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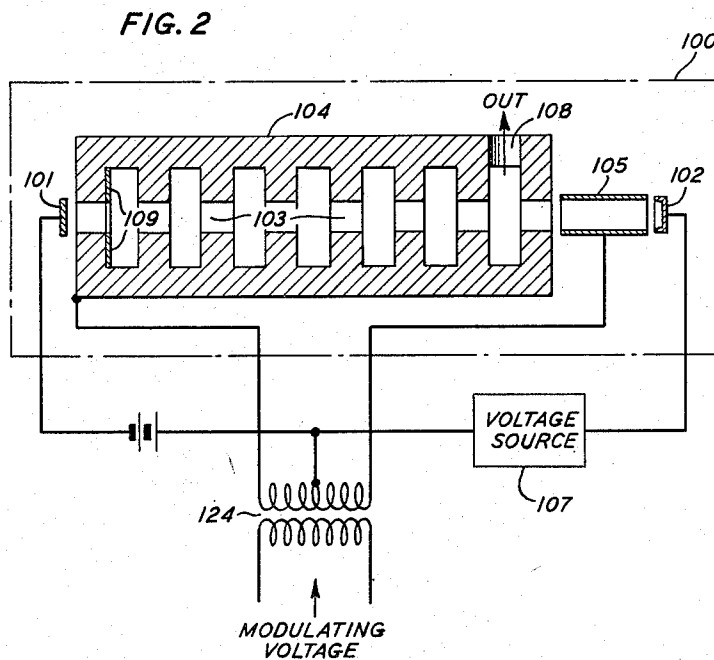
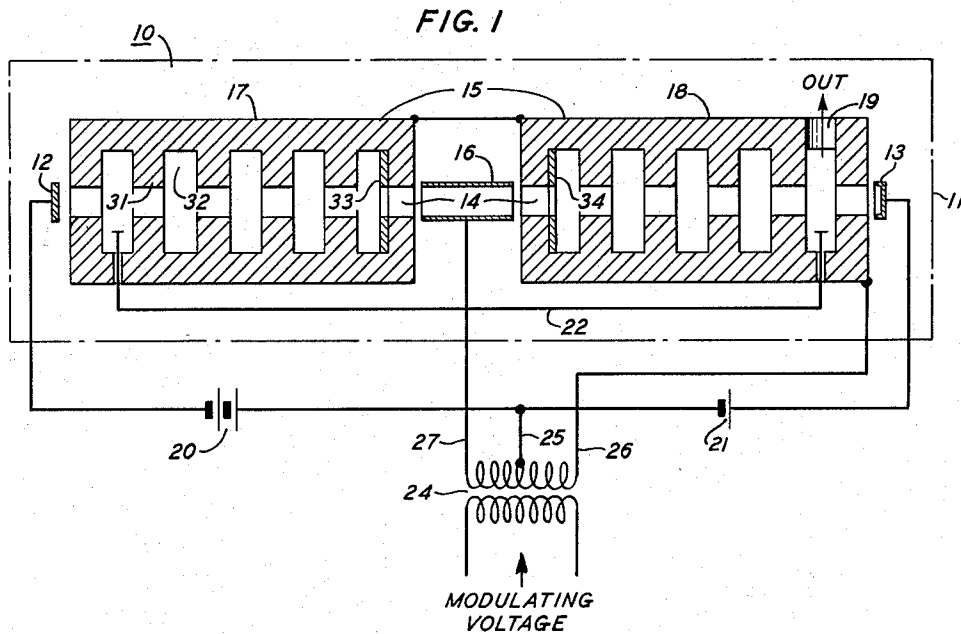
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2,760,161

