Feb. 21, 1967 H. A. C. HOGG 3,305,749

ELECTRON DISCHARGE DEVICE HAVING PLURAL ELECTRON BEAMS, SLOW WAVE STRUCTURES, AND R.F. SIGNALS, EACH SIGNAL INTERACTING WITH A PLURALITY OF BEAMS

Filed May 6, 1963 2 Sheets-Sheet 1

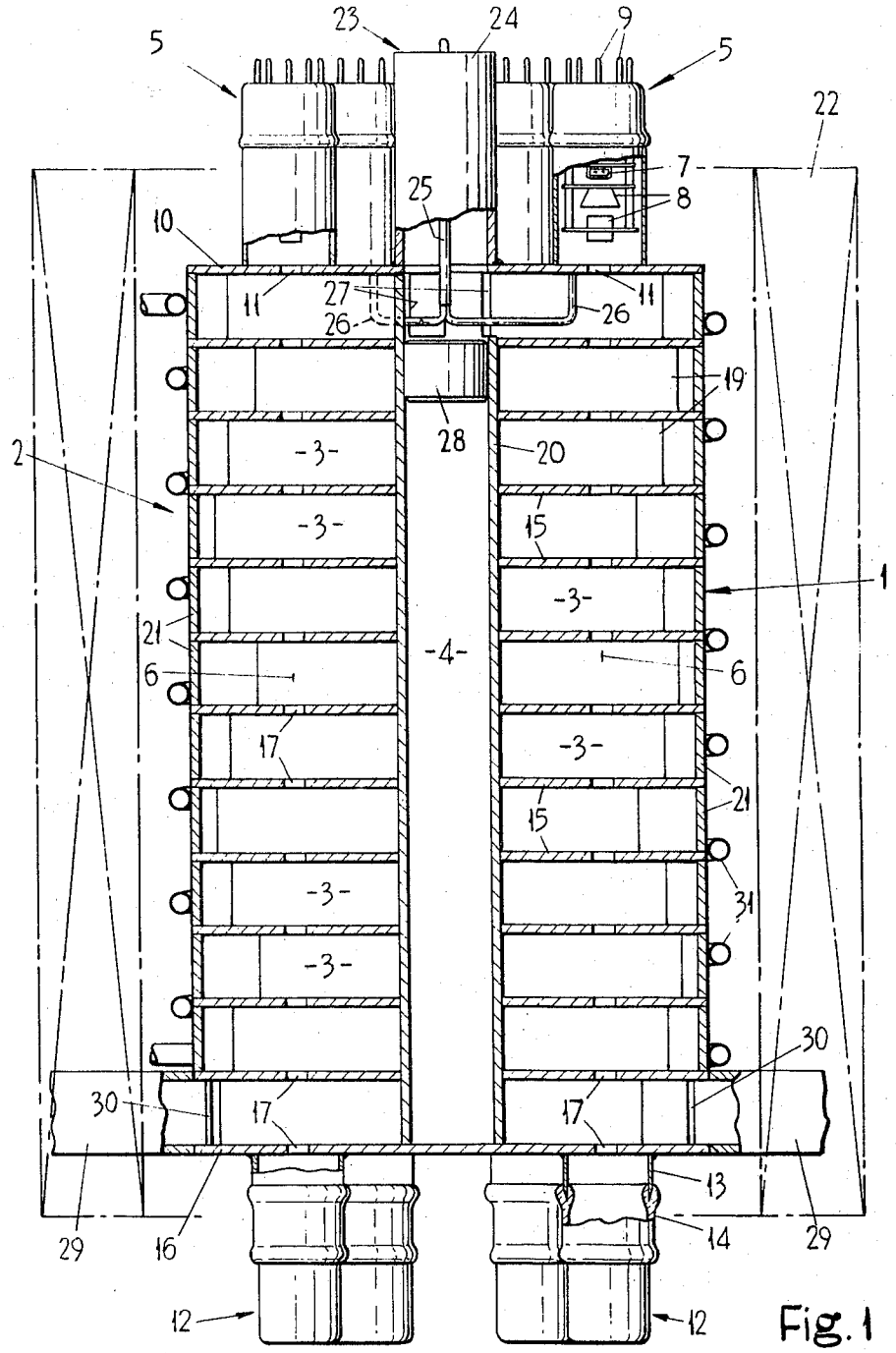


Fig. 1

