radius r_1 in plates 33. Plates 33 are spaced longitudinally in the same way as plates 12 are spaced in Fig. 1. In this embodiment, however, every other plate 33 is rotated angularly ϕ degrees with respect to the adjacent plates so that groups of loops 31 in one plate and groups of loops 32 in a different plate will be displaced relative to each other as shown, thereby forming spatial harmonic circuits of the interdigital type. In such circuits the phase shift of the electric field between successive discontinuities, such as between a loop 31 and a loop 32 adjacent thereto, is approximately π radians over a considerable frequency range and this constant phase shift is the cause of the wide operating bandwidth of a backward mode interdigital type traveling wave tube. When the structure of Fig. 2 is used as an amplifier or oscillator one or more electron streams may be beamed through the dotted areas 36.

Fig. 4 shows a variation of the structure shown in Fig. 3. Here a group of posts or fingers 41 lying in the plane of one plate 42 is rotated angularly with respect to a group 43 lying in the plane of an adjacent plate 42. Electrons may be beamed through areas 44. Impedance matching can most easily be accomplished by tapering the lengths of post 41 instead of their widths as was done with segments 13 in Fig. 1. This arrangement has the advantage of structural simplicity.

Fig. 5 shows a portion of the longitudinal cross section taken as indicated by lines 5—5 in Fig. 1, of a traveling wave tube 50 embodying slow wave structure 10. One or more electron guns 51 located around the outside of circular wave guide 52 beam electrons lengthwise down the paths indicated by area 21 in Fig. 2. Collector electrodes (not shown) may be similarly located at the other end of the tube. An alternative to the use of guns 51 lies in the use of cathodes coated directly upon the first few of segments 13. A tapered length of guide 53 extending over a length which can be roughly two guide wavelengths long serves to match the impedance of guide 52

to that of structure 10. A similar tapered section may be used at the opposite end although for convenience this has not been shown.

Structure 10 is arranged so that electron beam focusing can be accomplished in any one of several different ways in addition to focusing by the customary uniform longitudinal magnetic field. Focusing is caused here by the periodic direct voltage electric field existing in the region between plates 12. The optimum intensity of this field for most efficient focusing can be easily found by varying voltage source 54 which is connected between plates 12 in the way shown. Periodic magnetic focusing can be achieved in an analogous way by inserting permanent magnets in the openings between plates 12.

When tube 50 is operating as a forward mode spatial harmonic amplifier, wave energy in the proper mode which may be obtained directly from a circular wave guide propagating a TE_{01} wave or through appropriate transducers, from other guides is applied to structure 10 via guide 52. The amplified signal may then be extracted at the other end of structure 10 by any appropriate means. When operating in a backward wave mode, wave energy is extracted from tube 50 via guide 52.

While the foregoing will serve to illustrate the pertinent details of the present invention, it is not intended as a complete exposition of all possible embodiments which can be devised according to the principles set forth. Various modifications and changes in the geometry or physical relations of structure 10 or 30 and in the ways of utilizing these structures will occur to those skilled in the art and may be made without departing from the spirit or scope of the invention.

What is claimed is:

1. In combination, means forming a path of electron flow, a wave interaction circuit for propagating electromagnetic wave energy in coupling proximity with said electron flow, said wave interaction circuit comprising a plurality of conductive members arranged in spaced succession along said path of flow and insulated from each other, each conductive member being substantially transverse to said electron path and including a plurality of conductive segments circumferentially spaced around said electron path.

2. The combination of elements as in claim 1 in which the conductive segments are sectors of a solid metallic annulus.

3. The combination of elements as in claim 1 in which the conductive segments are metallic wire loops.

4. The combination of elements as in claim 1 in which the conductive segments are radially extending metallic posts.

5. In combination, means forming a path of electron flow, a wave interaction circuit for propagating electromagnetic wave energy in coupling proximity with said electron flow, said wave interaction circuit comprising a plurality of conductive members arranged in spaced succession along said path of flow, each conductive member being substantially transverse to said electron path and including a plurality of conductive segments circumferentially spaced around said electron path, and focusing means including a voltage source for maintaining alternate conductive members of the succession at the same potential and adjacent conductive members at a different potential.