TRAVELLING WAVE FREQUENCY MODULATOR

Filed Oct. 10, 1951

2 Sheets-Sheet 1



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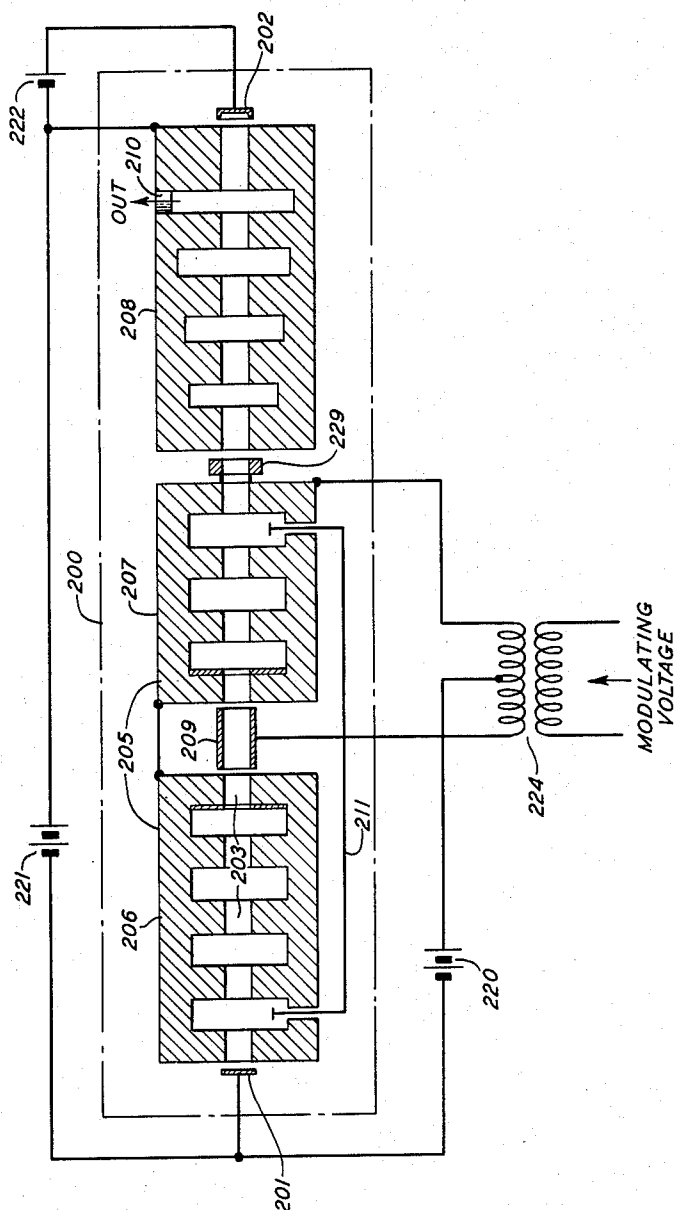
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2 Sheets-Sheet 2

FIG. 3



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TRAVELING WAVE FREQUENCY MODULATOR

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2 Claims. (Cl. 332—25)

This invention relates to microwave devices, and more particularly to such devices which utilize the interaction between a traveling electromagnetic wave and an electron stream.

The utilization of interaction between an electromagnetic wave and an electron stream to secure gain in a microwave amplifier is well known. In such a microwave amplifier, an electric circuit propagates radio frequency electromagnetic waves therethrough at velocities slower than the velocity of light and an electron stream is projected in the direction of wave propagation through the electric field set up by the electric circuit. By proper adjustment of the velocities of the electron stream and the propagated wave the two can be made to interact whereby the wave is amplified and the stream is density and velocity modulated. In operation, the radio frequency field of the electric circuit accelerates electrons in the beam, giving rise therein to an A.-C. velocity component which sets up an A.-C. convection current component. This latter in turn sets up a radio frequency field of its own which combines with the radio frequency field of the electric circuit. When the radio frequency wave and electron stream are properly synchronized, the cumulative action and reaction between the radio frequency field of the circuit and the A.-C. current component in the stream results in a wave which grows in magnitude as it travels along the electric circuit.