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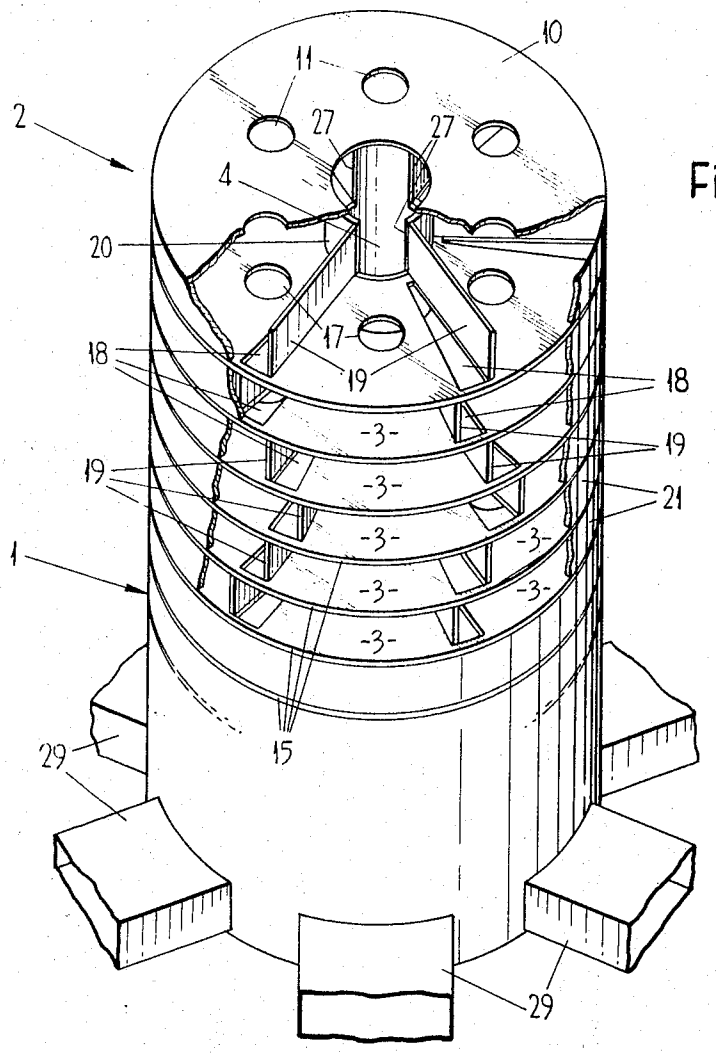


Fig 2

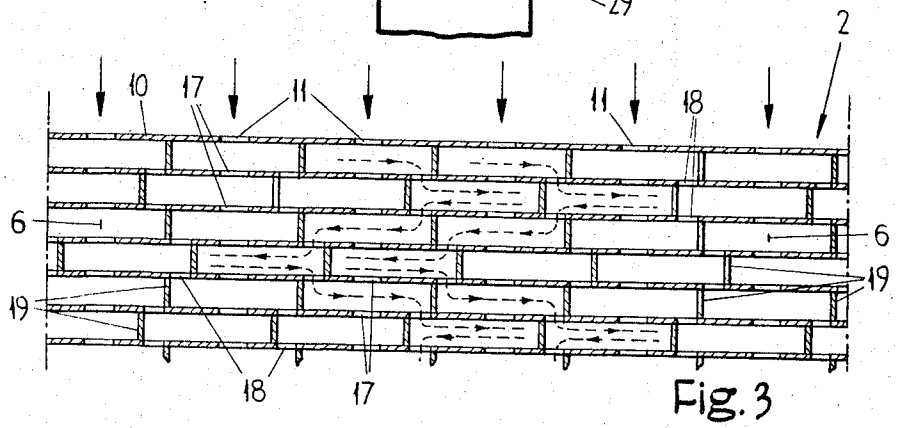


Fig. 3

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ELECTRON DISCHARGE DEVICE HAVING PLURAL ELECTRON BEAMS, SLOW WAVE STRUCTURES, AND R.F. SIGNALS, EACH SIGNAL INTERACTING WITH A PLURALITY OF BEAMS

