Feb. 20, 1951 J. T. RANDALL ET AL 2,542,966

HIGH-FREQUENCY ELECTRICAL OSCILLATOR

Filed Aug. 20, 1941 3 Sheets-Sheet 1

Fig. 1.

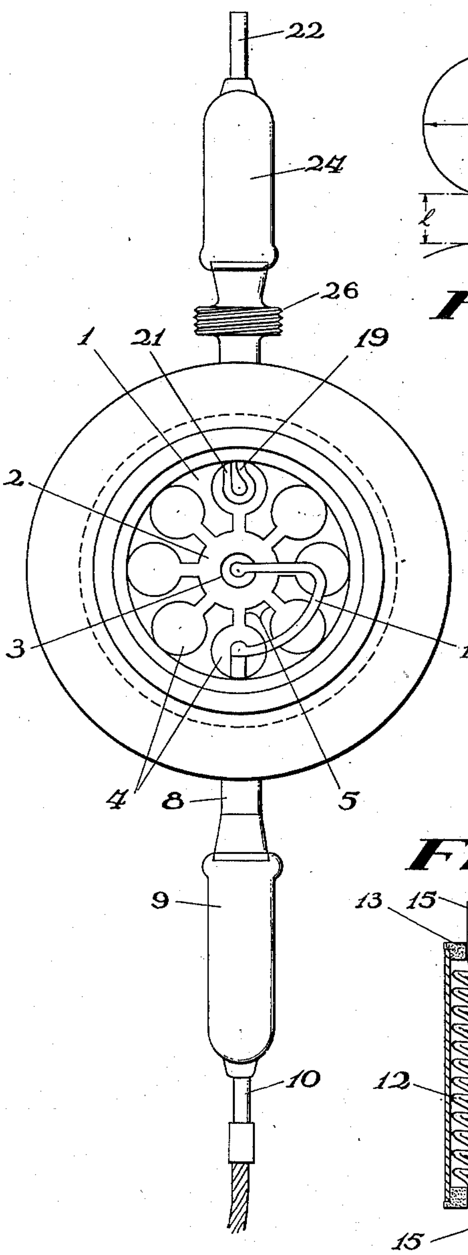


Fig. 4.

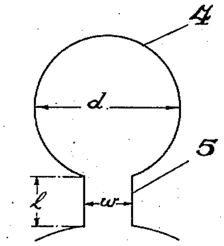


Fig. 2.

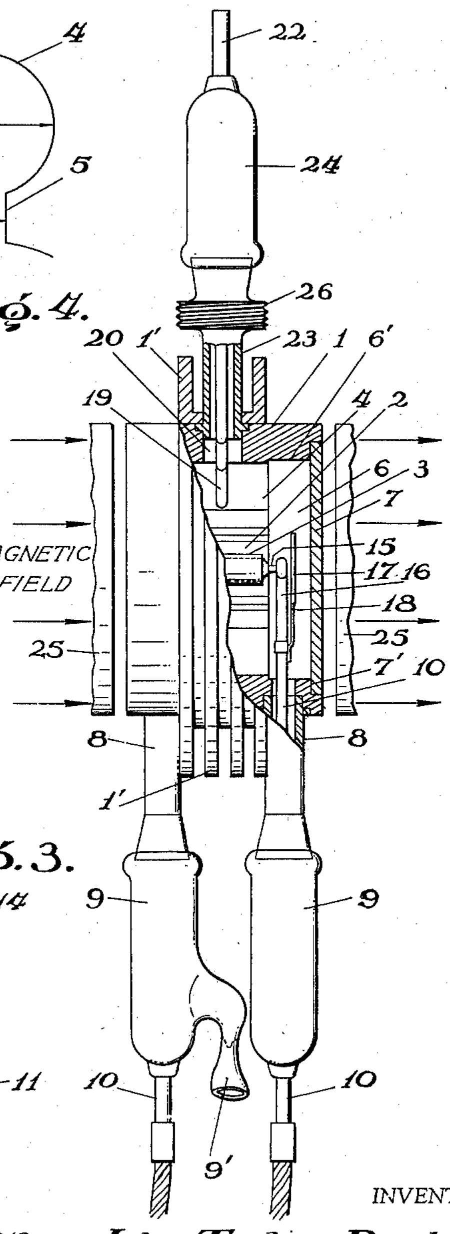
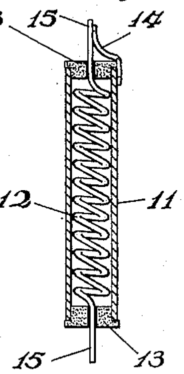


Fig. 3.



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Feb. 20, 1951 J. T. RANDALL ET AL 2,542,966

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Filed Aug. 20, 1941 3 Sheets-Sheet 2

Fig. 5.

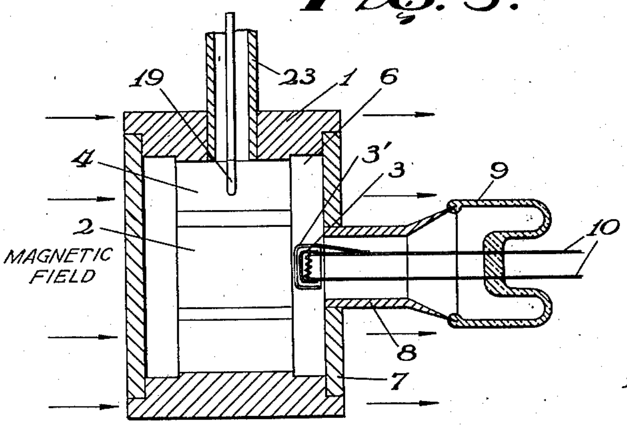


Fig. 12.

