PATENT SPECIFICATION

(11) 1433 236

(21) Application No. 39710/73 (22) Filed 22 Aug. 1973

(44) Complete Specification published 22 April 1976

(51) INT CL[2] H01J 25/08

(52) Index at acceptance

H1D 18A1X 18A1Y 18AY 34 4A1 4A7 4B3B 4B3Y 4B5 4E1 4F6X 4F6Y 4K1 4K4

(19)

1433236

(72) Inventors GERSH ITSKOVICH BUDKER
SERGEI NIKOLAEVICH MOROZOV
OLEG ALEXANDROVICH NEZHEVENKO
GENNADY NIKOLAEVICH OSTREIKO
MARLEN MOISEEVICH KARLINER
IVAN GRIGORIEVICH MAKAROV and
ISAI ABRAMOVICH SHEKHTMAN

(54) IMPROVEMENTS IN OR RELATING TO ELECTRON DISCHARGE DEVICES

(71) We, INSTITUT YADERNOI FIZIKI SIBIRSKOGO OTDELENIA AKADEMII NAUK SSSR, a Corporation organised and existing under the laws of the Union of Soviet Socialist Republics of Novosibirsk, U.S.S.R., do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The invention relates to microwave devices.

According to the invention there is provided a microwave device comprising means for forming a charged-particle beam, beam-accelerating means for accelerating the beam to impart relativistic energies to the beam particles, a deflection system for circularly sweeping the accelerated beam at a predetermined frequency, and a travelling-wave annular resonator having annular slots in opposed end walls thereof to permit the ingress of the circularly-swept beam and egress of this beam into a collector of the resonator, the resonator being provided with means for extracting electromagnetic microwave power therefrom.

A microwave device embodying the invention will now be particularly described, by way of example, with reference to the accompanying drawings, in which:

Fig. 1 is a schematic diagram of the microwave device, a travelling-wave annular resonator of the device being shown in section;

Fig. 2 is a schematic diagram of the device with the annular resonator and an additional deflection system being shown in section;

Fig. 3 is a schematic diagram of the device, showing, in section, a modified form of travelling-wave annular resonator;

Fig. 4*a* is a section through an annular resonator having coaxial cylinders at its slot edges;

Fig. 4*b* is a diagram showing the approximate current distribution in the front and back walls of the resonator of Figure 4*a*;

Fig. 5*a* shows the arrangement of two directional power terminals of the device when the device is operating in a microwave amplification mode;

Figs. 5*b*, 5*c*, 5*d*, and 5*e* show respective arrangements of power terminals of the device when the device is operating in a frequency multiplication mode; and

Fig. 5*f* is a part-sectional plan view of a travelling-wave annular resonator with four power terminals arranged for operation of the device in the amplification mode.

As shown in Figure 1, the microwave device comprises means for forming a charged particles beam in the form of a particle gun 1 which produces an axially symmetric pencil beam of charged particles, and a sectionalized accelerating tube 2 for imparting relativistic energies to the particles, the tube 2 being disposed at the output of the gun 1 and supplied from a high-voltage rectifier 3.

The device may use any charged particles, but it can be most easily accomplished using electrons. The following description considers an embodiment of the device intended for work with electrons.

The electron gun 1, accelerating tube 2 and rectifier 3 form a relativistic electron source 4. Apart from these elements, the microwave device contains also a deflection system 5 for circular sweep of the electron beam. The system 5 is disposed along the axis of the accelerating tube 2 and subsequent to the latter in the beam travel direction. The deflection system 5 consists of two capacitors 6 with a mutual 90° spatial shift which are connected to an input signal source 7 through coaxial cable transmission lines 8.

Disposed subsequent to the deflection system 5 and coaxial with the latter is a travelling-wave annular resonator 9 for converting the kinetic energy of the particles into the energy of an electromagnetic field. The resonator 9 has end walls 10 and side walls 11, the end walls 10 being provided with axially symmetric annular slots 12 for passing the electron beam into the resonator 9 and exiting the beam out of the resonator 9 into a collector 13. The travelling-wave resonator 9 has a circular D.C. electromagnet 14 used to compensate for the radio-frequency magnetic field induced by the wave at a place of beam traversal through the resonator 9, and a directional coupler 15 for extracting microwave power (a means for microwave power extraction).