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This invention relates to electric discharge devices of the kind having an interaction circuit in which, in operation, interaction takes place between radio frequency energy propagated along a slow wave structure incorporated in the device and the electrons of at least one electron beam arranged to travel through the interaction circuit.

It is an object of the present invention to provide an electric discharge device of the kind specified which is capable of operating at very high power levels.

According to the present invention, an electric discharge device comprises: an interaction circuit including at least two slow wave structures which extend alongside each other and along which electromagnetic waves are arranged to be propagated respectively in operation, each slow wave structure being formed by a sequence of hollow waveguide sections arranged end to end with their axes parallel to each other and with each adjacent pair of wave guide sections coupled together and in non-alignment, each waveguide section of each slow wave structure having substantially parallel end walls arranged perpendicular to the axis of the section and being adapted to operate in a mode such that there are strong axial electric fields at the center of the section and strong transverse magnetic field loops near the periphery of the section, and the axes of all the waveguide sections of the slow wave structures being parallel to each other; and at least two electron guns each of which is arranged to project an electron beam through the interaction circuit in a direction parallel to the axes of the waveguide sections, each electron beam passing in operation through a series of waveguide sections which series is different for each beam and is constituted by waveguide sections included in at least two slow wave structures, and each beam passing through an approximately central region of each waveguide section of the relevant series via holes formed in the end walls of the section; the arrangement being such that in operation each waveguide section of each slow wave structure has an electron beam passing through it, and each electromagnetic wave interacts with at least two electron beams and each electron beam interacts with at least two electromagnetic waves in such a manner that the electromagnetic waves are locked together in a fixed phase relationship with respect to each other as they are propagated along the interaction circuit.

According to one aspect of the invention, in an electric discharge device in accordance with the immediately preceding paragraph, each adjacent pair of waveguide sections of each slow wave structure overlap each other over a relatively narrow region contiguous with the peripheries of the sections, and are coupled together by means of a slot disposed in the overlapping region.

According to a further aspect of the invention, an electric discharge device in accordance with either of the last two preceding paragraphs includes radio frequency input means connected to that end of the interaction circuit adjacent the electron guns, and radio frequency output means for respectively extracting output signals from those end waveguide sections of the slow wave structures remote from the electron guns.

One arrangement in accordance with the invention will

now be described by way of example with reference to the accompanying drawings, in which:

FIGURE 1 is a part sectional side elevation of a travelling wave tube adapted to operate as a forward wave amplifier at frequencies in the range 4000 to 6000 megacycles/second;

FIGURE 2 is a perspective view, partly broken away, illustrating the interaction circuit of the travelling wave tube; and

FIGURE 3 is a developed sectional view of part of the interaction circuit, the section being taken through the axes of the channels for the electron beams.

Referring first particularly to FIGURE 1 of the drawings, the travelling wave tube includes an evacuated envelope **1** part of which forms the outer wall of an interaction circuit **2** comprising six interleaved slow wave structures through which six electromagnetic waves are arranged to be respectively propagated in operation. The interaction circuit **2** is in the form of an elongated circular cylindrical structure which is split up into a large number of hollow waveguide sections **3** as will be explained later, the interaction circuit **2** having an outside diameter of the order of 10 centimeters and a length of the order of 20 centimeters; a circular cylindrical hole **4**, about 2 centimeters in diameter, extends coaxially along the whole length of the interaction circuit **2**.