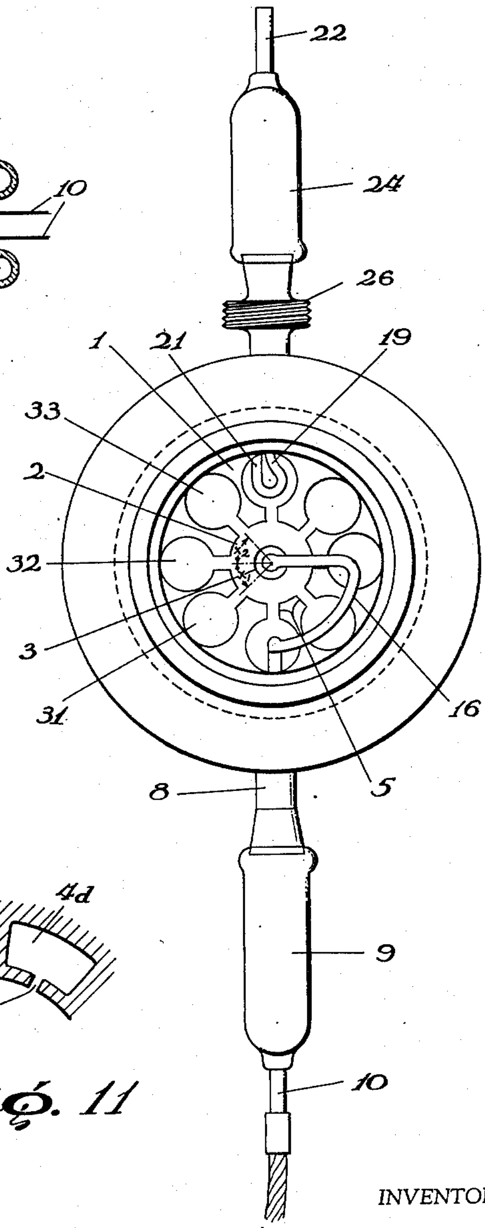
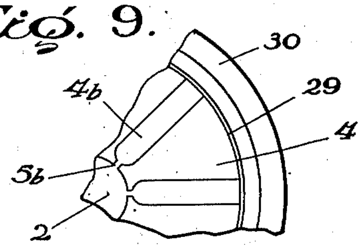
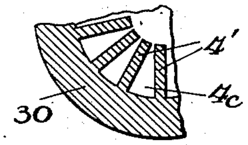


Fig. 9.





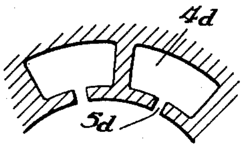


Fig. 10. Fig. 11

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Feb. 20, 1951 J. T. RANDALL ET AL 2,542,966

HIGH-FREQUENCY ELECTRICAL OSCILLATOR

Filed Aug. 20, 1941 3 Sheets-Sheet 3

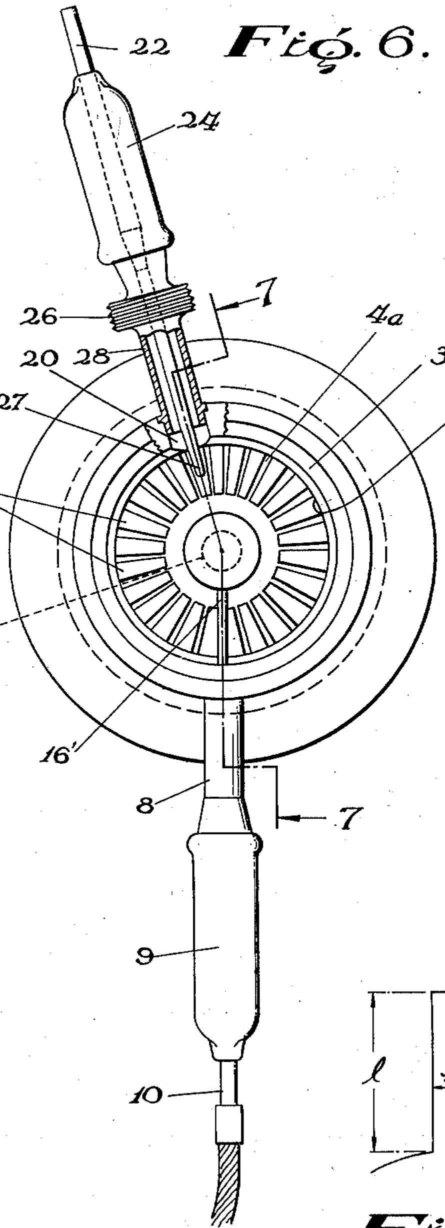

Fig. 6.

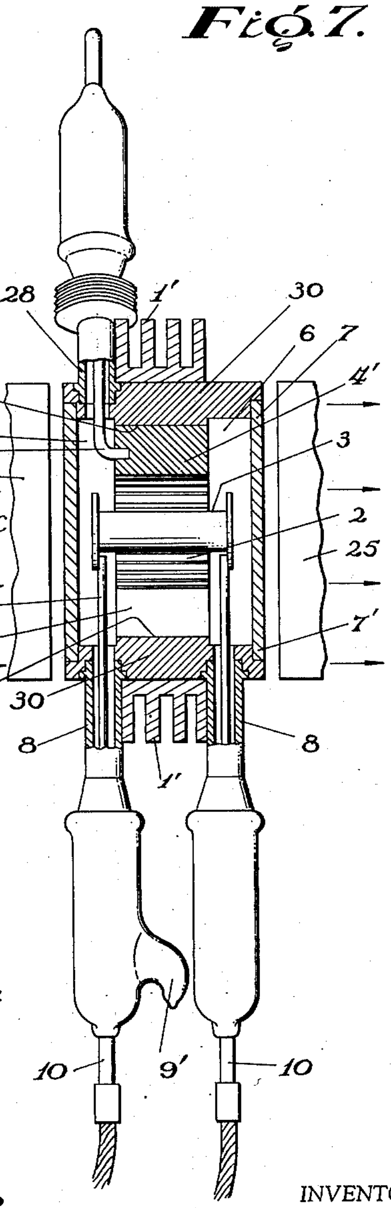

Fig. 7.

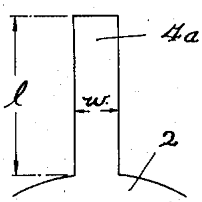

Fig. 8.

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2,542,966

HIGH-FREQUENCY ELECTRICAL OSCILLATOR

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Application August 20, 1941, Serial No. 407,680
In Great Britain August 22, 1940

26 Claims. (Cl. 250—36)

1

This invention relates to high frequency electrical oscillators of the magnetron type. Such magnetrons depend for their operation upon the curvilinear motion imparted to a moving electron by a magnetic field; electrons emitted by the cathode are thus caused to follow substantially circular or spiral paths, and various arrangements exist whereby such electrons are caused to give up their energy to external circuits in which oscillatory currents of very high frequency may thereby be induced.

It is known that an electron moving freely under the action of a uniform magnetic field and subjected to no other influence will theoretically traverse a circular path, its period of rotation being independent of its velocity and the radius of the circular path but a function of the field strength. During recent years it has been proposed, for the generation of ultra-short waves, to employ magnetron devices depending for their operation upon the reaction between the electron stream and one or more substantially closed resonant cavities; so far as we are aware, however, there has hitherto been considerable difficulty in obtaining large powers from magnetrons of this or other types, particularly at wavelengths below about 50 cm.

The primary object of the present invention is to provide a magnetron device capable of generating short or ultra-short waves of considerable power, and adaptable to either continuous wave or interrupted continuous wave working. A further object is the provision of a magnetron capable of acting as a sensitive detector of such waves. The invention is particularly applicable to systems of the kind used for determining the position of aircraft or other objects by means of radio echoes, since such systems in general depend upon the use of sharply defined beams of ultra-short wave radiation of considerable power; the invention is, however, by no means confined to this particular application, but may also be applied to radio communication, radio beacon systems or other purposes.