The form of the device shown in Fig. 2 comprises an additional deflection system 16 interposed between the deflection system 5 and the travelling-wave resonator 9 along the same axis. The additional deflection system 16 takes the form of a part-spherical capacitor having an inner electrode 17 and an outer electrode 18.

The additional deflection system 16 may be not only electrostatic, but also magnetic, for instance, taking the form of a thin magnetic lens (not shown) embracing the swept beam.

The Fig. 3 form of the device differs from that of Fig. 1 in that it has an annular resonator 9′ the front and back walls 10 of which are oriented perpendicularly to the path of particles in the circularly deflected beam, the side walls 11 being so shaped that the lines of force of the electric field induced by the travelling wave inside the resonator 9′ are perpendicular to the end walls 10 at places traversed by the beam particles travelling through the resonator 9′.

Fig. 4*a* is a sectional view of a form of the travelling-wave annular resonator 9 wherein in order to minimize a loss of the electromagnetic power, the annular slots 12 are arranged so that their centre lines coincide with the line along which there are no transverse radio-frequency electric currents passing over the inner surface of the resonator 9 (or so that they are coincident with the nodal lines of the radio-frequency current flowing transverse to the slots 12). Along the edges of the slots 12 are disposed coaxial cylinders 19 made of some conducting material which are electrically connected to the surface of the resonator 9 and serve as cut-off wave-guides.

Fig. 4*b* shows the magnitude of transverse current I flowing in the end walls 10 of the resonator 9 (shown in Fig. 4*a*).

Fig. 5*a* is a diagrammatic arrangement of two identical non-directional power terminals (A and B) mounted on the surface of the resonator 9 with an azimuth shift equal to one quarter wavelength ($\lambda_b/4$). The device illustrated in this figure acts as a power amplifier.

Figs. 5*b*, 5*c*, 5*d* and 5*e* show various arrangements of identical non-directional power terminals (A, B, C, D, E) with the device operating as a frequency multiplier (quadrupler). In Fig. 5*b*, two terminals A and B have a mutual azimuth shift of $\lambda_b/4$, in Fig. 5*c*, three terminals, A, B and C have a shift equal to $\lambda_b/3$ between adjacent terminals. In Fig. 5*d*, the resonator has four terminals A, B, C and D arranged in two pairs in the opposite quarters of the resonator and having a $\lambda_b/4$ shift in each pair. Fig. 5*e* shows a resonator with five terminals A, B, C, D and E arranged as follows: two terminals A and B in one quarter of the resonator 9 with a shift of $\lambda_b/4$, and three terminals —C, D and E in the adjacent quarter of the resonator 9 with a shift of $\lambda_b/3$ between adjacent terminals.

Fig. 5*f* is a plan view of the travelling-wave resonator 9 (arranged for operation of the device as a power amplifier) having four identical non-directional terminals 20 distributed through equal intervals along the circumference of the resonator 9. Each terminal 20 consists of a coupling slot 21 and a wave-guide 22 connected to a termination 23 (power consumer).

The device operates as follows.

The electron gun 1 (Fig. 1) producing an electron beam carries a voltage of 1—3 MV with respect to the last electrode of the sectionalized accelerating tube 2 which receives voltage from the rectifier 3. The electron beam generated by the electron gun and accelerated to relativistic energies enters the deflection system 5 which is excited from the input signal source 7. The input signal is divided in two parts and enters the deflection system 5 through the two transmission lines 8, the lengths of the lines being so selected that signals arriving at the capacitors 6 are 90° out of phase. Such a deflection system sets up a radio-frequency deflecting electric field with circular polarization and causes the electron beam to circularly scan the resonator.