The travelling wave tube also includes six electron guns **5** (only four of which are seen in FIGURE 1) which are mounted in the envelope **1** adjacent one end of the interaction circuit **2** and which are arranged to project six electron beams in the same direction respectively through six channels **6** which each extend along the whole length of the interaction circuit **2**, the axes of the channels **6** being arranged at equal intervals around the axis of the interaction circuit **2**. Each electron gun **5** includes a cathode **7** and two grids **8**, electrical contacts **9** for the various electrodes of each gun **5** being sealed through the relevant part of the envelope **1**. An annular anode plate **10** having six circular apertures **11** through which the electron beams respectively pass in operation is interposed between the electron guns **5** and the adjacent end of the interaction circuit **2**, the anode plate **10** constituting the relevant end wall of the interaction circuit **2**; the apertures **11** are all 0.4 centimeter in diameter, and the centers of the apertures **11** all lie on a circle which is concentric with the annular plate **10** and which is disposed midway between the inner and outer peripheries of the plate **10**, the apertures **11** being spaced apart at equal intervals. Six collector electrodes **12** (only four of which are seen in FIGURE 1), one for each beam, are disposed at that end of the interaction circuit **2** remote from the electron guns **5**. Each collector electrode **12** is sealed to a tubular extension **13** of the interaction circuit **2** by means of a tubular glass seal **14**, that end of the relevant channel **6** remote from the electron guns **5** opening into the tubular extension **13**.

The interaction circuit **2** will now be described in more detail. The interaction circuit **2** is split up into segments along the whole of its length by means of annular metal plates **15** which are arranged with their main faces perpendicular to the axis of the interaction circuit **2** and which are spaced apart by equal intervals, each adjacent pair of annular plates **15** being spaced about one centimeter apart; the outer periphery and inner periphery of each annular plate **15** are respectively in register with the outer periphery of the interaction circuit **2** and the periphery of the cylindrical hole **4**. That end wall of the interaction circuit **2** remote from the electron guns **5** is formed by a disc-like plate **16**. Six circular apertures **17**, each about 0.4 centimeter in diameter, are formed in each of the plates **15** and **16**, the centers of the apertures **17** all lying on a circle which is concentric with the relevant

plate 15 or 16 and which is disposed midway between the inner and outer peripheries of the plate 15 or 16, and the apertures 17 being spaced apart at equal intervals. The apertures 17 in each of the plates 15 and 16 are respectively aligned with the apertures 11 formed in the anode plate 10, and the electron guns 5 are arranged to project the six electron beams respectively through the six series of apertures 11 and 17; thus, it will be appreciated that each series of apertures 11 and 17 serves to define the relevant channel 6.

Referring now particularly to FIGURES 2 and 3, the plates 15 also each have formed in them six radially extending slots 18, each slot 18 extending for the major part of the distance between the inner and outer peripheries of the relevant plate 15 and being generally in the form of a sector of a circle having an angular width of the order of 10 degrees; each slot 18 is disposed between an adjacent pair of the apertures 17 formed in the relevant plate 15, and the six slots 18 formed in each plate 15 are spaced at equal intervals around the plate 15.

Each segment of the interaction circuit 2 is divided into six equal sectors by means of six metal vanes 19 which are arranged with their main faces parallel to the axis of the interaction circuit 2 and which extend radially between an inner circular cylindrical metal member 20 and one of a number of outer circular cylindrical metal members 21; the outer surface of each member 21 forms part of the outer curved surface of the interaction circuit 2, while the inner surface of the member 20 forms part of the bounding surface of the cylindrical hole 4. Each such sector forms a hollow waveguide section 3.