A magnetron according to the invention is characterized by the provision of a member comprising the anode within which a plurality of resonator cavities, of substantially the same natural frequency, are disposed about and open into a central axially disposed anode-cathode space. The openings or gaps connecting said cavities to said space serve, when the device is in operation, to couple the cavities to the space. The device is further characterized by the presence of some or all of a number of improved

2

features, which serve to increase the power and efficiency of the device. Among these may particularly be mentioned the provision of means for preventing the escape of high-frequency electromagnetic field from the device other than by the output means, and of means, independent of the first mentioned openings between the resonator cavities and the axial discharge-space, for coupling each of the cavities to an adjacent cavity. This additional coupling may be provided by the provision of one or more transversely extending spaces into which the axial discharge space and the resonator cavities open or to which they are connected.

The resonators, together with the central anode-cathode space, are preferably drilled from a solid metal block which constitutes the anode, this arrangement being rendered possible by the well known skin-effect whereby the ultra-high frequency oscillatory currents are confined exclusively to the internal surface layer of the resonators. In a preferred construction each resonator is of circular form in cross-section and has a relatively small gap opening into the anode-cathode space, with which it is coaxial.

In the preferred construction the resonator cavities and the central axial space open at both ends into common end spaces, which serve as additional coupling means for the resonator cavities, as above stated. A cathode (or cathodes) may be mounted in the central axial space or in one or both of the end spaces which form a continuation thereof. Closure means of conducting material are provided at the ends of the device, so that the total space comprised by the interiors of the resonators, the central space and the end spaces is completely enclosed by a conducting envelope having only such openings therethrough as are necessary for external connections.

As will subsequently be explained, the efficient operation of the device appears to depend largely upon the existence of a relatively high degree of electromagnetic coupling between the resonators, and the feature described above whereby the whole of the interior of the device is enclosed as far as possible in a conducting envelope is designed to achieve this end. If the resonators and central space opened at their ends into spaces which were closed only by non-conducting material a large stray electromagnetic field would exist, and the degree of coupling between the resonators would be relatively small. By the arrangement described whereby the resonators and central space open at their ends into end spaces which are substantially closed by conducting material the existence of such a stray field is prevented; this arises from the fact that at the extremely high frequencies involved the induction of eddy currents in the internal surface layer of the conducting envelope prevents the magnetic field from penetrating this envelope to more than a very limited extent, and the field is thus effectively conserved within the envelope. The provision of the common end spaces is necessary to enable the field from one resonator to link with that from the next, since if individual resonators were closed at their ends the effect described above would prevent the existence of any appreciable electromagnetic coupling between the resonators.

Preferred constructions according to the invention will now be described by way of example with reference to the accompanying drawings, throughout which a given reference numeral is always used to indicate the same or a corresponding part. In these drawings—

Fig. 1 is an end elevation of a magnetron in accordance with the invention, the pole pieces of the electromagnet providing the magnetic field and one of the end plates which normally cooperate with the anode in closing the magnetron envelope being omitted in order to show the internal construction of the device;

Fig. 2 is a side elevation of the magnetron of Fig. 1, partially in section and showing only fragments of the electromagnet pole pieces;

Fig. 3 is a longitudinal section, on an enlarged scale and with certain parts shown in full, of an indirectly heated cathode suitable for use in magnetrons of the present invention;

Fig. 4 is a sectional view, on an enlarged scale, of a single resonator of the type shown in Figs. 1 and 2;

Fig. 5 is a sectional view of a modified form of magnetron embodying the invention particularly adapted for the generation of continuous waves, a number of the parts being omitted in the interest of simplicity;

Figs. 6 and 7 are end and side elevations, respectively, similar to Figs. 1 and 2, of a modified form of magnetron embodying the invention;

Fig. 8 is a sectional view, on an enlarged scale, of a single resonator of the type shown in Figs. 6 and 7;

Fig. 9 is a fragmentary end elevation of another magnetron, showing a modified form of resonator;

Figs. 10 and 11 are fragmentary sectional views, on different scales, transverse to the axis of the magnetron, showing further modifications in the form of the resonator cavities; and

Fig. 12 is an end elevation of a magnetron similar to that shown in Fig. 1, but having the resonator cavities unevenly spaced apart circumferentially for the purpose of propagating harmonic oscillations.

Referring first to Figs. 1 and 2, the magnetron illustrated therein comprises a block **1**, preferably of tellurium-copper alloy, having a cylindrical cavity **2** drilled therein to form the main anode-cathode space, the anode being formed by the block **1** and the cathode **3** being constructed as hereinafter described with reference to Fig. 3 and lying along the axis of the cavity **2**. The resonators are formed by a plurality of further cylindrical holes or cavities **4** arranged symmetrically about the cavity **2** and having their axes parallel to and equidistant from its axis. The wall separating each resonator from the central cavity **2** is split by a relatively narrow longitudinal slot **5** parallel to and embracing the plane defined by the axes of the cavity **2** and of the resonator in question.

The resonators **4** and central cavity **2** open at both extremities into end spaces **6** formed in the main block **1**; these end spaces are closed by circular copper end plates **7** sealed in a gas-tight manner as hereinafter described within recesses **7'** formed at the ends of the cylindrical walls **6'** of the end spaces **6**. A copper tube **8** whose axis is at right angles to that of the cavity **2** opens into each end space **6**, being soldered or otherwise secured to the cylindrical wall **6'** over an opening therein. The other end of each tube **8** is sealed to a thimble-shaped member **9** of heat-resisting glass, preferably of the kind known under the registered trade-mark "Pyrex." Through the ends of these Pyrex thimbles are sealed tungsten rods **10** which form the cathode connections, these rods passing through the copper tubes **8** and carrying at their inner ends, within the end spaces of the magnetron, the cathode mountings described below. Tubes **9'** formed integrally with the walls of the Pyrex thimbles **9** are used during manufacture for the exhaustion of the magnetron to a very high vacuum, after which these tubes are sealed off.

The cathode **3**, which is illustrated separately in Fig. 3, consists of a nickel or alloy tube **11** coated externally with the usual oxide coating. The tube is heated by means of a tungsten spiral **12** which is a sliding fit in the tube and which is insulated from it by a coating of alumina on the wire. The ends of the heater pass through holes in two insulating plugs **13** at the ends of the cathode. These plugs are made of steatite or similar substance which will stand the high temperature without evolving gas. One end of the heater **12** is connected to the cathode by means of a small nickel tag **14** spot welded onto the tube **11**.

