July 1, 1952 J. S. DONAL, JR., ET AL 2,602,156

MODULATED MICROWAVE GENERATOR

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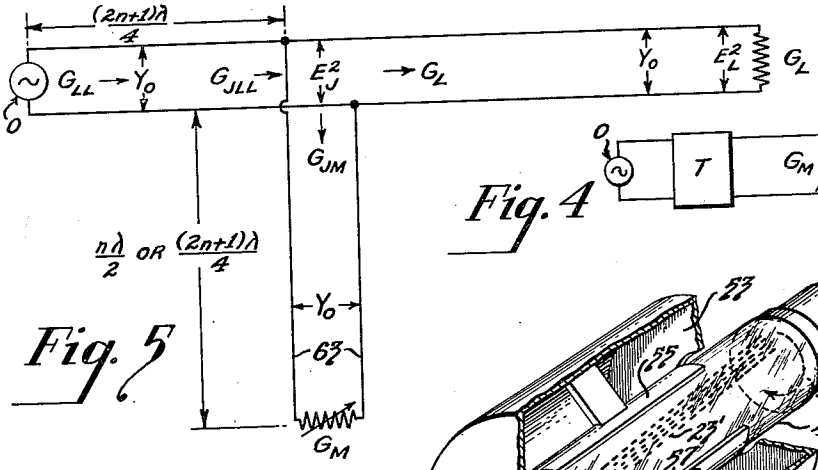
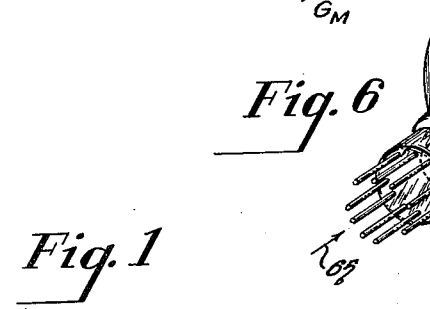


Fig. 5

Fig. 4



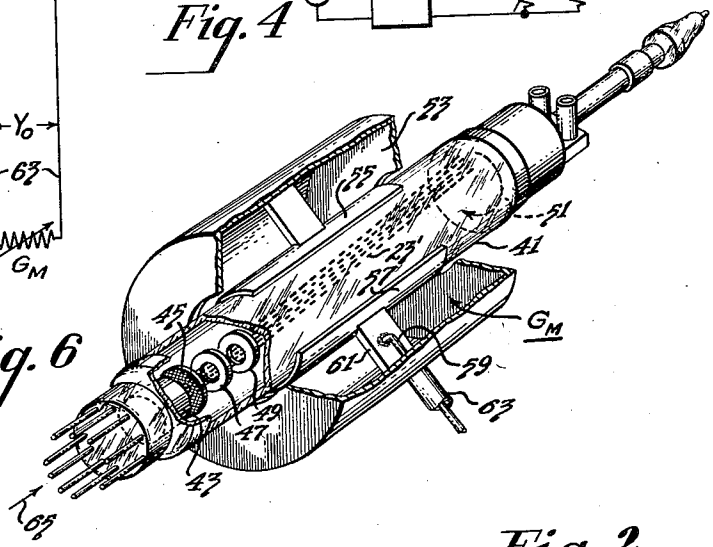


Fig. 6

Fig. 1

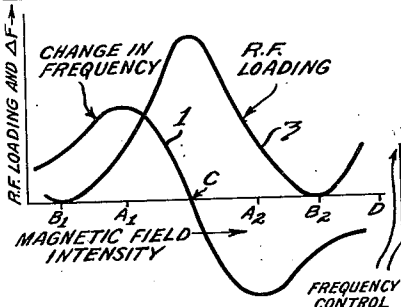


Fig. 2

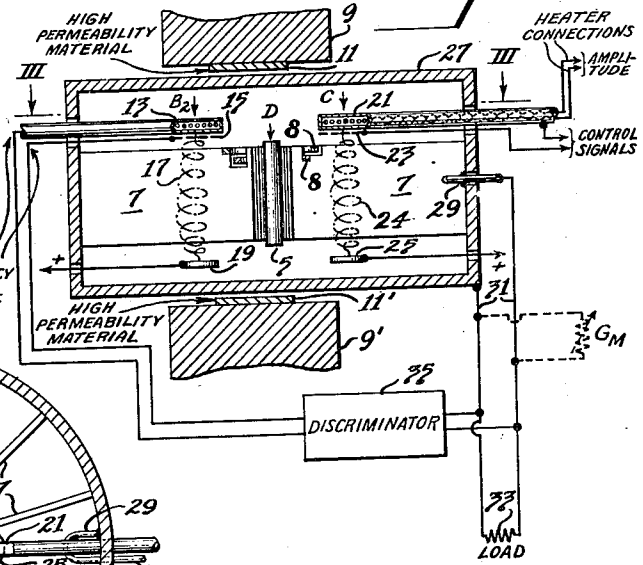
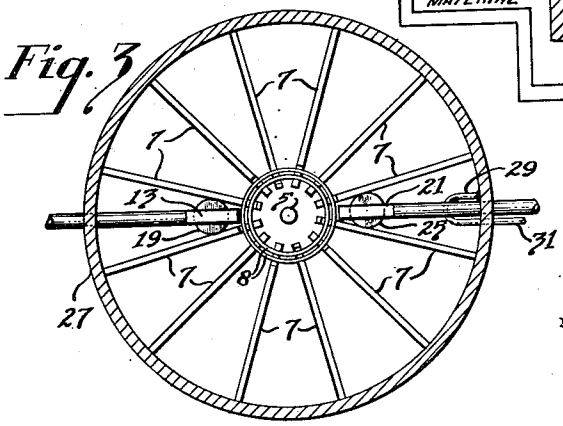


Fig. 3



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MODULATED MICROWAVE GENERATOR

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Application June 28, 1947, Serial No. 757,755

10 Claims. (Cl. 332—5)

1

This invention relates generally to modulated microwave generators and more particularly to improved methods of and means for amplitude-modulating and frequency-controlling microwave generators, especially of the magnetron type.

