May 23, 1961 R. KOMPFNER 2,985,790

BACKWARD WAVE TUBE

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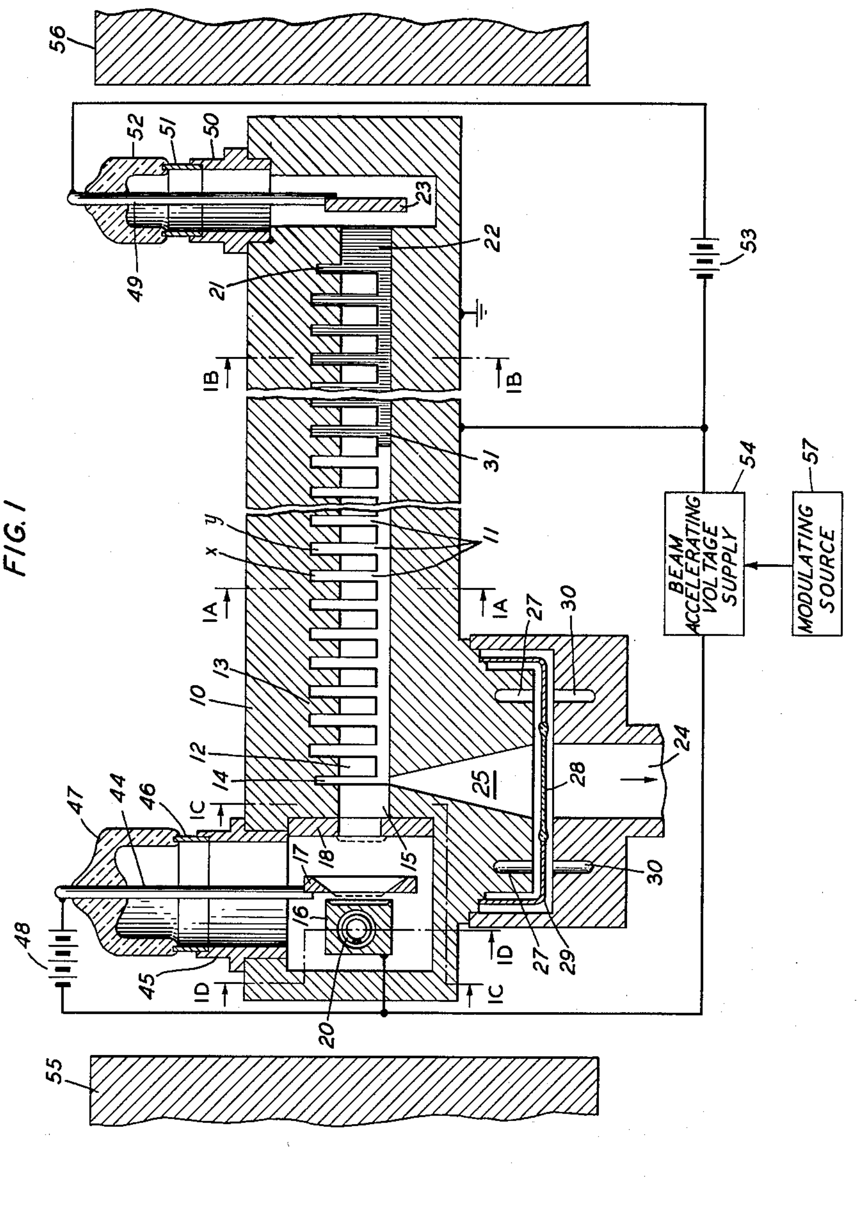