The cathode is supported by the ends **15** of the heater wire **12** on to which are pinched the ends of nickel members **16** (Figs. 1 and 2); these are made of wire or strip according to the weight of the cathode and the current to be carried, and their other ends are preferably joined to the ends of the tungsten rods **10** by arc welding in an atmosphere of hydrogen. The members **16** are of such a form that by bending them the cathode can be adjusted to any position in the plane of Fig. 1.

For the purpose of preventing or minimising the passage of stray electrons into the end spaces **6**, which would diminish the efficiency, circular end shields **17** (Fig. 2) of approximately the same diameter as the cavity **2** are provided at both ends of the cathode in known manner; these shields are arranged to be at cathode potential, so that they will repel any electrons approaching them back into the cavity **2**. The shields **17** are preferably of nickel sheet or a non-magnetic alloy such as that known under the registered trade-mark "Ferry," and are provided with tags **18** attached by spot welding to the rods **10**. The end shields **17** and end plates **7** are omitted from Fig. 1 for clarity.

For the purpose of conveying energy from the magnetron to the transmitting aerial a single copper loop **19** is inserted in one of the resonators **4** with its plane at right angles to the axis of the resonator, this loop serving to pick up energy by virtue of its electromagnetic coupling with the resonator system. One end of this loop passes out through a hole 20 which is drilled through the main block 1 at right angles to the axis of the resonator, and enters the resonator at a point diametrically opposite to the slot 5 connecting the resonator to the central cavity 2; the other end of the loop is connected to the main block at a point 21 at one side of the resonator. The free end of the loop 19 is soldered to a stout tungsten wire 22 which passes through a copper tube 23 and is sealed through a Pyrex cap 24 in a manner similar to that employed for the filament connections 10. Although it is located in one resonator only, the loop 19 is, by virtue of the electromagnetic coupling between the resonators, drawing energy from the whole system.

The magnetic field is preferably applied by means of a powerful electromagnet whose pole pieces 25 are in close proximity to, but insulated from, the copper end plates 7 of the device. The field is thus substantially parallel with the axes of the resonators and the central hole. Brass cooling fins 1' are provided on the outer part of the block 1.

The mode of operation of the device appears to be somewhat as follows. Electrons emitted by the cathode 3 will, under the joint action of the electrostatic and magnetic fields, follow substantially spiral paths in known manner. It is clear that these electrons, in passing the gaps of the resonators 4, will tend initially to induce feeble oscillations in the resonators. Now the resonators have all the same natural period of oscillation, and further, by virtue of the electromagnetic coupling between them, any given resonator is constrained to oscillate in a definite phase relationship with the adjacent resonators on each side of it. The resonators will thus tend to oscillate as a whole, and as soon as they commence to do so, the alternating fields set up across their gaps 5 will react back upon the moving electrons in the central space. The effect of this reaction appears to be that the electrons, instead of being uniformly distributed, form themselves into concentrated circumferentially moving groups. Now if such a group approaches a resonator gap at an instant when the field across this gap is such as to oppose the motion of the electrons, it is clear that the group as a whole will be slowed up, and will thus impart some of its energy to the oscillating system. A number of such groups of electrons, symmetrically spaced and moving with the correct angular velocity (determined by the strength of the magnetic and electric fields) are thus capable of imparting to the resonators timed impulses which will keep them in a state of continuous oscillation. The composition of these groups of electrons is, of course, not constant, as superimposed upon their movement is a continuous flow of electrons from the cathode to the anode.

The above explanation should be regarded as being only tentative, as the actual conditions are very complex and apparently incapable of exact mathematical analysis. The explanation is, however, supported by the fact that theoretical design formulae based thereon have been found to form a sound guide to the operation of the device in practice.

The oscillations are preferably fed to the transmitting aerial by means of a concentric transmission line of known form which constitutes an extension of the free end of the output lead 22 and of the tube 23, which is provided with a screwed member 26 for attachment to this transmission line. The aerial may conveniently consist of the free end of the central core of the transmission line, which is arranged to project a quarter wave length beyond the open end of the surrounding tube. For directional transmission, the aerial may be inserted through the side of a large copper tube one end of which, near the aerial, is closed by an adjustable plunger serving as a reflector. Provided that the conductivity of the internal surface of this tube is kept high by making it clean and smooth, the waves may be confined within the tube in known manner without serious loss and emitted from the other end, where they may be directed in a beam of any desired angular width by a suitably designed horn. Alternatively transmission may be effected from a dipole aerial in known manner, in conjunction, if desired, with a parabolic reflector for directional transmission.

Consideration will now be given to the problem of designing a magnetron according to the invention to fulfill given requirements. In this connection three fundamental equations have been developed; these are:

$$V=2\times10^{7}.\pi^{2}D^{2}/N^{2}W^{2}A^{2} \qquad \text{(I)}$$

$$H=7.24\times10^{4}\pi/NWA \qquad \text{(II)}$$

$$P=4\times10^{4}\pi^{3}D^{3}LE/N^{2}W^{2}A^{2} \qquad \text{(III)}$$

where

V=potential difference between anode and cathode (volts).
H=magnetic field (oersteds).
P=output power (kilowatts).
D=diameter of central cavity 2 (cm.).
N=number of resonators 4.
L=axial length of resonators and, in the form of magnetron shown in Figs. 1 and 2, axial length of cathode 3 (cm.).
A=phase difference between oscillations in adjoining resonators (radians).
W=wavelength (cms.).
E=efficiency (ratio of output to input power).

These equations have been developed from first principles, and are based on the hypothesis previously set out concerning the mode of operation of the device. It has been assumed (1) that the cathode diameter=0.4D, as in magnetron design generally this dimension has been found to provide optimum field conditions at the cathode, and (2) that the emission current density is .5 amps. per square cm., which for apparatus of this general kind is usually considered to be roughly the maximum permissible value to avoid flash arcs.

In order to obtain relatively simple expressions certain further assumptions have been made; the equations must not, therefore, be taken to represent an exact mathematical analysis of the working of the device under all conditions. It is known, for example, that the emission current value given above can be almost doubled under certain conditions, and it is found that the device will work with increased efficiency on higher values of V and H than those given by the equations. Moreover, the cathode diameter is not necessarily confined to the value of 0.4D referred to above. The value of these equations resides in the fact that magnetrons designed on the basis thereof will always operate satisfactorily in accordance with the values given, and the equations therefore form a simple and useful basis for design work.

In order to make use of the equations it is necessary to know the values of A and E that will obtain. If we consider the phase difference between consecutive resonators in turn until we complete the circle, it will be seen that NA must be a multiple of 2π in all cases. For any even value of N it appears that $A=\pi$, while for odd values of N it is at present necessary to determine A experimentally for each case; thus for $N=5$ it has been found that under certain operative conditions $A=8\pi/5$. As regards E, this again must be determined experimentally for the particular class of design concerned, and an estimated value used in Equation III for assessing P. Values of E from 0.1 to 0.6 have been obtained for various constructions and under various operative conditions. It will also be noted that P is directly proportional to L, and the extent to which P may be increased by increasing L is limited mainly by the extent to which it is possible to obtain the required value of H over a large gap.