In the past, such a device has been adapted as a radio frequency oscillator by returning a portion of the radio frequency output energy to the input. Indeed, one of the difficulties inherent in a microwave amplifier of this kind is its tendency to oscillate because of internal reflection effects which return sufficient wave energy from the output to the input to sustain oscillations.

It is a further characteristic of such traveling wave tubes that noise fluctuations in the electron stream, even apart from any signal wave, tend to excite a wave in the electric circuit which thereafter acts in the manner of an input wave. If the wave circuit is adapted to provide an axial propagation velocity to the excited wave similar to the longitudinal velocity of the electron stream, interaction results and the excited wave is amplified and the stream is density and velocity modulated. Wave energy of this kind also can act to sustain oscillations when sufficient coupling is provided between the output and input. In such a case, the frequency of oscillations will be that frequency near the frequency of maximum amplification for which the phase of the returned energy is proper for self excitation. If the wave circuit is made dispersive, i. e., the velocity of wave propagation therethrough is a function of the frequency of the wave, then the frequency of maximum gain is related to the velocity of the electron stream which in turn will be determined by the beam accelerating voltage which is provided in the device.

In effect, there becomes available a microwave oscillator whose frequency of oscillation is controlled by the potential which fixes the velocity of the electron stream.

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It would appear that by varying this potential it should be possible to vary the frequency of oscillations. Such a device would have a wide range of uses. It could, for example, serve as a swept oscillator providing an output whose frequency could be varied over wide ranges, or as a modulator in a frequency modulation system. Various other applications will be evident to the worker in the microwave art.

However, in practice it has been found that this simple arrangement sometimes operates erratically because the two primary conditions for stable oscillations are not automatically met simultaneously as the stream accelerating potential is changed to vary the frequency of oscillations. As is well known from the study of conventional regenerative oscillators, to maintain stable oscillations it is necessary that the phase shift at the frequency of oscillations around the feedback loop be $2\pi n$ radians (n being any integer) and that at the same time the gain around this loop at this frequency be initially greater than unity. Moreover, if these conditions are met for more than one frequency, there may result oscillations at more than one frequency, or there may be shifting from one frequency to another.

Accordingly, it is an object of the present invention to modify this basic form of traveling wave oscillator to permit stable oscillations over a wide range of frequencies and permit a continuous sweep of frequencies in this range.

To this end, there is provided a microwave oscillator of the general type described comprising a dispersive slow wave circuit wherein there is excited a traveling wave by interaction with an electron stream which is projected through the slow wave circuit. Oscillations are achieved by providing a feedback path for self-excitation between two points of different energy levels along the wave circuit. The frequency of these oscillations is then dependent on the velocity of electron flow through the region of wave interaction, which velocity is fixed by the accelerating potential provided between the electron stream and wave circuit.

One improvement of the present invention consists of the provision of means to maintain the necessary phase relationships automatically as the accelerating potential which controls the beam velocity is modulated to vary the frequency of oscillation. For this purpose, there is provided along the path of electron flow an auxiliary region along which the accelerating potential acting on the stream is modulated oppositely to the variations made in the accelerating potential along the principal region of wave interaction. In a preferred form, the auxiliary region is made a drift space, i. e. a space along which there is an absence of cumulative interaction between the electron stream and a traveling wave. In an illustrative embodiment to be described below, there is inserted along the path of electron flow to provide such a drift space a control electrode whose voltage with respect to the electron stream is varied oppositely to the voltage modulations introduced between the stream and wave circuit for varying the frequency of oscillations. In particular, by applying a modulating voltage to the primary winding of a transformer whose secondary winding has one terminal connected to the control electrode, the other terminal connected to the wave circuit, and an intermediate tap connected to the electron source, the various voltage changes are automatically made in the right sense.