6. In a device which utilizes the interaction between an electron beam and an electromagnetic wave, means defining a path of electron flow, an interaction circuit for propagating electromagnetic wave energy in coupling proximity with said electron flow, said interaction circuit comprising a spaced succession of conductive members along the electron path, each conductive member being transverse to said electron path and including a plurality of substantially uniform conductive segments circumferentially spaced around said path, a coupling connection

comprising a circular hollow wave guide for propagating energy in the circular electric mode, and a wave guiding transition section interposed between said wave circuit and said hollow wave guide for propagating electromagnetic energy therebetween, said transition section comprising a spaced succession of conductive members, each conductive member comprising a plurality of circumferentially disposed conductive segments, the dimensions of said segments increasing along the wave transition section in the direction from the hollow wave guide to the interaction circuit.

7. In combination, an interaction circuit comprising wave guiding means for propagating electromagnetic wave energy along an axis substantially in the fundamental transverse circular electric mode, said means comprising a spaced succession of conductive members insulated from one another along said axis each of said members having a plurality of radial slots therein, and means for generating an electron beam and projecting said beam through said radial slots.

8. In combination, a coupling connection comprising a circular hollow wave guide for propagating an electromagnetic wave along an axis in the fundamental transverse circular electric mode, a wave guiding transition section coupled to said coupling section comprising radially extending conductive means for confining the electromagnetic wave energy into sectoral regions, said radially extending conductive means comprising a succession of groups of radially extending conductive elements, each group lying in a plane transverse to said axis and spaced apart from adjacent groups of said succession in a direction parallel to said axis, the angle subtended by said radially extending members increasing along the length of said transition section, interaction circuit means coupled to said transition section, said interaction circuit comprising a succession of groups of radially-extending substantially uniform conductive elements, each group lying in a plane transverse to said axis and spaced apart from adjacent groups of said succession in a direction parallel to said axis, and means for projecting a beam of electrons parallel to said axis for interaction with the wave energy passing along said interaction circuit means.

9. A traveling wave tube amplifier for amplifying energy in the fundamental transverse circular electric mode comprising electrodes spaced apart for defining therebetween a path of electron flow, wave interaction means positioned along said path of electron flow for propagating electromagnetic wave energy in coupling proximity with said electron flow, said interaction circuit comprising a succession of groups of conductive members along an axis parallel to said path of flow, each group lying in a plane transverse to the path of electron flow and spaced apart from adjacent groups of said succession along said axis, and the conductive members of each group being uniform and circumferentially spaced about said axis, a circular hollow wave guide coupling connection to said traveling wave tube amplifier, and impedance matching means for coupling wave energy between said circular hollow wave guide and the interaction circuit, said impedance matching means comprising a succession of groups of conductive members along the axis of the circular hollow wave guide, each group lying in a plane transverse to said wave guide axis and spaced apart therealong, the conductive members of each group being circumferentially spaced about said wave guide axis, and the angle subtended by the conductive members increasing along said succession away from the circular hollow wave guide.

10. In an interaction device for amplifying energy in the fundamental transverse circular electric mode a section of circular hollow wave guide, an impedance matching section axially aligned with said section of circular hollow wave guide for receiving wave energy therefrom, an interaction circuit positioned along the same axis and forming a continuation of the impedance matching sec-

tion for receiving wave energy therefrom, and means for defining a path of electron flow along the length of the interaction circuit and substantially parallel to said axis in coupling proximity to the wave energy propagating along the interaction circuit, said interaction circuit comprising a succession of groups of conductive elements, the conductive elements of each group circumferentially arranged about the axis and successive groups spaced apart along the axis, and the impedance matching section comprising a like succession of groups of conductive elements wherein the angle subtended by the circumferentially arranged conductive elements increases along the axis of the impedance matching section from the circular hollow wave guide section to the interaction circuit.

11. In combination, interaction circuit means for propagating along an axis an electromagnetic wave substantially in the fundamental transverse circular electric mode, said means comprising a linear array of groups of conductive elements, each group lying in a plane transverse to said axis and successive groups spaced apart

along the axis, impedance matching means positioned along the axis of propagation of said fundamental transverse circular electric mode, and means for projecting an electron beam in coupling proximity to said interaction circuit and substantially parallel to said axis.

12. The combination as in claim 11 in which the conductive elements are sectors of a solid metallic annulus.

13. The combination as in claim 11 in which the conductive elements are metallic wire loops.

14. The combination as in claim 11 in which the conductive elements are radially extending metallic posts.

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