After acceleration and scanning, the beam enters the travelling-wave annular resonator 9 through the axially symmetric slot 12 and builds up direct current passing through this resonator 9. Continuously varying its entry point into the resonator 9, the current excites a wave travelling, or rotating, in a circle. The dimensions of the resonator 9 are selected such that the natural frequency of the oscillations built up in the resonator is close to, or is a multiple of, the beam rotation frequency, and that the electric field associated with the travelling wave is perpendicular to the end walls 10 of the resonator 9. Voltage at the resonator 9 rises so that, if the Q-factor of the resonator is sufficiently high and coupling with the termination is properly adjusted, the voltage becomes close to the beam accelerating voltage. To avoid the deleterious effects from generation of secondary electrons, the particles that have given their energy to the electromagnetic field exit from the resonator through the other annular slot 12 into the collector 13. Useful power is extracted into the matched termination through the directional coupler 15.

Apart from the radio-frequency electric field, a magnetic field is also built up in the travelling-wave resonator 9. This field turns the particles in a direction opposite to that of wave propagation. The magnetic field is sufficiently large to turn the particles having a kinetic energy of 20—40% of the initial energy through an angle of 90° which limits the efficiency of the device to 60—80%. For compensation of the radio-frequency magnetic field, the resonator 9 has the D.C. electromagnet 14 which sets up a constant magnetic field offsetting the radio-frequency field at the place where the beam traverses the resonator 9.

To achieve high power outputs from the device it is necessary to reduce heating of its elements and increase its efficiency. This can be accomplished by making the paths of the charged particles parallel to the lines of force of the electric field set up by the travelling wave within the resonators 9; the form of the device shown in Fig. 2 causes the charged particles to travel such a path.

The relativistic electron beam derived from the source 4 enters the deflection system 5 where the electrons are deflected at a preset angle from the longitudinal axis. The velocity component perpendicular to the axis is proportional to the tangent of the deflection angle. On passing between the electrodes 17 and 18 of the part-spherical capacitor, the electron beam is deflected by the electric field of this capacitor by the same angle as during passage through the deflection system 5, but in the opposite direction. The beam then enters the travelling-wave resonator 9 parallel to the electric lines of force of the radio-frequency field associated with the travelling-wave. With properly selected operating characteristics of the resonator 9, the electrons are decelerated practically down to zero velocity, and the electronic efficiency of the device will then be limited by the second-order effects, for example, by the particle energy scatter and space charge.

The same desirable particle path can be produced by using a magnetic lens for the additional deflection system 16.

Another way of raising the efficiency of the device is the use of the form of the device shown in Fig. 3 in which the resonator 9′ has its end walls 10 arranged perpendicularly to the travel of the circularly-swept electron beam. The side walls 11 of this resonator are so inclined as to make the lines of force of the electric field of the resonator 9′ in the beam traversal area normal to the end walls 10. A required shape of the walls is determined easily either by computation on an electronic computer or by a simulation.

In this case, the electron beam enters the resonator 9′ also parallel to the electric lines of force of the radio-frequency field set up by the travelling wave. Here, too, the efficiency of the device is determined by the second-order effects.

When the microwave electron discharge device employs the form of resonator 9 shown in Fig. 4*a* in which the annular slots 12 thereof are arranged so that their centre lines coincide with the line along which there are no transverse electric currents, and in which coaxial conducting cylinders 19 are mounted at the edges of the slots 12, electromagnetic radiation from the resonator 9 is reduced as a result of which power loss and distortion of the particle paths is also reduced.

Since the line along which there are no transverse currents passes through the centre of the annular slot 12, practically no H_{11} waves are excited in the cylinders 19 which would be free to propagate along the coaxial line formed by the cylinders 19. On the other hand, E_{11} waves are attenuated sufficiently quickly. To prevent the Q-factor of the resonator 9 from going down by more than 5% on account of radiation, (as shown by calculations for slots of the width equal to 5—10% of the wavelength) a shift of the centre line of the annular slot 12 with respect to the line with no transverse electric currents must not exceed 7—10% of the width of the slot 12, while the height of the coaxial cylinders 19 must be comparable with the width of the slot 12.