In the copending applications of Lloyd P. Smith, Serial Number 563,732, filed November 16, 1944, and entitled High Frequency Apparatus, and John S. Donal, Jr., et al., Serial Number 757,756, filed June 28, 1947 and entitled Frequency Modulated Magnetron Microwave Generator, now Patent No. 2,534,503, granted December 19, 1950, there is disclosed a system for modulating or controlling the frequency of a magnetron microwave generator by projecting an electron beam along a constant magnetic field and through a cavity resonator which may be either a cavity resonator of a magnetron generator or an external cavity resonator coupled to a magnetron generator. Control of the energy of the modulating electron beam provides a variable shunt reactance for the frequency determining parameters of the magnetron generator.

The instant invention is an improvement upon the devices disclosed in said copending applications in that applicants have found that either frequency or amplitude-modulation of the magnetron generator may be provided substantially to the exclusion of, or independently of, the other, depending upon the intensity of the applied unidirectional magnetic field. Furthermore, applicants have found that optimum magnetic field intensities exist for most efficient magnetron microwave generation, for amplitude modulation to the exclusion of frequency modulation, and for frequency modulation to the exclusion of amplitude modulation.

The instant invention utilizes these realizations of optimum magnetron modulating and operating characteristics and comprises improved methods of and means for providing an efficient amplitude-modulated magnetron generator which may, if desired, include frequency stabilization.

A first embodiment of the invention comprises a magnetron generator of the multi-cavity type which includes means for providing a frequency-stabilizing electron beam projected through one or more of the magnetron resonant cavities and additional means for providing an amplitude-modulating electron beam projected through one or more of said magnetron resonant cavities, and thus effectively directly in shunt with the load. In order to provide optimum operating characteristics for the generation of microwave oscillations in the magnetron proper, as well as to provide

2

optimum frequency-stabilization and amplitude-modulation of the microwave oscillations, the intensities of the unidirectional axial magnetic fields applied to the magnetron proper and to the modulating and control electron beam structures are adjusted to optimum values by proper proportioning of the magnetic structure operable upon the different portions of the system.

A modification of the invention contemplates the use of an external amplitude-modulating electron beam device connected to the output transmission line connecting a microwave generator to its load. The amplitude-modulating electron beam device comprises an electron beam generating gun which projects a modulating electron beam through a coaxial cavity resonator to a collector electrode. The electron gun includes a control grid to vary the beam current. When a unidirectional axial magnetic field of proper intensity is applied to the device, the latter operates as a variable non-reactive shunt conductance connected to the microwave load transmission line. The variable shunt conductance is connected, either through a half-wave transmission line, or through a quarter wave transmission line, to a point on the load transmission line removed some odd multiple of a quarter wavelength at the operating frequency from the microwave generator.

The amplitude-modulating systems comprising the instant invention provide a much more efficient method of amplitude-modulating microwave oscillations than is possible by grid modulation of triode generators or by anode voltage modulation of magnetron or Klystron generators. Furthermore, in addition to more efficient operations, the amplitude modulation of microwave oscillations may be accomplished without the usual undesirable frequency-modulation as is the case when a magnetron is modulated by varying the anode-cathode potential. Also, any residual frequency-modulation or frequency instability in the device may be compensated for by the inclusion of a separate frequency control electron beam device responsive to frequency deviations in the modulated generator oscillations.

Among the objects of the invention are to provide improved methods of and means for modulating microwave oscillations. Another object is to provide improved methods of and means for amplitude-modulating magnetron generators. A further object is to provide an improved method of and means for amplitude-modulating a magnetron generator at a high modulation percentage. An additional object is to provide improved

methods of and means for amplitude-modulating microwave generators and for simultaneously stabilizing the frequency of the generated oscillations. Another object is to provide methods of and means for selecting optimum magnetic field intensities for microwave magnetron generating and modulating devices. A further object of the invention is to provide improved methods of and means for insuring optimum operating parameters in an amplitude-modulated magnetron generator by providing optimum unidirectional axial magnetic field intensities for the magnetron generator per se, and for the amplitude or frequency-modulating or control electron beam devices associated with the magnetron generator. A still further object of the invention is to provide improved methods of and means for coupling a variable conductance device to the load circuit of a microwave generating system for providing amplitude-modulation of the generated microwave oscillations.

Other objects of the invention include improved methods of and means for amplitude-modulating microwave oscillations substantially to the exclusion of accompanying resultant frequency modulation. Another object is to provide improved methods of and means for frequency-modulating, stabilizing, or controlling microwave oscillations substantially to the exclusion of accompanying resultant amplitude-modulation. Another object of the invention is to provide an improved magnetron microwave generator including an amplitude-modulating electron beam device projected through one of the magnetron cavity resonators and a frequency-stabilizing electron beam device also projected through one of the magnetron cavity resonators, said magnetron generator including means for applying unidirectional coaxial magnetic fields of different intensities to the generating and modulating elements of the device.

The invention will be described in greater detail by reference to the accompanying drawings of which Figure 1 is a family of graphs illustrating the operating characteristics of the system; Figure 2 is a partially schematic, cross-sectional elevational view of a first embodiment of the invention; Figure 3 is a fragmentary, cross-sectional plan view taken along the section line III—III of Figure 2; Figure 4 is a schematic circuit diagram to be referred to in the description of the operation of said first embodiment; Figure 5 is a schematic circuit diagram of a modification of said first embodiment of the invention; and Figure 6 is a perspective, partially sectional view of a modulating electron beam device comprising the variable conductance G_M of the circuit of Figure 5. Similar reference characters are applied to similar elements throughout the drawing.