Another improvement relates to the addition of an amplifying section following the oscillatory wave circuit, such that the modulations of oscillatory frequency on the electron beam induce a traveling wave of corresponding frequency in the amplifying section. Advantageously, the frequency response characteristic of the amplifying section is made complementary in its fre-

quency response characteristics to the oscillatory wave circuit whereby the output level is substantially uniform over the modulation band.

The invention will be better understood from the following more detailed description taken in connection with the accompanying drawings of which:

Fig. 1 shows a microwave oscillator in accordance with one embodiment of the invention, characterized by the positioning of a drift space region intermediate between sections of the wave circuit.

Fig. 2 shows a microwave oscillator forming a second embodiment of the invention characterized by the positioning of a drift space region at one end of the wave circuit so as to be adaptable either for reflex or secondary emission type of electron flow operation; and

Fig. 3 shows a microwave oscillator forming a third embodiment of the invention which includes, as a modification of the embodiment of Fig. 1, electron coupling to an amplifier section disposed further along the electron path.

In Fig. 1, there is shown schematically a microwave oscillator 10 in accordance with the invention for utilization as a frequency modulator. The various tube elements are enclosed in an evacuated tube envelope 11 represented here by the broken line. Housed at one end of the envelope and insulated therefrom is the electron gun 12, of conventional structure, to serve as source of an electron stream. Such an electron gun customarily includes an electron emissive cathode surface, a heater unit, and various electrodes for collimating and accelerating the stream, of which only the cathode surface has been shown here for the sake of the simplicity. At the opposite end of the envelope, there is disposed a collector 13 positioned in target relationship with the electron gun 12, the electron gun and collector defining an electron path 14. It is usually desirable to employ magnetic flux producing means, not shown here, outside the tube envelope to provide a longitudinal magnetic field to maintain accurate alignment of electron flow with the electron path. Extending along the electron path is a wave circuit 15 adapted for propagating electromagnetic waves therethrough at a velocity slow compared to the velocity of light. Many of the various slow wave circuits known in the microwave art should be suitable although it is preferable to utilize a circuit which can be made frequency selective, as will be discussed more fully hereinafter. For purposes of illustration the wave circuit here shown is a corrugated cylindrical wave guide, i. e., a hollow cylindrical wave guide whose inner surfaces include a series of transverse corrugations 31 separated by notches or slots 32. The properties of such corrugated wave guides are discussed more fully in my copending application Serial No. 68,549, filed December 31, 1948 which issued on November 17, 1953 as United States Patent 2,659,817. It is shown therein that such a structure is adaptable as a dispersive slow wave circuit whose propagation characteristics can be controlled by adjustment of the width, depth and spacing of these corrugations. For use here, this circuit should be designed to provide both a high impedance, for efficient coupling with the stream at frequencies in the range contemplated for oscillator operation, and also a characteristic axial velocity of wave propagation suitable for interaction with the electron stream over the velocity range of the stream in accordance with the well-known principles of traveling wave tube operation. Additionally, along the electron path, there is inserted for control purposes a drift space region. To this end, the hollow cylindrical conductive control electrode 16 is positioned to surround the electron stream for a portion of its path of flow intermediate between the two sections 17 and 18 of the wave circuit 15, which is severed for the insertion of the control electrode. Substantially an equivalent effect can be realized without severing the wave circuit by interposing a control electrode between the path of flow of the stream and the