Extraction of the radio-frequency power from the travelling-wave resonator 9 is effected through several identical non-directional terminals which are arranged along the azimuth of the resonator 9 so as to compensate for the deflected waves arising at the terminals in the travelling-wave resonator 9.

This is achieved as follows:

If the device is used for power amplification of the input signals, one wavelength is accommodated along the azimuth of the resonator and power is extracted through two or more terminals. Where two terminals are employed, these are shifted 90° with respect to each other along the azimuth of the resonator 9; where more than two terminals are used, they are equally spaced along the resonator azimuth. Fig. 5*a* illustrates schematically the arrangement of two power terminals (A and B) for extracting power from the resonator.

If the device is used for frequency multiplication, *n* wavelengths are accommodated along the resonator azimuth (where *n* is a frequency multiplication factor). Again, two or more terminals can be used for power extraction, these terminals being arranged at 90° of the desired output wave where there are two terminals (Fig. 5*b*) and, for example, being equally spaced along a wavelength where there are more than two terminals (Fig. 5*c*). The terminal arrangements shown in Figures 5*b* to *e* are for a device acting as a frequency quadrupler (n=4), the number of terminals (A, B, C, D, E) being determined by the amount of power to be extracted and consumer's requirements.

In the form of the resonator 9 shown in Fig. 5*f* power is extracted through four identical coupling slots 21 and then transmitted through the wageguides 22 to the termination 23. Thus, each coupler 20 extracts one quarter of the total power taken out of the resonator 9 into the termination 23.

It should be pointed out that apart from increasing power output and facilitating the operating conditions of the terminals, use of several identical non-directional terminals has the following additional advantages:

first, use of several power terminals makes it easier to distribute power for supply of several consumers, for example, when feeding multi-resonator accelerating systems of charged particle accelerators;

second, power extraction does not depend on the direction of wave propagation in the annular resonator;

third, when identical reflected waves arise in the terminations, no standing wave is built up in the resonator, whereas if power is extracted through a non-directional terminal power reflected from the termination causes a standing wave to appear in the annular resonator which leads to a non-uniform heat load on the collector.

The microwave device described hereinbefore provides high microwave power outputs and has high electronic efficiency (about 100%). The device can be used in radio systems and charged particle accelerators.

WHAT WE CLAIM IS:—

1. A microwave device comprising means for forming a charge-particle beam, beam-accelerating means for accelerating the beam to impart relativistic energies to the beam particles, a deflection system for circularly sweeping the accelerated beam at a predetermined frequency, and a travelling-wave annular resonator having annular slots in opposed end walls thereof to permit the ingress of the circularly-swept beam and egress of this beam into a collector of the resonator, the resonator being provided with means for extracting electromagnetic microwave power therefrom.

2. A device according to claim 1, in which the annular resonator is provided with means for creating a constant magnetic field to counteract the effect on the beam of the radio-frequency magnetic field set up by the travelling-wave present in the resonator during operation of the device.

3. A device according to claim 1 or claim 2, in which an additional deflection system is interposed between the first-mentioned deflection system and the annular resonator, the additional deflection system being operative during operation of the device to deflect the charged-particle beam such that the beam travels through the resonator perpendicularly to the end walls of the resonator.

4. A device according to claim 3, in which the additional deflection system comprises a magnetic lens.

5. A device according to claim 3, in which the additional deflection system comprises a part-spherical capacitor.

6. A device according to claim 1 or claim 2, in which the end walls of the annular resonator are perpendicular to the path of charged particles through the resonator, the side walls of the resonator being so shaped that the lines of force of the electric field associated with the travelling wave present in the resonator during operation of the device are parallel to the direction of movement of the charged particle beam where the beam passes through the resonator.

7. A device according to any one of the preceding claims, in which the annular resonator slots are so arranged that their circular centre lines are coincident with the imaginary lines on the inner surfaces of the resonator end walls across which no transverse radio-frequency currents would flow if no slots were present.