Referring to Figure 1 of the drawing, the graph 1 illustrates the variation in frequency of microwaves generated by a multi-cavity magnetron as a function of the unidirectional axial magnetic field intensity applied to a modulating electron beam coupled into or projected through one of the magnetron cavity resonators. Graph 3 illustrates the radio frequency loading of the magnetron by the modulating beam as a function of said unidirectional magnetic field intensity. Comparison of the graphs indicates that maximum frequency modulation is obtained for values A_1 and A_2 of magnetic field intensity although some radio frequency loading occurs for these values. Appreciable frequency modulation may be provided for values B_1 and B_2 with negligible radio frequency loading. Also substantially no frequency modulation will obtain and a maximum of radio frequency loading will be provided for a magnetic field intensity indicated by the value C. In addition, it has been determined that most magnetrons function most efficiently as a microwave generator for even higher values of magnetic field intensity as indicated by the value D.

As a result of the information deduced from the graphs 1 and 3, applicants have provided a multi-cavity magnetron microwave generator in which the magnetron cathode and anode are operated at a magnetic field intensity of a value D to obtain good operating efficiency, a frequency control electron beam is projected through one of the magnetron cavities for stabilizing the operating frequency, and a second modulating electron beam is projected through another of the magnetron cavities for modulating the amplitude of the generated microwave oscillations in response to modulating signals. The frequency control electron beam preferably is subjected to an axial magnetic field intensity of the value B_2 which provides substantially negligible radio frequency loading with appreciable frequency control. The amplitude modulating electron beam is subjected to a lesser magnetic field intensity corresponding preferably to the value C which provides maximum radio frequency loading and negligible frequency modulation. A unitary structure including these features is shown in Figures 2 and 3 of the drawing.

The magnetron generator comprises a central axial cathode 5 surrounded by a plurality of radially extending anode cavity resonator vanes 7 which are alternately connected together by anode vane straps 8, and are positively biased with respect to the cathode 5. The inner ends of the vanes 7 provide anode segments. The spaces between adjacent radially extending anode vanes comprise anode cavity resonators tuned to the desired operating microwave frequency. An axial unidirectional magnetic field is derived by an external magnetic structure, not shown, terminated in pole pieces 9, 9' which include small pole tips 11, 11', of highly permeable material, located adjacent to the central axis of the magnetron.

The frequency control electron beam generating device comprises a first auxiliary cathode 13 and a frequency control grid 15 located above one of the spaces between two adjacent anode cavity resonator vanes for projecting an electron beam 17 through a cavity resonator to a collector electrode 19 which is positively biased with respect to the cathode 13. Similarly the amplitude modulation control electron beam device comprises a second auxiliary cathode 21 with an amplitude control grid 23 located above the space between two other adjacent anode vanes for projecting a second electron beam 24 through an anode cavity resonator to a second collector electrode 25 which is positively biased with respect to the second auxiliary cathode 21. The auxiliary cathodes 13 and 21 may be either directly or indirectly heated in accordance with known thermionic tube technique.

The pole pieces 9, 9' are so positioned with respect to the axis of the magnetron structure as to provide the desired coaxial magnetic field intensity B_2 for the frequency-control electron beam, the magnetic field intensity value C for the amplitude-control electron beam device and the magnetic field intensity D for the main cathode-anode space. The magnetron cathode and

anode vanes 7 and the frequency control and amplitude control electron beam devices all are enclosed within an evacuated envelope 27 through which suitable operating leads are provided.

Output energy is derived from an output coupling loop 29 coupled into one of the anode cavity resonators. The output loop 29 may be coupled through any suitable type of microwave transmission line 31 to the load 33.

The stabilization of the operating frequency by the frequency control electron beam 17 is effected by connecting a discriminator 35, for example of the "magic T" waveguide type, to the output line 31 and deriving control voltages from the discriminator which are applied between the cathode 13 and grid 15 of the frequency control electron beam device. The amplitude modulation of the output signals is effected by applying desired modulation signals to the cathode 21 and grid 23 of the second auxiliary electron beam device which projects the beam 24 through the magnetron anode cavity resonator. The frequency-control beam 17, being operated at an axial magnetic field intensity B_2, provides substantially only reactive effects upon the magnetron oscillations with negligible radio frequency loading thereof. The amplitude-control beam 24 provides maximum loading of the generated microwave oscillations wtih negligible frequency modulation thereof, since it is operated with an axial magnetic field having the value C. In operation, the amplitude modulation electron beam 24 effectively provides a non-reactive variable shunt conductance G_M indicated by the dash line resistor connected across the output transmission line. Varying the control grid potential varies the beam current, which varies the energy absorbing ability of the beam. The theory and operation of this embodiment of the invention is described in greater detail by reference to Figure 4 of the drawing which follows. It should be understood, however, that the amplitude modulaiton electron beam may alternatively be incorporated in an external variable conductance device as illustrated and described by reference to Figure 6 of the drawing, and such an external variable conductance device would be coupled directly into one of the magnetron anode cavities or connected to the load transmission line as will be discussed in greater detail hereinafter.

Reference is made to the circuit of Figure 4, where O is the magnetron generator, G_L the load conductance, G_M the variable or modulating conductance, and T a lossless transformer. By varying G_M, the dry means of the control grid 23, the power in G_L will be varied, if the generator power output and thus the power output of the transformer are constant. In this case, if a is a fraction and

$$G_M = aG_L \tag{1}$$

then the power in the load is

$$P_L = P_o(1+a)^{-1} \tag{2}$$

where P_o is the power output of the magnetron generator.

Alternatively, if the transformer were not present, and if the generator were a constant voltage generator, the power in G_L would remain constant regardless of the value of G_M. Therefore, to determine the effectiveness of such a modulation scheme, the power output characteristic as a function of the load must be determined and the effect of various types of transformers must be considered.

General characteristics

In the region of operation, the power output of the magnetron may be expressed by

$$P_o = KG_{LL}{}^u \quad O<u<1 \tag{3}$$

where K is a constant, and G_{LL} is the conductance seen by the generator.