wave circuit for shielding the stream from the wave circuit such that the stream velocity is there controlled by the potential of the control electrode rather than that of the wave circuit, provided precautions are taken so that undesirable reflection effects are avoided. Additionally, it is possible to achieve a drift space region by other techniques. For example, by appropriate D.-C. insulation from the remainder of the wave circuit, one section thereof may be maintained at a D.-C. potential that will provide an electron stream velocity therethrough sufficiently different from the wave velocity to inhibit interaction between the wave and stream. In the absence of modulating signals, the electron stream is projected from the gun source to the collector electrode. Perturbations in the electron stream excite an electromagnetic wave in the upstream end of section 17 of the wave circuit, which wave then travels along the section with the characteristic velocity of the wave circuit which is sufficiently like that of the electron stream to provide amplification of the wave and modulation or bunching of the electron stream. The downstream end of section 17 is terminated with impedance matching elements 33 for the absorption of the wave energy to avoid undesirable reflection effects which might otherwise occur because of the impedance mismatch at the start of the drift space region. However, as a result of traversal of the first wave guide section, the electron stream has become modulated and accordingly, when passing through the second wave guide section 18, excites a new traveling wave therein which undergoes further amplification in its travel through the second section. At the downstream end of this second section, at the output 19 there is available an amplified wave for utilization. To maintain oscillations a portion of the output wave is coupled to the input in the correct phase. In this embodiment the coupling is external to the tube by way of the feedback circuit 22, which although shown schematically here as a single conductor, will ordinarily be some form of microwave transmission circuit, for example a wave guide, and which may, in special instances, be provided with special frequency selective and phase shifting elements. To minimize undesirable reflection effects the upstream end of the wave section 18 is terminated in impedance matching element 34. Velocity is provided to the electron stream along the electron path by the accelerating potential provided between the stream source and the wave circuit. To this end both sections of the wave circuit are maintained at the same positive potential with respect to the electron source by the voltage supply 20 connected therebetween. Additionally, to inhibit secondary emission effects the collector 13 is maintained at a potential positive with respect to the wave circuit by means of the voltage supply 21, although various other techniques can be employed to this end.

In operation, to start oscillations, the electron flow is increased slowly at a particular beam velocity. As in the case of conventional regenerative type oscillators, oscillations commence when the phase shift around the closed loop is a multiple of 2π radians and the gain around the loop exceeds unity. In this instance, the loop starts at the upstream end of the first wave guide section, continues along the tube to the downstream end of the second wave guide section, and returns by way of the feedback circuit 22. To minimize the possibility that oscillations occur at more than one frequency, it is desirable that the wave circuit be designed to provide gain only over the frequency band desired. For this reason, frequency selective type of wave circuits are preferred over very broad band circuits such as the helix. However, it is possible to employ such broad band circuits if frequency selective elements are inserted in the feedback path. Additionally, it may be desirable in any case to insert phase shifting elements therein to secure optimum phase relationships. The frequency of oscillations can most conveniently be controlled by the

adjustment of the average velocity of the electron flow through the wave circuit, which in turn is controlled by the potential difference provided by the voltage supply 20 between the electron source and the wave circuit. Apart from the action of a drift space, as the stream accelerating voltage is varied for changing the average stream velocity, the frequency of oscillations tends to remain at the frequency for which the phase shift around the loop is initially a multiple of 2π radians until the operating conditions have changed enough so that there is another frequency for which this phase condition is satisfied at which the gain is greater. Thus, if the stream accelerating voltage is swept continuously over a wide range, the frequency will jump from one frequency to another in discrete steps, instead of varying continuously as is desired. If the wave circuit is made electrically longer, the electrical length being the length measured either in wavelengths or in radians phase shift at the operating frequency, to include more wavelengths, these frequency steps are brought closer. However, in accordance with the basic feature of the present invention, the correct electrical length and hence correct phase is maintained automatically, as the beam velocity is varied, by providing compensation in the closed loop. In a preferred embodiment, this compensation is secured by the insertion of a drift space region along the electron path. In this drift space region, the electron flow is modified in a manner to maintain the electrical length of the loop constant throughout the modulation cycle. In the arrangement shown, this is achieved by introducing the modulating voltage which is to be used to vary the beam velocity and hence frequency of oscillations in a manner that variations in the potential difference between the electron stream and wave circuit are balanced by opposite variations in the potential difference between the electron stream and the control electrode 16. To this end, the modulating voltage is applied to the primary winding of a transformer 24 of whose secondary an intermediate tap 25 is connected to the electron source, a terminal 26 to the wave circuit, and a terminal 27 to the control electrode. It is found that the positioning of the intermediate tap 25 between the two terminals is determined by the relative lengths of the wave circuit and drift space regions, the shorter the relative length of the drift space, the larger the share of the modulating voltage across the secondary being needed to maintain the desired conditions. By proper adjustment of these relationships, there is derived at the output 19 wave energy frequency modulated about a standard frequency in accordance with the modulating voltage impressed on the input of the transformer 24.