The arrangement of the slots 18, apertures 17 and vanes 19 associated with each segment of the interaction circuit 2 will now be described with particular reference to FIGURE 2. Considering the first segment of the interaction circuit 2 (that is to say the segment bounded by the anode plate 10 and by that annular plate 15 nearest the electron guns 5) each of the apertures 17 in the relevant plate 15 is centrally disposed with respect to an adjacent pair of the vanes 19, while the slots 18 in this plate 15 are respectively arranged contiguous with, and on corresponding sides of, the vanes 19; the axis of each slot 18 is displaced in a clockwise sense (considering that end of the interaction circuit 2 nearer the electron guns 5 as the front end of the circuit) relative to the adjacent vane 19. With regard to the second segment, the vanes 19 of the segment are displaced slightly in a clockwise sense relative to the vanes 19 of the first segment, the arrangement being such that each slot 18 of the first annular plate 15 (that is to say the first annular plate 15 from that end of the interaction circuit 2 adjacent the electron guns 5) is contiguous on one side with a vane 19 of the first segment and is contiguous on the other side with a vane 19 of the second segment; it will be appreciated that the centers of the apertures 17 in the two plates 15 bounding the second segment of the interaction circuit 2 are each offset slightly from the central radius of the relevant waveguide section 3. The slots 18 formed in the second annular plate 15 (which forms one of the bounding plates of the second segment of the interaction circuit 2) are in register with the slots 18 formed in the first plate 15, and thus the axis of each slot 18 of the second plate 15 is displaced in an anti-clockwise sense relative to the adjacent vane 19 of the second segment. Considering now the third segment of the interaction circuit 2, the vanes 19 of this segment are displaced slightly in an anti-clockwise sense relative to the vanes 19 of the second segment by such an amount that the vanes 19 of the third segment are aligned with the vanes 19 of the first segment. The slots 18 formed in the third plate 15 are arranged contiguous with, and on corresponding sides of, the vanes 19 of the third segment, the axis of each of these slots 18 being displaced in an anti-clockwise sense relative to the adjacent vane 19. With regard to the fourth segment of the interaction circuit 2, the vanes 19 of this segment are displaced slightly in an anti-clockwise sense relative to the vanes 19 of the third segment by an amount equal to that by which the vanes 19 of the third segment are displaced relative to the vanes 19 of the second segment. The slots 18 formed in the fourth plate 15 are in register with the slots 18 formed in the third plate 15, and thus the axis of each slot 18 of the fourth plate 15 is displaced in a clockwise sense relative to the adjacent vane 19 of the fourth segment. Each successive group of four segments of the interaction circuit 2 is arranged in a similar manner to that in which the first four segments are arranged, the vanes 19 of the fifth segment being in register with the vanes 19 of the first segment, the vanes 19 of the sixth segment being in register with the vanes 19 of the second segment, and so on; similarly, it will be appreciated that the slots 18 in the fifth plate 15 are in register with the slots 18 in the first plate 15, the slots 18 in the sixth plate 15 are in register with the slots 18 in the second plate 15, and so on.

As stated above, each sector of each segment of the interaction circuit 2 forms a hollow waveguide section 3, the axis of each section 3 being parallel to the axis of the interaction circuit 2 and the end walls of the section 3 being formed by the pair of the plates 10, 15 and 16 bounding the relevant segment of the interaction circuit 2; each waveguide section 3 is of such dimension as to operate in a mode such that there are strong axial electric fields at the center of the section 3 and strong transverse magnetic field loops near the periphery of the section 3.

Referring now particularly to FIGURE 3 of the drawings, each waveguide section 3 of one segment of the interaction circuit 2 is coupled to a waveguide section 3 of the next segment of the interaction circuit 2 by means of one of the slots 18 formed in the annular plate 15 separating these two sections of the interaction circuit 2; it will be appreciated that each pair of waveguide sections 3 which are coupled together in this manner overlap each other over a relatively narrow region only. Thus, the interaction circuit 2 comprises six distinct slow wave structures along which six electromagnetic waves (two of which are indicated by two series of arrowed dotted lines in FIGURE 3) may be respectively propagated, the structures each consisting of a sequence of waveguide sections 3 which are arranged end to end in such a manner that the structures all meander in a similar manner along the whole length of the interaction circuit 2. It will be appreciated that in operation each waveguide section 3 of each slow wave structure has an electron beam passing through it and that each electromagnetic wave interacts with three electron beams (the direction of travel of all the electron beams being indicated by the arrowed solid lines in FIGURE 3).