The validity of this assumption may be confirmed by experimental data. Power output and frequency may be measured as a function of load impedance, from standing wave measurements, and the data plotted on a familiar "Smith chart" or "Rieke diagram." From these data, the power output is noted as a function of R_L/v_0, where R_L is the load resistance and Z_0 the surge impedance of the line. The zero reactance line is determined from the frequency contours. Data taken indicates that the assumed relation of Equation 3 does provide a good approximation to actual characteristics and that u varies from about 0.1 to 0.6 for different types of magnetrons.

Power relations without transformer

If the transformer T were not present, or if the transformer were a transmission line of an integral number of half wavelengths, then the load and modulating conductance would be effectively in direct shunt with the generator. If the modulating conductance, G_M, were increased under these conditions, it would absorb more power from the load, G_L, but the conductance, G_{LL}, seen by the generator is increased and therefore from (3), the power output of the magnetron generator increases. Therefore, the decrease in power in G_L is the difference between the additional power absorbed in G_M and the increase in power output of the magnetron. This condition obtains when the amplitude modulating electron beam is projected through one of the magnetron cavity resonators as in the device described by reference to Figures 2 and 3.

The conductance seen by the generator is

$$G_{LL} = G_L(1+a) \tag{4}$$

from Equation 3 the magnetron power output is

$$P_o = KG_L{}^u(1+a)^u \tag{5}$$

and the power in the load is, from Equation 2:

$$P_L = KG_L{}^u(1+a)^{u-1} \tag{6}$$

The magnetron efficiency is defined by

$$\eta = \frac{P_o}{P_{in}} \tag{7}$$

where P_{in} is the power input to the tube. In a given tube, this efficiency will have a maximum value, either limited by stability or because it represents a match between the tube and its effective load. Since it will be assumed that P_{in} is constant, maximum efficiency will occur when G_{LL} is a maximum; or it will occur when a has reached its maximum value, i. e.,

$$\eta_{max} = \frac{K}{P_{in}} G_L{}^u(1+a)^u \tag{8}$$

where it is to be understood that, in Equation 8, a has some maximum value, and during modulation, varies between zero and this maximum value.

In practice, a modulation efficiency ξ is frequently defined as half the maximum power

swing during modulation divided by the average power input. This efficiency, so defined, is zero when there is no modulation present, and is unity when a tube with 100% plate efficiency at all values of power output obtained during modulation is modulated 100%. It is independent of the "carrier level."

$$\xi=\frac{P_{max}-P_{min}}{2P_{in}} \quad (9)$$

P_{max} occurs when a is zero and P_{min} when a is maximum in the case being considered and so from Equation 6.

$$\xi=\frac{K}{2P_{in}}G_L{}^u[1-(1+a)^{u-1}] \quad (10)$$

where it is again to be understood that a has its maximum value. Expressing this modulation efficiency in terms of the maximum magnetron efficiency from Equation 8.

$$\xi=\frac{1}{2}\eta_{max}[(1+a)^{-u}-(1+a)^{-1}] \quad (11)$$

This function has a maximum with respect to a which occurs when

$$a=u^{\frac{1}{u-1}}-1 \quad (12)$$

and has a value of

$$\xi_{max}=\frac{1}{2}\eta_{max}\left[u^{\frac{u}{1-u}}-u^{\frac{1}{1-u}}\right] \quad (13)$$

The modulation efficiency, ξ, thus is a function of a for different values of u.

It is frequently convenient to define a modulation factor, m, as the ratio of the maximum voltage amplitude of the envelope to the average voltage of the carrier. This may be written

$$m=\frac{M-1}{M+1} \quad (14)$$

where M is defined by

$$M^2=\frac{P_{max}}{P_{min}} \quad (15)$$

Using Equation 6, (15) becomes

$$M^2=(1+a)^{1-u} \quad (16)$$

From Equations 14 and 16, m may be calculated as a function of a for different values of u;

The value of M^2 when a has the value, given by Equation 12, for maximum ξ, is

$$M^2=1/u \quad (17)$$

and the value of m for maximum ξ is

$$m=\frac{1-u^{1/2}}{1+u^{1/2}} \quad (18)$$

Effect of transformers

As discussed heretofore, the power characteristic of the magnetron works in opposition to that of the shunt combination of G_M and G_L. It is therefore desirable to introduce between the magnetron and the two conductances, a transformer T which will effectively invert the characteristic of the generator.

This is most easily accomplished by the use of an external modulator and a quarter-wave transformer, a transmission line of an odd number of quarter wavelengths long, between the generator and the junction of the load and modulator lines, as shown in Figure 5, since an increase in the conductance at the junction of the load and modulator lines will result in a decrease in the conductance seen by the generator O. This will decrease the power output of the generator, and so the power in the load is decreased for this reason in addition to the decrease from increasing G_M.

Any length of transmission line transformer other than an integral number of half or quarter wavelengths would reflect a reactive component back to the generator, and since this would result in frequency modulation, it is not feasible for amplitude modulation.

It is also possible to insert a transformer between the modulating conductance, G_M, and the point of junction with the load line as shown in Fig. 5. If this were a half-wave transformer, no change would result, since it would have the same effect as a direct shunt across the load. If it were a quarter-wave transformer, an inversion would result such that when G_M is zero, the load would be short-circuited. This would reflect an open circuit to the generator, with a quarter wave transformer between the generator and the junction.

It is assumed that the load conductance, G_L, is equal to the surge admittance, Y_0, of the line and so the distance between the actual load and the junction point with the modulating branch is not important.

Power relations with quarter-wave load-line transformer

If a quarter-wave transformer is used between the generator and the junction with the modulating branch, and a half-wave transformer between the junction and G_M, the arrangement is represented by Figure 5.