8. A device according to any one of the preceding claims, in which cylinders of conducting material are disposed around the edges of the slots and are electrically connected to the resonator end walls.

9. A device according to any one of the preceding claims, in which the said means for extracting electromagnetic microwave power comprises two identical non-directional power terminals disposed on the resonator surface and having a mutual azimuth shift equal to one quarter wavelength of the wave travelling in the resonator during operation of the device.

10. A device according to any one of claims 1 to 9, in which the said means for extracting electromagnetic microwave power comprises three or more identical non-directional power terminals disposed on the resonator surface with an azimuth shift relative to one another such that the terminals are uniformly distributed along a wavelength of the wave travelling in the resonator during operation of the device.

11. A microwave device, substantially as hereinbefore described with reference to Figure 1, Figure 2 or Figure 3 of the accompanying drawings.

12. A microwave device, substantially as hereinbefore described with reference to

Figure 1, 2 or 3 as modified by Figure 4 of the accompanying drawings.

13. A microwave device, substantially as hereinbefore described with reference to Figure 1, 2 or 3, or Figure 1, 2, or 3 as modified by Figure 4, and having power terminals arranged as illustrated in any one of Figures 5*a* to 5*f* of the accompanying drawings.

MATHISEN & MACARA,
Chartered Patent Agents,
Lyon House,
Lyon Road,
Harrow,
Middlesex, HA1 2ET,
Agents for the Applicants.

Printed for Her Majesty's Stationery Office, by the Courier Press, Leamington Spa, 1976.
Published by The Patent Office, 25 Southampton Buildings, London, WC2A 1AY, from which copies may be obtained.