It should be understood that there is some electric coupling between each adjacent pair of waveguide sections 3 of each series of waveguide sections 3 through which any particular electron beam passes due to the presence in the plates 15 of the circular apertures 17 through which the beam passes, but this electric coupling is less than the magnetic coupling discussed above; the nature of the electric coupling is such that it enhances the overall coupling between waveguide sections 3 of each slow wave structure.

The travelling wave tube is provided with focusing means for inhibiting dispersion of the electron beams as they travel along the length of the interaction circuit 2, such means taking the form of a solenoid 22 (schematically indicated in FIGURE 1) surrounding the envelope 1 and arranged coaxially with the interaction circuit 2 so as to provide in operation a magnetic field directed parallel to the axis of the interaction circuit 2.

The travelling wave tube also includes a radio frequency input connection and a radio frequency output connection for the interaction circuit 2. The input connection comprises a coaxial line 23 one end of the outer conductor 24 of which effectively forms a continuation of the

cylindrical member **20**, while the corresponding end of the inner conductor **25** of the coaxial line **23** divides into three separate conductors **26** which are respectively adapted to excite in-phase electromagnetic waves in alternate waveguide sections **3** of the first segment of the interaction circuit **2**; the conductors **26** respectively pass through three apertures **27** formed in the adjacent end of the cylindrical member **20**, and those ends of the conductors **26** remote from the inner conductor **25** are electrically connected to the anode plate **10**. A metal closure member **28** is fitted in the cylindrical member **20** in the region of the second segment of the interaction circuit **2**, with one face substantially in register with the first annular plate **15**. It will be appreciated that three in-phase eletromagnetic waves will be respectively propagated along alternate slow wave structures corresponding to the three waveguide sections **3** in which are disposed the conductors **26**. Also, by virtue of the interleaved arrangement of all the slow wave structures, three further electromagnetic waves are spontaneously excited in, and propagated along, the other slow wave structures, these further electromagnetic waves being locked in a fixed phase relationship with respect to the first mentioned electromagnetic waves by virtue of the fact that they are coupled to the first mentioned electromagnetic waves via the electron beams; it would appear that in fact the further electromagnetic waves are in antiphase with the first mentioned electromagnetic waves.

The output connection is arranged to extract a combined output signal from those ends of the slow wave structures remote from the electron guns **5**, and comprises six waveguides **29**. The waveguides **29** are respectively coupled to the waveguide sections **3** of the last segment of the interaction circuit **2** via six apertures **30** formed in the outer cylindrical member **21** of this last segment, the waveguides **29** being each coupled with a common output waveguide (not shown) and the arrangement being such that the electromagnetic waves propagated in operation along the waveguides **29** are all in phase as they enter the common output waveguide; ceramic windows (not shown) are respectively sealed inside the waveguides **29**.

Means are provided in the travelling wave tube for cooling the interaction circuit **2**, such means taking the form of a coiled pipe **31** which surrounds the interaction circuit **2** and through which water is passed in operation.

In operation, a potential difference of the order of 20 kilovolts is applied between the anode plate **10** (which is electrically connected to the interaction circuit **2**) and the cathodes **7** of the electron guns **5**, and the electromagnetic wave propagated along each slow wave structure interacts with the relevant three electron beams in such a manner that the beams give up energy to the wave and thereby bring about amplification of the wave as it travels along the slow wave structure.

The travelling wave tube described above is capable of producing an output signal of very high power, typical values being a peak power of the order of 10 megawatts and a mean power of the order of 200 kilowatts.

It should be understood that the present invention provides an electric discharge device of the kind specified in which, in operation, more than one electromagnetic wave interacts with more than one electron beam in such a manner that the electromagnetic waves are all coupled together and thereby locked in a fixed phase relationship with respect to each other along the whole length of the interaction circuit so that, after passing through the interaction circuit, the individual electromagnetic waves can be combined to form a common output signal having greatly increased power. It should be understood that this ability to lock the phases of several individual electromagnetic waves and then combine these waves to form a common output signal is an important factor in enabling the travelling wave tube described above to produce a very high output power without imposing excessive requirements on the velocity and current density of the electron beams.