The conductance seen by the generator will be

$$G_{LL}=\frac{Y_0{}^2}{G_M+G_L} \quad (19)$$

and since $G_L=Y_0$,

$$G_{LL}=G_L(1+a)^{-1} \quad (20)$$

the power output of the tube is

$$P_O=KG_L{}^u(1+a)^{-u} \quad (21)$$

and the power in the load is

$$P_L=KG_L{}^u(1+a)^{-1-u} \quad (22)$$

The tube efficiency is

$$\eta=\frac{K}{P_{in}}G_L{}^u(1+a)^{-u} \quad (23)$$

but, in contrast to the transformerless situation, the maximum tube efficiency occurs when a is zero, giving

$$\eta_{max}=\frac{K}{P_{in}}G_L{}^u \quad (24)$$

As defined by Equation 9, the modulation efficiency becomes

$$\xi=\tfrac{1}{2}\eta_{max}[1-(1+a)^{-1-u}] \quad (25)$$

This function does not have a maximum for finite a, but increases with a.

The ratio M^2 is

$$M^2=(1+a)^{1+u} \quad (26)$$

From Equations 26 and 14 m may be calculated as a function of a.

Comparison between the two types of load line transformer connection may be easily made. As an example, if $u=0.3$ and $a=1$, the half-wave transformer connection gives a value of ξ of $0.156\eta_{max}$, while the quarter-wave transformer

connection gives a value of ξ of $0.297\eta_{max}$. For the half-wave transformer connection and $u=0.3$, the maximum value of ξ is $0.209\eta_{max}$ and occurs when $a=4.6$. This same efficiency obtains in the quarter-wave transformer connection when $a=0.6$.

The quarter-wave load line transformer connection gives an appreciably higher modulation efficiency for a given range in modulating conductance and will give the same efficiency as the half-wave transformer connection at a much lower range of modulating conductance.

Modulating device

It is, of course, desirable to vary the conductance, G_M, electronically. Moreover, it is desirable that G_M be real at all times, so that no frequency modulation occurs, and that G_M be a function of an independent parameter, such as a control grid potential, and independent of the average voltage appearing across it. A high plate conductance triode would provide the means of control but its conductance decreases with decreasing plate voltage. As the conductance is increased by decreasing the negative grid voltage, the power in the load decreases, but this decreases the radio frequency voltage on the plate of the triode, tending to decrease its conductance.

A type of variable conductance device which does meet all of the above requirements and is more efficient than a triode is one similar to the spiral beam reactance tube described in said copending applications and used for frequency-modulating magnetrons. Such a device is shown in Figure 6.

Since the admittance across the device is to be real, and has been assumed to be equal to Y_0 only for sake of simplicity, the magnetic field, H, should be adjusted so that

$$\omega=H\frac{e}{m} \tag{27}$$

where ω is the angular operating frequency and e/m is the charge to mass ratio of the electrons. The quantity

$$\frac{He}{m}$$

in Equation 27 is the angular velocity of cyclotron frequency ω_c of electrons traveling in circular paths in a magentic field of strength H. Hence Equation 27 may also be written

$$\omega=\omega_c \tag{27a}$$

When the magnetic field H is adjusted to make the angular cyclotron frequency ω_c equal to the angular frequency ω of the generator to which the modulating device is coupled, the admittance across the device is real and is given by

$$G=\frac{e}{m}\frac{I_0\tau^2}{d^2}\frac{}{4} \tag{28}$$

where I_0 is the total beam current, d is the distance between the plates, and τ is the transit time of the electrons. It is known also that the velocity at which the electrons are collected under the condition expressed by Equation 27 is

$$v=\frac{\phi_0}{d}\frac{e}{m}\frac{\tau}{2}$$

where ϕ_0 is the radio frequency amplitude. The energy absorbed by each electron is then

$$W=\phi_0 e\left[\frac{\phi_0 e/m\tau^2}{8d^2}\right]$$

By proper selection of τ and d, the term in brackets can easily be made appreciably greater than unity. Since the energy absorbed by each electron in a triode is simply $\phi_0 e$, the triode would be less efficient as an energy absorbing device.

If it be required that the electrons not be captured by the plates, but be collected at the end of the tube by a collector, then τ is independent of the radio frequency voltage between the plates. Since I_0 will be determined by the accelerating beam voltage V_b, which is in the direction of the magnetic field, and a control-grid voltage V_g, G will be independent of the radio frequency voltage.

To meet the requirement that no electrons are captured by the plates, it is necessary that the spiral deflection be less than $\frac{1}{2}(d-t)$, where t is the cathode width. It is known that the amplitude of the spiral is

$$\overline{y}=\frac{e}{m}\frac{E_0}{2\omega}\tau \tag{29}$$

where

$$\omega=H\frac{e}{m}$$

and in which the transit time is

$$\tau=\frac{l}{\sqrt{2\frac{e}{m}V_b}} \tag{30}$$

where l is the length of the plates. E_0 is the amplitude of the radio frequency field between the plates. When $\overline{y}$ is set equal to $\frac{1}{2}(d-t)$, a maximum value of τ results which when inserted in Equation 28, gives for the maximum obtainable conductance

$$G_{max}=\frac{I_0\omega^2d^2}{4\frac{e}{m}\phi_0^2}(1-t/d)^2 \tag{31}$$

where ϕ_0 is the radio frequency voltage between the plates and is equal to E_0d.

Since the beam current is limited by the current density from the cathode, which is

$$J_0=\frac{I_0}{wd(t/d)} \tag{32}$$

where w is the cathode length, the maximum conductance may be written

$$G_{max}=\frac{J_0\omega^2wd^3}{4\frac{e}{m}\phi_0^2}[(1-t/d)^2t/d] \tag{33}$$

The quantity in brackets is maximum when $t/d=\frac{1}{3}$ and has a maximum value of

$$\frac{4}{27}$$

Thus

$$G_{max}=\frac{J_0\omega^2wd^3}{27\frac{e}{m}\phi_0^2} \tag{34}$$

In order for space charge to permit the current density, J_0, to pass through the cavity, the expression

$$J_0=\frac{4}{9\pi}\sqrt{2\frac{e}{m}}V_b^{3/2}\frac{1}{d^2}\frac{F_{max}}{t/d} \tag{35}$$

must hold. F_{max} is a function of t/d and varies from 2 for $t/d=1$ to 0.866 for $t/d=0$. When $t/d=\frac{1}{3}$, $F_{max}=1.10$.