1433236 COMPLETE SPECIFICATION

3 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 1

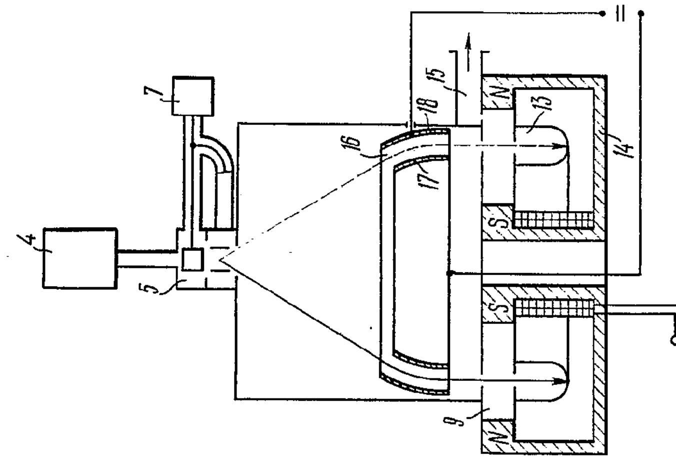

FIG.2

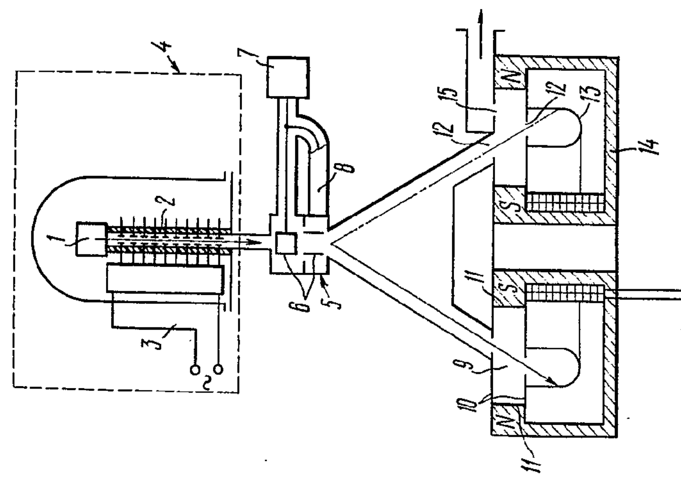

FIG.1

1433236 COMPLETE SPECIFICATION
3 SHEETS *This drawing is a reproduction of the Original on a reduced scale*
Sheet 2

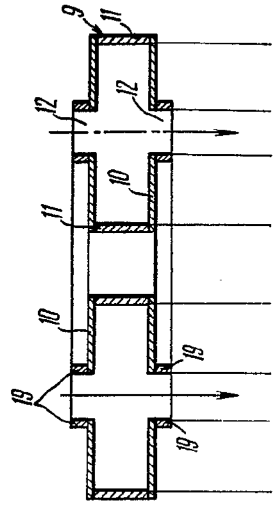

FIG. 4a

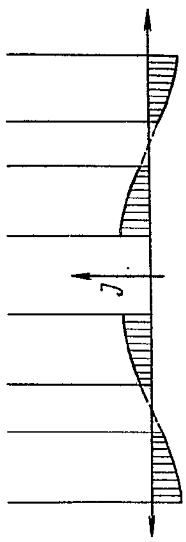

FIG. 4b

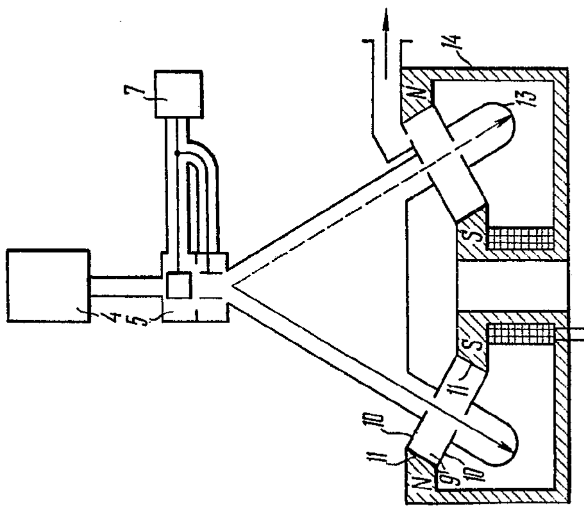

FIG. 3

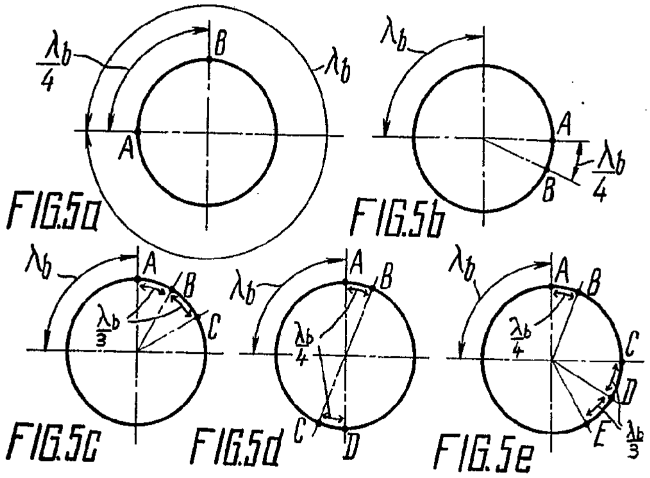

FIG.5a FIG.5b FIG.5c FIG.5d FIG.5e

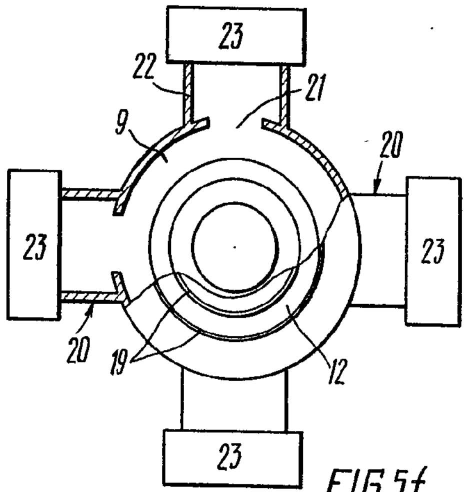

FIG.5f