FIG. 1

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FIG. 1C

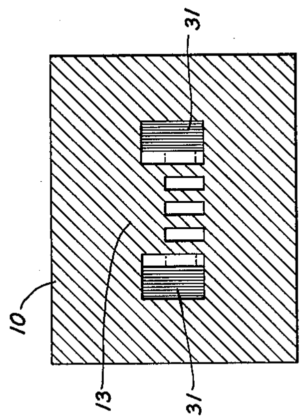


FIG. 1B

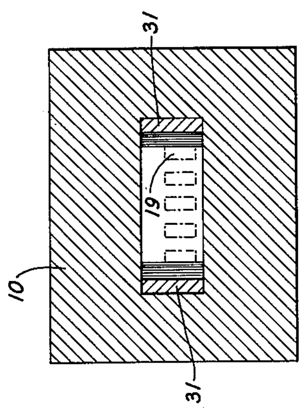


FIG. 1A

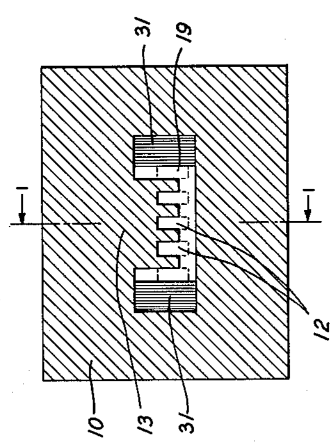
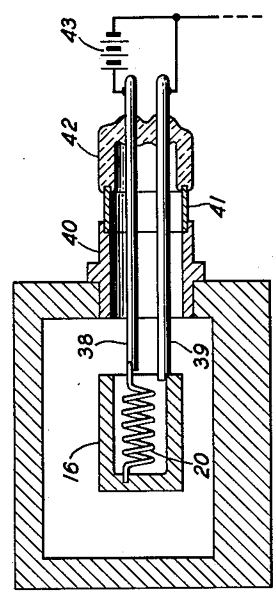


FIG. 1D



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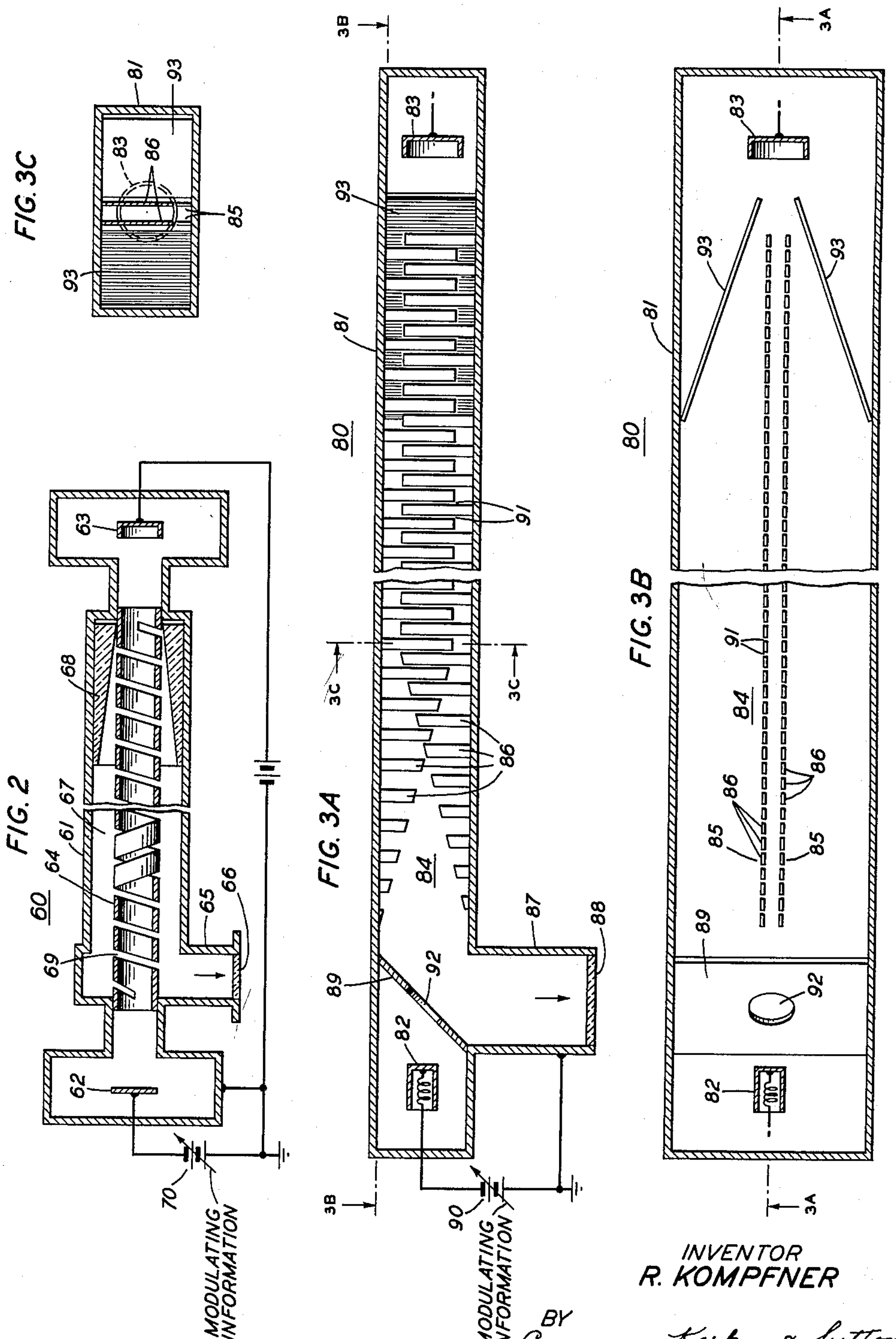