From Equation 34, it is seen that if G_{max} is to be made large, w and d must be large. From

Equation 35, large values of d will require a large V_b, and since Equations 29 and 30 must be such that $y=\frac{1}{2}(d-t)$, a large V_b will mean a large value of l. However, a large w means a large I_0, which with a large V_b means high total beam power. Therefore, it is desirable to use as low a value of G, as possible, but it is limited only by practical factors.

Finally, it should be pointed out that if the electrode arrangement considered is to be part of a resonant cavity, the G calculated above will be the conductance which appears between the "pole faces" of the cavity and will be transformed to a new value, appearing across the transmission line, by a coupling arrangement, such as a loop or window. It is this conductance which appears across the line as G_M in the foregoing analysis. In general, it will be possible to make G_M appreciably higher than the electronic conductance, G, and if the proper coupling is used, G_M will be directly proportional to G. Since the gap filled by the beam is an integral part of the resonant circuit, the capacitance of the gap must be considered in the design.

However, in estimating the maximum value of G_M from Equation 34, the coupling problem need not be considered since ϕ_0^2 appears in the denominator of Equation 34. The radio frequency power dissipated in the beam is $\frac{1}{2} G\phi_0^2$ and this must be equal to the power which would be dissipated in a conductance G_M across the end of the line where an R.-F. voltage, ϕ_1 appears. Thus Equation 34 will give the maximum value of G_M directly, if ϕ_0 is replaced by ϕ_1.

If the beam is to be placed inside the magnetron, as in the system of Figure 2, a direct shunt with the load results and the first or transformerless analysis is applicable, and lower modulation efficiency is obtained than if a quarter-wave load line transformer is used.

Linearity

The degree of over-all linearity of the external modulator may be determined by expressing the amplitude of the radio frequency voltage across the load as a function of the applied signal voltage. This radio frequency voltage amplitude is

$$V_L=\sqrt{\frac{2P_L}{G_L}} \tag{36}$$

which becomes, when Equations 6 and 22 are used,

$$V_L=\sqrt{2KG_L^{(u-1)}}(1+a)^{-\frac{(1\pm u)}{2}} \tag{37}$$

The + sign refers to the quarter-wave transformer connection, and the − sign to the half-wave transformer connection. Since this voltage is maximum when a is zero, then

$$V_L=(V_L)_{max}(1+a)^{-\frac{(1\pm u)}{2}} \tag{38}$$

a may be related to the beam current by using Equations 1 and 28:

$$a=BI_0 \tag{39}$$

where

$$B=\frac{e}{m}\frac{\tau^2}{4d^2G_L} \tag{40}$$

Presumably, a beam forming gun will be used in the modulating tube. If V_g is the control grid voltage, V_a the accelerating voltage, and μ the amplification factor, the current from the gun is

$$I_0=P\left(\frac{V_a}{\mu}+V_g\right)^{3/2} \tag{41}$$

where P is the "perveance" of the gun. Inserting Equation 41 into Equation 39

$$a=BP\left(\frac{V_a}{\mu}\right)^{3/2}\left(1+\frac{V_g}{V_a/\mu}\right)^{3/2} \tag{42}$$

When $V_g=0$, a has its maximum value since it is assumed that V_g is never to be positive and so Equation 42 may be rewritten

$$a=a_{max}\left(1+\frac{V_g}{V_a/\mu}\right)^{3/2} \tag{43}$$

Using this expression in Equation 38,

$$V_L=(V_L)_{max}\left[1+a_{max}\left(1+\frac{V_g}{V_a/\mu}\right)^{3/2}\right]^{-\frac{(1\pm u)}{2}} \tag{44}$$

where the + and − signs again refer to the quarter and half-wave connections, respectively.

This modulation characteristic is valid only at low modulating frequencies; no attempt has been made to consider the "band width" of the over-all system which, to a great extent, will depend on the particular circuit configuration used.

The systems of Figures 2, 3 and 4 and the modification of the circuit of Figure 5 employing a coupling line having an effective length of any multiple of one-half wavelength between the modulating conductance device G_M and the quarter wave connection on the load transmission line all have the disadvantage of relatively low maximum depth of modulation. An important improvement of the devices described involves the use of a coupling transmission line, between the quarter wave point on the load transmission line and the modulating conductance G_M, of any odd number of quarter wavelengths

$$\frac{(2n+1)}{4}\lambda$$

at the operating microwave frequency. When the cavity resonator of the external absorption tube G_M is tuned to resonance, and connected through such a quarter-wave line to the quarter wave junction of the load transmission line, the very high resistive impedance of the modulating device appears as a very low resistance at the junction of the load transmission line. The shunt resistance is substantially 0 when it includes the shunt resistance of the load. The load resistance at the load line junction is transformed through the quarter-wave section of the load line to a very high resistance at the magnetron generator output coupling loop. Thus not only is the load impedance substantially short-circuited by the modulating conductance but the magnetron output energy is reduced to an extremely low value. This arrangement provides extremely efficient operation and good depth of modulation. In several tests of the system the decrease in output energy provided by keying the modulating beam **23'** of the device G_M on and off corresponded to a voltage modulation of 80%. Without consideration of modulator tube losses, the effective voltage modulation has been found to be of the order of 90%. Thus the improvement over the circuits described heretofore insofar as modulation percentage is concerned is of the order of two or three times.

The following mathematical discussion of the system pertains to the improved circuit employing a quarter-wave coupling line between the variable conductance device G_M and the quarter-wave load transmission line junction.