Although this preferred embodiment has been described as utilizing a drift space region for control purposes, in special instances it should be possible to achieve substantially the same effect by means of an auxiliary section intermediate the wave guiding circuit along which by any of the suitable means available the electron velocity is varied oppositely to that along the remainder of the wave circuit. For example, the wave guiding circuit can be severed to provide an intermediate section which can be maintained at a D-C. potential which can be modulated oppositely to the main circuit.

Because regenerative oscillators are relatively unstable, being inherently overloaded, it is usually found desirable to provide a buffer stage between such oscillators and utilization circuits. An oscillator of the kind shown in Fig. 1 can conveniently be modified to incorporate such a buffer stage as an integral part thereof. Fig. 3 shows, by way of example, such an oscillator in which there is incorporated an amplifier section which is electron coupled to the oscillatory circuit. As in the oscillator of Fig. 1, there is included within a tube envelope 200 an electron source 201 and a collector electrode 202 which define an electron path 203. Disposed along this path is arranged a slow wave circuit 205, severed to form two

sections 206 and 207 which are separated by a drift space region along which extends the control electrode 209. To sustain oscillations wave energy is returned from the downstream end of the circuit section 207 to the upstream end of the circuit section 206 by way of the feedback path 211. The geometry of the wave circuit 205 and the stream accelerating potential provided by voltage source 220 are chosen to provide cumulative interaction during beam traversal of the wave circuit 205. With respect to these elements which form the oscillatory portion of the tube, the operation is similar to that described above. Oscillations arise when perturbations in the electron stream excite a traveling wave in the circuit section 206 which interacts to modulate the stream which thereafter excites a new traveling wave in the circuit section 207. Frequency stability is achieved by maintaining the electrical length of the feedback loop constant over the modulation cycle by applying modulating voltages through a transformer 224 in the manner described before. As a modification on this basic arrangement, there is provided along the electron path downstream from the wave circuit 205 the wave circuit 208 which acts as an amplifier stage both to provide additional gain and to isolate the output which is derived at the downstream end of the wave circuit 208 by a suitable outlet 210, from the oscillatory portion of the tube. To achieve the desired isolation, the circuit section 207 is separated from the wave circuit 208 by the energy absorbing element 229 which acts to prevent transfer of wave energy from section 207 to the wave circuit 208 so that the electron coupling provided by the modulated stream provides all the coupling between the two wave circuits. Additionally, to realize still greater isolation, the wave circuit 208 is operated under different conditions of wave velocity and electron flow than those which characterize the wave circuit 205. It is, of course, still important to provide for cumulative interaction between stream and wave in this region if an amplified output wave is to be derived for utilization. To this end, the geometry of wave circuit 208 and the accelerating potential, which provided by the voltage supply 221, acting on the electron stream in this region should be adjusted to provide velocities to the electron stream and traveling wave conducive to cumulative interaction. Also it may be desirable to vary the geometry of the wave circuit 208 along its length as shown to provide a non-uniform gain-frequency response in the amplifier section to compensate for non-uniformity in the gain-frequency response of the oscillator circuit, whereby a flat overall gain-frequency response is obtained for the band of interest.