Also, another important factor in enabling the travelling wave tube described above to have a very high output power is that the slow wave structures of the device have a rugged form of construction from which heat may be readily dissipated in operation.

I claim:

1. An electric discharge device having:

(A) an interaction circuit including

(I) at least two slow wave structures along which electromagnetic waves are arranged to be propagated respectively in operation;

(II) each slow wave structure being formed by a sequence of hollow wave guide sections,

(a) each of which waveguide sections has substantially parallel end walls which extend perpendicular to the axis of the section; and

(b) each of which sections is of such dimensions as to operate in a mode such that there are strong axial electric fields at the center of the section and strong transverse magnetic loops near the periphery of the section,

(c) the waveguide sections of each sequence being disposed end to end with adjacent sections coupled together and disposed with their axes parallel, but in non-alignment, so that adjacent waveguide sections in each sequence only partially overlap;

(III) the slow wave structures being disposed alongside one another

(a) with the axes of all the waveguide sections parallel, and

(b) the waveguide sections of the different slow wave structures interleaved so that each wave guide section in each slow wave structure partially overlaps a waveguide section in another slow wave structure,

(c) thereby forming at least two different series of partially overlapping waveguide sections;

(IV) each said series thus being constituted by waveguide sections included in at least two slow wave structures and

(V) each said slow structure being constituted by waveguide sections included in at least two said series; and

(B) at least two electron guns

(I) each of which is arranged to project an electron beam through a different said series of waveguide sections in a direction parallel to the axes of the waveguide sections so that each electromagnetic wave interacts with and thereby couples at least two electromagnetic waves;

(II) each electron beam passing through an approximately central region of each waveguide section of the relevant series via holes formed in the end walls of the section, and

(III) every waveguide section having an electron beam passing through it so that by virtue of the couplings between electron beams and electromagnetic waves, each electromagnetic wave is coupled to every other electromagnetic wave

(IV) whereby the electromagnetic waves are locked together in a fixed phase relationship with respect to one another as they are propagated along the interaction circuit.

2. An electric discharge device according to claim **1**, in which each adjacent pair of waveguide sections of each slow wave structure overlap each other over a relatively narrow region contiguous with the peripheries of the sections, and are coupled together by means of a slot disposed in the overlapping region.

3. An electric discharge device according to claim **1**, including radio frequency input means connected to that end of the interaction circuit adjacent the electron guns,

and radio frequency output means for respectively extracting output signals from those end waveguide sections of the slow wave structures remote from the electron guns.

4. An electric discharge device according to claim 1, in which the interaction circuit includes a generally cylindrical outer wall and incorporates an even number of slow wave structures, the axis of the interaction circuit is parallel to the axes of the waveguide sections, and the interaction circuit is partitioned along its length into a number of segments, each such segment being partitioned into compartments which correspond in number to the slow wave structures and which respectively form waveguide sections of all the slow wave structures by means of a corresponding number of dividing walls which extend generally radially with respect to said outer wall, the dividing walls of one segment of each adjacent pair of segments of the interaction circuit being offset with respect to the dividing walls of the other segment of the pair.

5. An electric discharge device according to claim 4, including radio frequency input means connected to that end segment of the interaction circuit adjacent the electron guns in such a manner that, with regard to any adjacent pair of the waveguide sections of this end segment, an electromagnetic wave is directly excited by means of said input means in one only of the adjacent pair of waveguide

sections, and radio frequency output means for extracting output signals from all the waveguide sections of that end segment of the interaction circuit which is remote from the electron guns.

6. An electric discharge device according to claim 5, including at least four slow wave structures, and in which said input means is adapted to excite in-phase electromagnetic waves in alternate waveguide sections of the relevant end segment of the interaction circuit.

7. An electric discharge device according to claim 1, including more than two slow wave structures, and in which the slow wave structures are arranged in such a manner that each electromagnetic wave interacts with at least three electron beams and each electron beam interacts with at least three electromagnetic waves.

8. An electric discharge device according to claim 1, including means for cooling the interaction circuit.

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