Determination of G_{LL}:

$$G_{JM}=\frac{Y_0^2}{G_M}$$

$$G_{JL}=G_L$$

$$G_{JLL}=G_{JL}+G_{JM}=\frac{Y_0^2}{G_M}+R_L$$

$$G_{LL}=\frac{Y_0^2}{G_{JLL}}=\frac{Y_0^2}{\frac{Y_0^2}{G_M}+G_L}=\frac{G_M Y_0^2}{Y_0^2+G_L G_M}$$

But $G_M=aG_L$ by definition of "a" and $G_L=Y_0$ (assumed)

$$\therefore G_{LL}=\frac{aG_L Y_0^2}{Y_0^2+aG_L^2}=\frac{aG_L^3}{G_L^2+aG_L^2}=\left(\frac{a}{1+a}\right)G_L \quad (45)$$

Magnetron generator output: (P_o)

$P_o=KG_{LL}^u$ (from experimental data, $u\cong 0.33$)

$$\therefore P_o=Ka^u G_L^u (1+a)^{-u} \quad (46)$$

To express ratio of

$$\frac{P_L}{P_M}$$

in terms of ratio

$$\frac{G_L}{G_M}$$

$$P_L=\frac{E^2_J}{R_L}=E^2_J G_L$$

$$P_M=E^2_J G_{JM}=\frac{E^2_J Y_0^2}{G_M} \text{ since } G_{JM}=\frac{Y_0^2}{G_M}$$

$$\therefore \frac{P_L}{P_M}=\frac{E^2_J G_L}{\frac{E^2_J Y_0^2}{G_M}}=\frac{G_L G_M}{Y_0^2}=\frac{G_M}{G_L} \text{ (since } Y_0=G_L) \quad (47)$$

To express P_o in terms of P_M, a and P_L, a:

$$P_o=P_L+P_M$$

$$\frac{P_L}{P_M}=\frac{G_M}{G_L} \text{ from Equation 47}$$

from Equation 47

$$\therefore P_o=\frac{G_M}{G_L}P_M+P_M=(1+a)P_M \text{ or } P_M=\frac{P_o}{1+a} \quad (48)$$

or:

$$P_o=P_L+\frac{G_L}{G_M}P_L=P_L+\frac{P_L}{a}$$

$$=\left(\frac{1+a}{a}\right)P_L \text{ or } P_L=\frac{a}{1+a}P_o \quad (49)$$

$$\therefore P_L=aP_M$$

To evaluate P_L:

$$P_L=\frac{a}{1+a}P_o=\frac{a}{1+a}[Ka^u G_L^u (1+a)^{-u}]$$

from Equation 46

$$P_L=Ka^{u+1}G_L^u(1+a)^{-u-1} \quad (50)$$

To evaluate P_M:

$$P_M=\frac{P_o}{1+a}=\frac{1}{1+a}[Ka^u G_L^u(1+a)^{-u}]$$

$$=Ka^u G_L^u(1+a)^{-u-1} \quad (51)$$

Magnetron η:

$$\eta=\frac{P_o}{P_{in}}=\frac{K}{P_{in}}a^u G_L^u(1+a)^{-u} \quad (52)$$

(η is maximum when a is maximum)

To evaluate modulation efficiency ζ which is defined as

$$\zeta=\frac{P_{L\,max}-P_{L\,min}}{ZP_{in}}$$

but

$$P_L=Ka^{u+1}P_L^u(1+a)^{-u-1}$$

$$\therefore \zeta=\left[Ka^{1+u}\frac{G_L^u(1+a)^{-u-1}}{2P_{in}}\right]-0$$

$$=\frac{K}{2P_{in}}a^{u+1}G_L^u(1+a)^{-u-1} \quad (53)$$

when a is maximum. ζ in terms of π_{max} for a a maximum, see Equation 48.

From Equations 9 and 8:

$$\zeta=\frac{1}{2}\frac{a^u}{1+a}\left[\frac{K}{P_{in}}aG_L^4(1+a)^{-u}\right]$$

or

$$\zeta=\frac{1}{2}\frac{a^u}{1+a}(\eta_{max}) \quad (54)$$

Referring to Figure 6, the external amplitude modulating or absorption device corresponding to the element G_M of the circuits described heretofore may comprise an evacuated glass envelope **41** enclosing an electron beam gun comprising a thermionic cathode **43**, a control grid **45**, a screen grid **47**, and an accelerating grid **49**. The electron gun elements are suitably biased to project the electron beam **23'** to a positively biased collector electrode **51**. The evacuated envelope **41** is surrounded by a coaxial cavity resonator **53** including arcuate electrodes **55**, **57**. The resonator **53** is tuned to the operating microwave frequency, thus providing, by microwave energy absorption, a transverse microwave electric field between the electrodes **55**, **57** and causing the electron beam **23'** to follow the directrix of a hollow cone having a radius determined by the magnitude of the energy absorption. It should be understood that the entire assembly may be enclosed within a metal envelope, and that the glass envelope described merely comprises a convenient demountable design. A coupling loop **59** coupled into the resonator **53** and terminated on the bracket **61** supporting the electrode **57** delivers energy from the coupling transmission line **63** to the cavity resonator and to the electron beam **23'**. An axial unidirectional magnetic field, of suitable intensity C as described heretofore by reference to the graphs of Figure 1, is applied to the variable conductance device G_M as indicated by the arrow **65**.

It should be understood that the invention is not to be considered as limited to the specific microwave structures described herein and that the frequency-stabilizing and amplitude-modulating features may be employed either in combination, or as separate adjuncts to known types of microwave generators.

Thus the invention described and claimed herein comprises improved methods of and means for modulating the amplitudes of microwave oscillations especially as provided by magnetron microwave generators, and additional means for controlling the operating microwave frequency independently of the amplitude modulation. The relations between frequency variation and R.-F.

loading as a function of applied axial unidirectional magnetic field intensity are discussed and utilized in the various embodiments of the invention. Various circuits and structures are disclosed which provide improved amplitude modulation efficiency as well as substantial freedom from undesired frequency modulation.