A further important relationship exists between W and the dimensions of an individual resonator as illustrated in Fig. 4, in which d represents the diameter of the resonator **4**, w the width of the slot **5** and l its radial depth. The simplest fundamental calculation leads to the result

$$w=Kd\sqrt{l/w}$$

where K is a constant whose value is given by Mott as 7.23; we have found this value to agree reasonably well with a series of experimental results in which the observed values of W ranged from about 2 to 10 cm. An alternative method of dealing with the problem consists in the use of a series of empirical curves relating the variables involved. It may be mentioned in connection with Fig. 4 that if it is desired to obtain a very sharp frequency response curve the values of l and w should be such as to make the capacity across the slot as small as possible; in cases where this consideration is not of primary importance, however, other types of resonator not having these characteristics may be employed, as hereinafter described.

In addition to the relationships referred to above, a further purely geometrical relationship exists which is expressed in the equation—

$$t=2R\sin(\pi/N)-d$$

where t is the minimum thickness of the wall between two adjacent resonators, and R is the distance between the axis of the central cavity **2** and that of any resonator. The importance of the quantity t resides in the fact that in magnetrons designed to produce large powers it is desirable to make t as large as possible to aid efficient cooling; it is, however, clear that making t very large would tend to reduce the magnetic coupling between the resonators, but in designs involving large values of t it has not been apparent that this has any appreciable adverse effect.

It will be seen that the above equations define the relationships between the main factors involved in the design of a magnetron according to the invention. Given, for example, the wavelength, power output and, say, maximum permissible size and/or weight of the device, it will readily be apparent how the equations may be used to determine the optimum dimensions and approximate values of magnetic field and anode voltage that will be required.

The constructional techniques which may be employed in the manufacture of a typical magnetron as illustrated in Figs. 1 and 2 will now be briefly considered.

The anode block **1** is made of tellurium copper on account of its free machining properties, it being in this respect superior to machining brass, combined with high thermal and electrical conductivity. Its tellurium content in no way affects its use in high vacuum apparatus. The central cavity **2** is bored concentric with one end recess **6** which is used for the location of an accurately made drill jig for drilling the resonator holes **4**. In cases where the resonator diameter is small compared with their length they are drilled from each end with the aid of two jigs located by the central hole **2**. In all cases the holes are finished by reaming to obtain the requisite accuracy and finish. The slots **5** are cut on a slotter using a tool ground to the exact width of the slot with the work mounted on a horizontal indexing table. The end plates **7** are turned from arsenic-free high conductivity copper sheet to minimise the possibility of leaks occurring through their thickness.

The side stems **8**, **23** are turned from arsenic free copper bar, and the glass members **9** to which they are sealed are of glass whose expansion properties match those of the tungsten rods **10**. These side stems are preferably soldered to the main block **1** by a silver solder or any solder free from highly volatile constituents liable to interfere subsequently with the emission or vacuum.

All parts are carefully cleaned immediately before assembly by boiling in 5% H_2SO_4 followed by cold strong chromic acid containing a trace of H_2SO_4, and are finally rinsed in boiling distilled water.

The last parts to be assembled are the end plates **7**, which form the final closure. These are preferably sealed in place in known manner by the use of gold or tinned silver washers which are inserted between the end plates and the main block **1** within the recesses **7'**; sufficient pressure is then applied to provide a substantially gas-tight closure, the device is evacuated, and finally raised to a temperature sufficient to cause superficial alloying of the washer with the end plate and main block. This technique avoids any oxidation or contamination of the internal surfaces during the sealing operation, and may, if desired, also be used for securing the side stems **8**, **23** in position instead of using solder.

In an alternative method of effecting the final assembly the plates **7** and recesses **7'** are tinned, the whole is thoroughly cleaned, and the plates **7** are then sweated in position while inert gas is passed through the device by means of the tubes **9'** to avoid internal oxidation. The passage of inert gas is maintained until the device is cool, after which it is evacuated and the tubes **9'** sealed off.

For production in quantity the anode-block could have the end recesses **6** machined at high speed with form tools or an ordinary capstan lathe. The holes would be jig-drilled and reamed and slots broached one at a time in a single pass; or alternatively, in suitable cases, all together at one pass with a multi-splined broach.

Magnetrons according to the invention are adapted for use as generators of either continuous wave or interrupted continuous wave oscillations, the radiation in the latter case taking the form of a series of timed pulses. For continuous wave working, it is found that in cases where considerable power is developed the heat generated results in cathodes of the cylindrical type shown in Figs. 1 and 2 becoming raised to too high a temperature. The magnetron illustrated in Fig. 5, which is specially adapted for continuous wave working, has been designed to overcome this difficulty. In this design the cylindrical cathode is replaced by a disc type cathode 3 of the indirectly heated type located within one of the end recesses 6. The tungsten heater leads 10 are led out through a single tube 8 and glass member 9. The cathode proper may be surrounded by a focussing cylinder 3' connected, as shown, to one of the heater leads 10 or to a separate lead for control purposes; alternatively this focussing cylinder may be dispensed with. Cathodes such as 3 may be provided in both of the end spaces 6, in which case the heater leads may be brought out radially, as in Figs. 1 and 2, to reduce the overall length. This design may also be employed in the case of a single cathode. The further reference numerals in Fig. 5 have the same significance as in Figs. 1 and 2.

Figs. 6, 7 and 8 illustrate a modified form of magnetron in which the resonator cavities 4_a take the form of radial slots, uniform in cross section, extending about and opening into the central space 2 and having their ends opening into the two end spaces 6, as in the device of Figs. 1 and 2. The radial length of each of the slots 4_a is indicated in Fig. 8 as l' and the width as w'. Since it may not be practicable to include a coupling loop such as 19, Fig. 1, within one of these slots, power may be fed out through a lead 27 which forms a direct tap at a convenient voltage antinodal point along the end of one of the fins 4' separating the slots. This lead 27, which is so positioned as to link a part of the magnetic flux common to the two resonator slots lying on opposite sides of the fin 4' to which the lead is connected, passes out through a side tube 28 connected to the end space 6 as shown in Figs. 6 and 7, the tube 28 being similar to the tube 23 shown in Figs. 1 and 2 and the lead 27 being connected to the output wire 22 which is sealed through the insulating cap 24 as previously described.