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BACKWARD WAVE TUBE

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2 Claims. (Cl. 315—3.5)

This invention relates to microwave apparatus and more particularly to such apparatus which employs interaction between an electron stream and an oppositely directed or backward traveling wave.

In one important aspect, the invention is directed to a microwave oscillator which can be swept electronically over a wide band of frequencies. In a related aspect, the invention provides a frequency modulator in which an oscillatory frequency is varied in accordance with modulating information.

The utilization of interaction between an electromagnetic wave and an electron stream to secure gain in a microwave amplifier is now well known. In such an amplifier, a wave circuit propagates radio frequency waves therethrough at velocities lower than the velocity of light and an electron stream is projected through the electric field of the wave circuit. By proper adjustment of the velocities of the electron stream and the propagating waves, the two can be made to interact whereby the wave is amplified and the stream is bunched.

In the past, such as amplifier has been adapted for use as a microwave oscillator by returning a portion of the radio frequency energy from an output circuit connection of high signal level to an input circuit connection of low signal level to sustain oscillations. Feedback of this kind has been provided between output and input circuit connections either by external paths or internally as a result of wave reflections.

Generally, in such regenerative oscillators, the oscillations occur at the frequency of maximum loop gain (so long as it initially exceeds unity) at which the phase shift around the loop is an integral number of 2π radians and will be stable at this frequency so long as the loop gain remains at least unity and the phase shift remains an integral number of 2π radians.

In traveling wave tubes which include a dispersive circuit (one in which the phase velocity of wave propagation is dependent on the frequency of propagation), the frequency of maximum gain depends strongly on the beam velocity, which is controlled by the beam voltage. In such tubes if the total phase change around a closed loop between input and output connections is kept constant and equal to an integral number of 2π radians as the frequency of maximum gain is varied by changes in the beam voltage, there should result an electronically tuned oscillator. However, hitherto it has been found difficult to obtain oscillations continuously over a wide frequency band in arrangements of this type since it has been inconvenient to provide that the conditions for oscillations on the loop gain and phase shift be automatically maintained continuously over a wide band of frequencies. In an oscillator in accordance with the present invention, rather than a single closed loop around which the number of wavelengths must be an integer at the oscillatory frequency, there is instead a multiplicity of closed loops, each of which remains automatically an integral number of wavelengths long as the frequency of oscillations varies.

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To this end, each of these closed loops includes, as a component thereof, an electronic feedback path.

Normally one thinks of a feedback path in terms of a form of wave guiding structure. Even in oscillators which employ internal reflections to return energy from points of high level to points of low level, the feedback energy takes the form of reflected waves traveling back along the wave guiding structure. However, an electron beam can carry information too since under suitable conditions a signal can be transmitted by an electron beam in the form of space charge waves traveling along the beam. In this case, the beam may be said to serve as a wave guiding path for space charge waves.