The arrangement shown in Fig. 1 can be modified further to permit the positioning of the drift space region along the electron path outside the wave circuit to avoid severance of the wave circuit which usually creates reflection difficulties. In Fig. 2, there is shown a microwave oscillator in which the drift space region is positioned along the electron path beyond the wave circuit. Enclosed by the envelope 100 are an electron source 101 and a target electrode 102 positioned to define an electron path 103. Disposed along this path are the slow wave circuit 104 and the control electrode 105 which is operated as before to provide a drift space region employed to maintain the electrical length of the feedback loop substantially constant over the modulation cycle. In this case, it is preferable to utilize internal reflections instead of providing an external feedback circuit and, additionally the electron stream is made to retransverse the wave circuit. One convenient technique for the latter is reflex-type of operation. The target electrode 102 is operated at a potential negative to the electron stream by means of the voltage source 107 so that the electrons are subjected to a braking force as they pass through the drift space region and finally are redirected opposite to their original direction. The use of a strong axial magnetic field prevents the electron stream from being deflected out of the electron path 103. Velocity and density modula-

tion of the primary electron stream takes place in traversing the circuit from the source to the target because of cumulative interaction with the wave being propagated through the slow wave circuit. At the end, adjacent the drift space region of the wave circuit, the electromagnetic wave is diverted to the output 108 while the electrons continue on through the drift space until reversed by the influence of the target electrode 102. In retraversing the wave circuit, modulation of the stream continues and a backward traveling wave is propagated towards the electron source end of the circuit. There an intentional mismatch is provided by means of termination 109 which results in a forward traveling wave for starting a new cycle of operation. In other respects, the operation is as described for the tubes of Fig. 1, modulating voltages being applied by way of transformer 124 to vary the beam voltage along the wave circuit and drift space oppositely to maintain the electrical length constant during the modulation cycle.

It should be evident that in this last arrangement, the output wave energy can conveniently be derived at either end of the wave circuit provided that the other end is properly terminated to provide the necessary reflection.

Moreover this tube can be operated in substantially the same manner if secondary emission electrons are provided to retrace the wave circuit and set up a backward traveling wave. In such a case, the target electrode 102 and the voltage source 107 should both be designed to promote secondary electron emission in accordance with generally understood principles.

It is to be understood that the several arrangements described above are merely illustrative of the general principles of the invention. Numerous other arrangements can be devised by one skilled in the art without departing from the spirit and scope of the present invention. For example, other diverse forms of wave circuits and control electrodes can be used, or other equivalent arrangements can be employed for maintaining the electrical length despite changes in the electron velocity.

What is claimed is:

1. In a microwave device, an electron source and target electrode defining a path for electron flow, an oscillatory wave circuit positioned along said path for propagating electromagnetic waves suitable for interaction with the electron flow and having first and second sections,

control means forming a drift space region intermediate between said first and second sections, a feedback circuit connected between said first and second section for returning wave energy from a point of high level to a point of low level for sustaining oscillations, the frequency of which is controlled by the velocity of electron flow past the oscillatory wave circuit, means for providing first and second voltages for controlling the velocity of electron flow past the oscillatory wave circuit sections, respectively, modulating means for varying the first and second voltages in opposite directions simultaneously, and a wave circuit positioned along the electron path downstream from said oscillatory wave circuit in which the modulations on the beam induce a traveling wave for interaction with the electron flow.

2. In combination, an electron source and a target electrode defining a path for electron flow, an oscillatory slow wave circuit positioned along said path for propagating electromagnetic waves having components with phase velocities suitable for interaction with the electron flow, means for returning energy from regions of high level to regions of low level of said oscillatory wave circuit for sustaining oscillations, modulating means controlled by modulating intelligence for varying the velocity of electron flow past the oscillatory circuit for varying the frequency of oscillations, and a slow wave circuit positioned along the path of flow downstream from said oscillatory wave circuit in which the modulations on the beam impressed by the oscillatory wave circuit induce a traveling wave with components having a phase velocity suitable for interaction with the electron stream, the frequency response characteristics of the two wave circuits being made complementary over the modulation band.

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