The primary advantage of this slotted resonator design resides in the fact that a large number of resonators may be incorporated, thus enabling relatively low values of V and H to be employed, as will be seen from Equations I and II. Fig. 9 shows a further type of slotted resonator design in which each slot 4_b terminates in a gap 5_b of reduced width in the vicinity of the central cavity 2.

In a convenient manufacturing technique for the designs of Figs. 6 to 9 the slots 4_a or 4_b are first cut radially inwards on a solid cylindrical block whose outer curved surface is indicated by 29. The outer ends of the fins 4' thus formed are then soldered within an annular member 30 forming the main anode block, and the central cavity 2 is finally drilled out. Alternatively (in the case of Figs. 6 and 7) a single block may be employed in which the cavity 2 is first drilled, the slots 4 then being cut outwardly from within this cavity.

Fig. 10 illustrates a further design in which the fins 4' which separate the resonators 4_c may conveniently be formed separately and soldered within the annular member 30. Fig. 11 shows a still further design, in which a manufacturing technique similar to the first of those described in connection with Figs. 6 to 9 may be employed. This technique may also, if desired, be used for the design shown in Fig. 10.

In addition to operating at the fundamental mode of oscillation, the resonators 4 can theoretically oscillate at the higher harmonic modes in the series 1, 3, 5, etc. Consideration will now be given to the possibility of inducing such harmonic oscillations in magnetrons according to the invention, and thus obtaining extremely small wavelengths.

On the hypothesis previously set out concerning the operation of the device, it is assumed that the electrons are formed into groups by the action thereon of feeble oscillations initially induced in the resonators. It would, therefore, appear that if the resonators were constrained to oscillate at one of the higher harmonics from the outset the resulting relatively close grouping of the electrons would be such that, provided the groups arrived at the slots 5 of successive resonators in the correct phase, the device could be maintained in stable oscillation at this mode.

One possible method of carrying this conception into effect is based on the provision of an even number of resonators whose slots are spaced alternately X_1 and X_2 radians apart. Fig. 12 shows such an arrangement, the spacing between resonators 31 and 32 being X_1 radians while that between resonators 32 and 33 is X_2 radians. In all other respects, the device of Fig. 12 may be the same as that illustrated in Figs. 1 and 2. The principle of operation of this construction may briefly be explained as follows. Assume that the resonators have initially started to oscillate feebly at their fundamental frequency in the phase relationship determined by their electromagnetic coupling. Consider a particular group of electrons which has passed the slots of 31 and 32 in the correct phase. Owing to the difference between X_1 and X_2 this group will arrive "late" at 33; assuming that it arrives $1/r$ of a cycle late, the stimulus it will impart to 33 will apparently be such as to tend to induce the rth harmonic therein. Assuming further that as a result of the coupling corresponding harmonic oscillations are induced in the other resonators, the effect of these oscillations on the electron stream will apparently be the setting up of closely spaced groups such as to maintain this mode of oscillation.

The production of harmonic and like oscillations is not confined to the circular type of resonator shown in Fig. 12. Resonators of the slot type shown in Figs. 6 and 7 may, for example, be made to oscillate at harmonic frequencies in the series 1, 3, 5, etc., the length of each slot (measured radially) being one quarter wavelength for the fundamental mode and 3, 5 etc., quarter wavelengths for the higher harmonics. Resonators of any other form than circular may also be split up into a number of smaller resonators.

Various constructional modifications and further minor design details will now be considered.

In a modification of the cathode illustrated in Fig. 3 the heater 12 is made considerably smaller in diameter than the tube 11, so that it does not touch the latter at any point, and is held under slight tension along the centre of the tube. The alumina coating may thus be eliminated, and this gives freedom from heater failures due to breakdown of this coating, which may occur if any very high current discharge takes place in the magnetron. It may be mentioned in this connection that the effects of any such flash over are greatly minimised by using a resistance of about 100 ohms in series with the high tension supply. In cathodes of the larger sizes small pieces of nickel tube are forced into the holes in the insulating plugs 13 and the heater wire 12 passes through these tubes. The members 16, Fig. 1, are then pinched onto these tubes which are in turn flattened onto the heater wire 12. This method is used to avoid straining the brittle heater wire with the weight of the cathode. If desired the cathode may consist simply of a directly heated filament, suitably coated or otherwise, or may take any other convenient form.

According to a modified method of mounting the end shields 17 these are connected directly to each end of the heater wire 12, after which the assembly is held in position by means of a jig and the rods 10, which are made longer than in Fig. 2, are spot welded directly on to the end shields. This construction is shown in Figs. 6 and 7. According to a further method the whole assembly comprising the cathode, cathode connections and end shields if any, is mounted on a suitably formed end plate which is finally secured to the main block. Whatever method is employed for the cathode mounting one or more suitable high frequency chokes may be used to prevent loss of oscillatory power through the heater leads.

The coupling loop 19, Figs. 1 and 2, may have any desired number of turns, or may be replaced by a loop located in one of the end spaces 6 in any position where it will link with the magnetic flux flowing between an adjacent pair of resonators. With the single loop as shown in Figs. 1 and 2 it is found that good results are obtained when the loop encloses about 0.3 to 0.4 of the cross-sectional area of the resonator, but the size of the loop may be varied to suit requirements. In further modifications the loop may be replaced by a direct connection to a suitable voltage antinodal point on one of the anode segments which separate the resonator cavities, as in Figs. 6 and 7, or alternatively by a capacitative coupling.

In a modified transmission system the concentric transmission line is dispensed with, the free end of the loop 19 being formed into a similar loop within a bulb of glass or other non-conducting material, the interior of which is in communication with the evacuated interior of the magnetron; this second loop is inserted within a tube forming a wave guide, the axis of the tube lying in the plane of the loop.

Among further constructional and operational modifications may be mentioned the following. The air cooling system shown in Figs. 1 and 2 may be replaced by a water cooling system, water being circulated either through suitable ducts formed in the main anode block 1 or through external tubing. Tuning of the magnetron may be effected by the provision of one or more movable plates within the end spaces 6, the effect of adjusting these plates being to vary the mutual inductance between the resonators. For interrupted continuous wave working the high tension supply may consist of unrectified A. C., which itself provides the necessary modulation. The magnetic field may be applied by means of a permanent magnet instead of by an electromagnet as described; whichever is employed, it may be arranged within the body of the magnetron instead of externally as previously described. As a further alternative the magnetic field may be provided by a powerful solenoid surrounding the device; this construction is useful where large values of L are required. The main anode block need not be produced by machining as previously described; it may be formed in any other convenient manner, as for example by die-casting or by the assembling of a plurality of laminae. Further variations of the details of construction and materials employed may be made to suit particular requirements.

Dimensions and operational data of five typical magnetrons according to the invention, denoted by the letters (*a*) to (*e*), are given below. The values of V and H are optimum values, the values of P are estimated, and those of W found by actual measurement.