We claim as our invention:

1. A microwave system including a generator adapted to provide microwave oscillations, a variable-conductance electron beam modulating device coupled to said generator, means for providing a constant magnetic field coaxial with the beam of said device, the cyclotron frequency of said magnetic field being substantially equal to the angular frequency of said oscillations, and means for varying the conductance of said beam to modulate the amplitude of said oscillations with negligible frequency modulation thereof wherein said generator is coupled to said variable conductance electron beam modulating device by means of a load line and impedance inversion means coupling said variable conductance device to an intermediate point on said load line.

2. A microwave system in accordance with claim 1, wherein said intermediate point is removed an odd number of quarter wavelengths at the operating frequency from said generator.

3. A magnetron generator including a cathode, an anode cavity resonator adjacent said cathode, means for providing a first magnetic field coaxial with said cathode, said generator being adapted to be connected to a source of operating potentials to provide oscillations therefrom, means for projecting an electron beam through said resonator, means for providing a second magnetic field coaxial with said beam, the cyclotron frequency of said second constant magnetic field being substantially equal to the angular frequency of said oscillations, whereby said beam is substantially non-reactive, the intensity of said first magnetic field being substantially greater than that of said second magnetic field, and means for varying the conductance of said electron beam to provide amplitude modulation of said oscillations.

4. A magnetron generator including a central cathode surrounded by a plurality of anode cavity resonators, means for providing a first magnetic field coaxial to said cathode, said generator being adapted to be connected to a source of operating potentials to provide oscillations therefrom, means adjacent to one of said resonators for projecting an electron beam along a path extending therethrough, means for providing a second magnetic field coaxial with said path, the cyclotron frequency of said second magnetic field being substantially equal to the generated angular frequency of said magnetron generator, whereby said beam loads said generator non-reactively, the intensity of said first magnetic field being substantially greater than that of said second magnetic field.

5. A magnetron generator according to claim 4, further including means for varying the conductance of said electron beam to amplitude modulate said oscillations.

6. A microwave system including a generator adapted to provide microwave oscillations, a variable-conductance electron beam modulating device coupled to said generator, means for providing a constant magnetic field coaxial with the beam of said device, the cyclotron frequency of said magnetic field being substantially equal to the angular frequency of said oscillations, means for varying the conductance of said beam to modulate the amplitude of said oscillations with negligible frequency modulation thereof, a second electron beam modulating device coupled to said generator, means for providing a second constant magnetic field coaxially of said second modulating device and of such strength relative to the operating frequency that said second beam device provides appreciable reactive effect upon and negligible loading of said oscillations, and means for varying the energy absorbing ability of said second beam modulating device to provide frequency control of said oscillations.

7. A microwave magnetron generator including a cathode, an anode in operative relation to said cathode, said cathode and anode being adapted to be connected to a source of operating potentials to provide oscillations, a pair of electron modulating beam devices coupled to said anode, means for providing magnetic fields coaxially of said cathode and said modulating beam devices, said field providing means being constructed and arranged to provide portions of different intensity substantially to provide simultaneous maximum loading of and negligible reactive effect upon said oscillations by one of said electron beams, to provide appreciable reactive effect upon and negligible loading of said oscillations by the other of said electron beams and to provide high efficiency of oscillation generation by said cathode and anode, means for varying the energy-absorbing ability of said one of said electron beams to provide amplitude modulation of said oscillations, and means for varying the energy-absorbing ability of said other of said beams to provide frequency control of said oscillations.

8. An amplitude modulated microwave magnetron generator including a cathode, an anode having a plurality of radially disposed cavity resonators in operative relation to said cathode, said cathode and anode being adapted to be connected to a source of operating potentials to provide microwave oscillations, a pair of electron beam modulating devices directed through different ones of said resonators, means for providing a magnetic field coaxially of said cathode and said modulating beam devices, said field providing means being constructed and arranged to provide portions of different intensity substantially to provide simultaneous maximum loading of and negligible reactive effect upon said oscillations by one of said electron beams, to provide appreciable reactive effect upon and negligible loading of said oscillations by the other of said electron beams and to provide high efficiency of oscillation generation, means for varying the energy-absorbing ability of said one of said electron beams to provide amplitude modulation of said oscillations, and means for varying the energy-absorbing ability of said other of said beams to provide frequency control of said oscillations.

9. A microwave system including a generator adapted to provide microwave oscillations, a variable-conductance electron beam modulating device coupled to said generator, means for providing a constant magnetic field coaxial with the beam of said device, the cyclotron frequency of said magnetic field being substantially equal to the angular frequency of said oscillations, and means for varying the conductance of said beam to modulate the amplitude of said oscillations with negligible frequency modulation thereof, wherein said generator is coupled to said variable conductance device by means of a load line and a transmission line having an electrical length equal to an integral number of quarter wavelengths at

the operating frequency coupling said variable conductance device to an intermediate point on said load line.

10. A microwave system in accordance with claim 9, wherein said intermediate point is removed an odd number of quarter wavelengths at the operating frequency from said generator.

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REFERENCES CITED

The following references are of record in the file of this patent:

UNITED STATES PATENTS

Number	Name	Date
2,151,912	Habann et al.	Mar. 28, 1939
2,223,058	Christ	Nov. 26, 1940
2,241,976	Blewett et al.	May 13, 1941
2,439,387	Hansen et al.	Apr. 13, 1948
2,468,243	Spencer	Apr. 26, 1949
2,472,200	Everhart	June 7, 1949
2,477,317	Spencer	July 26, 1949
2,490,007	Peters	Nov. 29, 1949
2,502,077	Donal	Mar. 28, 1950
2,528,241	Peters et al.	Oct. 31, 1950
2,542,797	Cuccia	Feb. 20, 1951