	(*a*)	(*b*)	(*c*)	(*d*)	(*e*)
W (cms.)	9.1	7.9	5.18	2.63	1.9
d (cms.)	1.1	0.8	0.6	0.3	------
D (cms.)	3.5	1.6	0.6	1.4	------
N	10	10	6	16	30
l (cms.)	0.37	0.28	0.1	0.05	0.475
w (cms.)	0.37	0.16	0.1	0.05	0.053
L (cms.)	4.0	2.0	2.0	2.0	1.8
V (kv.)	25	9	8	22	12
H (oersteds)	800	1,100	2,300	1,700	1,600
P (kw.)	150	5–10	5–10	10–15	------

Magnetrons (*a*) to (*d*) have resonators of the type illustrated in Fig. 4. Magnetron (*e*), however, is of the type shown in Figs. 7 and 8, so that the dimensions D and *d* do not apply to it. The lengths (radial) l' and width w' of the slots 4_a, Fig. 8, are given for convenience under l and w in the table respectively. The estimates of power all refer to peak power in interrupted continuous wave or "pulsed" working.

The principal advantage of a magnetron according to the invention is the high power obtainable at very high frequency, both on continuous and intermittent working. One of the factors contributing largely to this result is the fact that high emission currents are obtainable without difficulty, since no beam arrangement is necessary as in oscillators of the Klystron type. A further important advantage of the invention is the fact that the power may be brought out along an axis at right angles to the cathode and magnetic field, which is of great value in setting up the device in conjunction with a reflector.

Although applicable mainly as a generator of ultra short waves, the device may be used as a sensitive detector of such waves by arranging that it is normally kept on the threshold of oscillation, and is thrown into oscillation by the incoming radiation, means being provided to quench this oscillation when the incident radiation ceases. Moreover, although primarily applicable to radio work, the device may also be applied to any other purpose for which oscillatory currents of ultra-high frequency are required.

Having now particularly described and ascertained the nature of our said invention, and in what manner the same is to be performed, we declare that what we claim is:

1. A high-frequency electrical oscillator of the magnetron type comprising an anode of conducting material having therein a plurality of electromagnetically coupled resonator cavities arranged about and each of which opens into a central space within said anode, said central space and resonator cavities opening at their ends into common end spaces at the ends of said anode, members of conducting material joined to said anode at both ends and providing therewith a substantially complete conducting envelope enclosing said resonator cavities and the chamber formed by said spaces, and a cathode in said chamber.

2. Apparatus as defined in claim 1, said cathode extending along the axis of said central space.

3. Apparatus as defined in claim 1, said cathode being disposed in an end space.

4. A high-frequency electrical oscillator of the magnetron type comprising an anode of conducting material having therein a plurality of electro-magnetically coupled resonator cavities arranged about and each of which opens into a central space within said anode, said central space and resonator cavities opening at their ends into common end spaces at the ends of said anode, members of conducting material joined to said anode at both ends and providing therewith a substantially complete conducting envelope enclosing said resonator cavities and the chamber formed by said spaces, a cathode in said chamber, shielding means for preventing escape of electrons from said central space to said end spaces, and means for applying potential to said shielding means.

5. A high-frequency electrical oscillator of the magnetron type comprising an anode of conducting material having therein a plurality of electromagnetically coupled resonator cavities arranged about and each of which opens into a central space within said anode, said central space and resonator cavities opening at their ends into common end spaces at the ends of said anode, members of conducting material joined to said anode at both ends and providing therewith a substantially complete conducting envelope enclosing said resonator cavities and the chamber formed by said spaces, a cathode in said chamber, a tube of conducting material connected to said envelope, and a cathode lead extending through said tube and connected to said cathode.

6. A high-frequency electrical oscillator of the magnetron type comprising an anode of conducting material having therein a plurality of electromagnetically coupled resonator cavities arranged about and each of which opens into a central space within said anode, said central space and resonator cavities opening at their ends into common end spaces at the ends of said anode, members of conducting material joined to said anode at both ends and providing therewith a substantially complete conducting envelope enclosing said resonator cavities and the chamber formed by said spaces, a cathode extending along the axis of said central space, tubes of conducting material extending radially from said envelope and communicating with said end spaces, and cathode supporting and energizing means extending through said tubes and connected to the ends of said cathode.

7. A high-frequency electrical oscillator of the magnetron type comprising an anode of conducting material having therein a plurality of electromagnetically coupled resonator cavities arranged about and each of which opens into a central space within said anode, said central space and resonator cavities opening at their ends into common end spaces at the ends of said anode, members of conducting material joined to said anode at both ends and providing therewith a substantially complete conducting envelope enclosing said resonator cavities and the chamber formed by said spaces, a cathode disposed in an end space, a tube of conducting material extending axially from said envelope and communicating with said end space, and a cathode lead extending through said tube and connected to said cathode.

8. A high-frequency electrical oscillator of the magnetron type comprising an anode of conducting material, said anode having a central space and a plurality of electromagnetically coupled resonator cavities arranged about and opening into said central space, and said space being enlarged at the ends of the anode to provide end spaces into which said resonator cavities open, members of conducting material joined to said anode at its ends and providing therewith a substantially complete conducting envelope enclosing said resonator cavities and the chamber formed by said spaces, and a cathode in said chamber, successive resonator openings being spaced circumferentially from each other by different amounts proportioned to induce desired harmonic oscillations.

9. A high-frequency electrical oscillator of the magnetron type comprising an anode of conducting material, said anode having a central space and a plurality of electromagnetically coupled resonator cavities arranged about and opening into said central space, and said space being enlarged at the ends of the anode to provide end spaces into which said resonator cavities open, members of conducting material joined to said anode at its ends and providing therewith a substantially complete conducting envelope enclosing said resonator cavities and the chamber formed by said spaces, a cathode in said chamber, and power output means comprising a coupling loop located within said envelope and linked with the magnetic flux between an adjacent pair of resonators.

10. A high-frequency magnetron device comprising an anode member having an axially extending space therein and a plurality of resonator cavities disposed about and opening into said space, the openings from said cavities into said space serving to couple said cavities to said space, a cathode axially positioned in relation to said space, means independent of said openings for coupling each of said cavities to an adjacent one of said cavities, and means for substantially preventing escape of high-frequency electromagnetic field from said device.

11. In a high-frequency magnetron device having a central discharge space and a plurality of frequency-determining cavity resonators disposed about said discharge space, each of said resonators being coupled to said space by way of an opening, means, independent of said openings, for coupling each of said resonators to an adjacent one of said resonators, and conducting end closure means for substantially preventing escape of high-frequency electromagnetic field from said space and cavities to the atmosphere.

12. A high-frequency magnetron device comprising an anode member having an axially extending space therein and a plurality of resonator cavities disposed about and opening into said space, the openings from said cavities into said space serving to couple said cavities to said space, said member also having a transversely extending space into which said first named space opens and to which said cavities are connected by separate openings, affording coupling means for said cavities additional to said first named openings, said spaces forming a continuous chamber, a cathode in said chamber, and closure means transverse to said first named space for substantially preventing escape of high-frequency electromagnetic field from said device.

13. A high-frequency magnetron device comprising an anode member having an axially extending space therein and a plurality of resonator cavities disposed about and opening into said space, the openings from said cavities into said space serving to couple said cavities to said space, a cathode axially positioned in relation to said space, conducting closure members extending transversely to said space, joined to the ends of said anode member and arranged and constructed substantially to prevent escape of high-frequency electromagnetic field from said device, and an output connection extending into the interior of the device into position to link with the high-frequency magnetic flux therein.

14. A high-frequency magnetron device comprising an anode member having an axially extending space therein and a plurality of resonator cavities disposed about and opening into said space, the openings from said cavities into said space serving to couple said cavities to said space, said member also having an end space enclosed therein into which the adjacent ends of said first named space and of said cavities all open, affording coupling means for said cavities additional to said first named openings, said spaces forming a continuous chamber, a cathode in said chamber, and conducting closure means transverse to said first named space arranged and constructed for substantially preventing escape of high-frequency electromagnetic field from said device.

15. A high-frequency magnetron device comprising an anode member having an axially extending space therein and a plurality of resonator cavities disposed about and opening into said space, the openings from said cavities into said space serving to couple said cavities to said space, said member also having an end space enclosed therein into which the adjacent ends of said first named space and of said cavities all open, affording coupling means for said cavities additional to said first named openings, a cathode in said first named space, shielding means to prevent the escape of electrons from said first named space to said end space, and means for applying cathode potential to said shielding means.

16. A high-frequency magnetron device comprising an anode member having an axially extending space therein and a plurality of resonator cavities disposed about and opening into said space, the openings from said cavities into said space serving to couple said cavities to said space, conducting end closure means for substantially preventing escape of high-frequency electromagnetic field from said device, a cathode in said space, shielding means between said cathode and the adjacent end closure means, and means for applying potential to said shielding means.

17. An electron discharge device of the magnetron type comprising a metallic anode structure having a central space and a plurality of electromagnetically coupled resonator cavities arranged about and opening into said central space, and a substantially cylindrically shaped hollow cathode in said central space, said anode and cathode being co-axially arranged, the spacing between the outside diameter of said cathode and the surrounding portions of said anode being less than the diameter of said cathode.

18. In a high frequency magnetron device having a plurality of spaced anode surfaces interconnected by a like plurality of open-ended cavity resonators, and in which adjacent anode surfaces and cavities are intercoupled by high frequency electromagnetic fields existing in a region adjacent the open ends of said resonators, means for withdrawing oscillatory energy from said device which comprises a conductor extending into the end space of said device and disposed adjacent said open resonator ends in a plane substantially midway between two adjacent cavities in position to link a part of the magnetic flux which is common to said resonators and to avoid linking flux which is exclusively associated with either one of said resonators singly.

19. The combination, in electromagnetic oscillation apparatus, which comprises at least two frequency-determining cavity resonators, said resonators having openings so juxtaposed as to provide a path from one of said resonators into another of said resonators for the mutal oscillatory magnetic flux which is common to both of said resonators, and means for abstracting energy from said resonators without introducing excessive asymmetry into the field patterns of said resonators, comprising a conductive loop disposed externally of both of said resonators and substantially midway along said path in position to link a portion of said mutual flux.

20. In combination with an electromagnetic oscillation device having at least two adjacent open-ended frequency-determining cavity resonators arranged substantially parallel to each other and separated by a conductive wall, which resonators, when the device is in operation, support oscillatory electromagnetic fields which are at least partly in antiphase relation, means for abstracting energy from said device which comprises a conductor disposed in the plane of said separating wall and beyond the end thereof which adjoins said open resonator ends in position to link a part of the magnetic flux which is common to said resonators and to avoid linking flux which is exclusively associated with either one of said resonators singly.

21. A high-frequency magnetron device comprising an anode member having an axially extending space therein and a plurality of resonator cavities disposed circumferentially about said space and opening into the latter through axially extending slots, and a cathode axially positioned in relation to said space, successive ones of said slots being spaced circumferentially from each other by different amounts proportioned to induce harmonic oscillations in said cavities.

22. A high-frequency magnetron device comprising an anode member having an axially extending space therein and a plurality of resonator cavities disposed circumferentially about said space, and a cathode axially positioned in relation to said space, said cavities being cylindrical and connected with said space by axially extending slots, the proportions of each of said cavities and said slots being approximately expressed by the formula

$$W=Kd\sqrt{l/w}$$

in which W is the wave length of the device, K is a constant, d is the diameter of each of said cavities, and l and w are the radial depth and width of its slot, respectively.

23. A high-frequency magnetron device comprising an anode member having an axially extending space therein and a plurality of resonator cavities disposed circumferentially about and opening into the latter, and means for emitting and causing electrons in separated groups to travel in curved paths around said space toward the bounding wall thereof constituting the anode

when subjected to a magnetic field parallel to the longitudinal axis of said device.

24. A high-frequency electrical oscillator of the magnetron type comprising an anode of conducting material, said anode having a central space and a plurality of electromagnetically coupled resonator cavities arranged about and opening into said central space, and said space being enlarged at the ends of the anode to provide end spaces into which said resonator cavities open, means including said anode forming a substantially complete conducting envelope enclosing said resonator cavities and the chamber formed by said spaces, and a cathode in said chamber.

25. A high-frequency electrical oscillator of the magnetron type comprising an anode of conducting material having therein a central space and a plurality of electromagnetically coupled resonator cavities of substantially the same natural frequency arranged symmetrically about and opening into said central space, a cathode in said central space, means including said anode forming a metallic envelope completely enclosing said resonator cavities and central space and providing spaces at the opposite ends of said anode into which said cavities and central space open, and means for withdrawing high frequency energy from the interior of said envelope.

26. A high-frequency oscillator of the magnetron type comprising an anode of conducting material having therein a cylindrical central space and a plurality of cylindrical resonator cavities of substantially the same natural frequency arranged symmetrically about said central space with their axes parallel to the axis of said space and each opening into said central space through a relatively small gap, a cathode in said central space, means including said anode forming a metallic envelope completely enclosing said resonator cavities and central space and providing spaces at the opposite ends of said anode into which said cavities and central space open, said cavities being electromagnetically coupled to one another by fields which traverse the end spaces, and means for withdrawing high frequency energy from the interior of said envelope.

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