An important feature of the present invention is electronic feedback coupling by which the electron beam acts to return energy from points of higher level to points of lower level along the electron stream for sustaining oscillations. It is a characteristic of such electronic feedback that the phase shift associated therewith can be varied by changing the velocity of the beam which in turn is controlled by the beam accelerating voltage. For use of such electronic feedback coupling, the invention utilizes interaction between an electron stream and an oppositely directed or backward traveling wave. There is described in an article entitled "A Spatial Harmonic Amplifier for Six Millimeters Wavelengths" by S. Millman published in the Proceedings of the I.R.E., volume 39, pages 1035 through 1051, in September 1951, amplification in a mode corresponding to a wave propagating in the direction opposite to that of the electron motion or in a backward propagation mode. Utilization of interaction of this sort is characteristic of the present invention.

In accordance with another feature of the invention the oscillatory output energy is abstracted upstream along the wave path which is the region of higher energy levels for interaction of the kind described. Moreover, for operation over a wide frequency band, it is also in accordance with the invention to terminate the downstream end of the wave path to inhibit reflections there. In this way, substantially all the wave energy available at the upstream end of the wave path is the result of interaction in a backward propagating mode.

The expressions "downstream" and "upstream" as used herein refer to the direction of electron flow and the direction opposed to the direction of electron flow, respectively, so that the "downstream end" of the wave path or tube is the end at which the target electrode is placed while the "upstream end" is the end at which the electron source is located. Similarly, expressions such as "upstream relative to" and "downstream of" mean "on the electron source side of" and "on the target electrode side of," respectively.

In an illustrative embodiment in accordance with the invention, an electron source and a target electrode define a path of electron flow along which is positioned a dispersive wave guiding structure in which the strength of the interacting component of the field associated with a wave propagating therethrough is made alternately large and small at successive fixed intervals along the structure. The velocity of the electron stream is adjusted to interact with spatial harmonics of an electromagnetic wave excited in the wave guiding structure which travels in a direction opposite to that of the electron flow. Oscillatory power is abstracted at the upstream end of the wave path and the downstream end of the wave path is made substantially reflectionless to inhibit internal reflections. The frequency of oscillations is varied by changes in the beam voltage which determines the velocity of the electron stream. Moreover, by applying modulating signals from an appropriate information source to vary the beam voltage, there is made available a frequency modulator.

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

Fig. 1 is a longitudinal cross section of an embodiment in accordance with the invention which employs a wave guiding structure which has a series of open lateral slots;

Figs. 1A, 1B, 1C, and 1D are cross sections taken along the lines 1A—1A, 1B—1B, 1C—1C, and 1D—1D, respectively, of the embodiment shown in Fig. 1;

Fig. 2 shows an embodiment which utilizes a ribbon helix as the wave guiding structure; and

Figs. 3A, 3B, and 3C are cross sectional views taken along planes parallel to the side, top and end, of an embodiment which employs an interdigital filter type of wave guiding structure.

With reference particularly to Fig. 1, the traveling wave tube shown by way of example is constructed largely of non-magnetic conducting material (e.g., copper). An elongated copper block **10** forms the main portion of the tube and has an evacuated hollow interior to guide electromagnetic waves. The wave guiding path includes a series of lateral slots **11** which are regularly spaced for most of the length of the tube. Three longitudinal slots **12** cross lateral slots **11** and extend for substantially the whole length of the tube. The lateral slots **11** are in the nature of resonators and serve to increase the field strength of the wave in their vicinity. Between the slots, the effect of the fins **13** is to reduce the strength of the interacting components of the field. The effect is to make the strength of the interacting component of the field of waves propagating therethrough alternately large and small at successive intervals along the guiding structure. The longitudinal slots **12** serve to increase the space in which the electron stream can interact with propagating waves.

Details of the wave guiding path are shown in the cross sectional views of Figs. 1A and 1B. Fig. 1A is a section taken between two slots **11**, along the line 1A—1A, while Fig. 1B is a section taken through a slot **11**, along the line 1B—1B.

As shown in Fig. 1B, the cross section of the hollow interior of the block **10** is rectangular at each slot **11**, with the short dimension vertical. The cross section of the hollow interior of the block **10** between slots **11** is much the same, as shown in Fig. 1A, except that a rectangular fin **13** extends down into the interior from the center of the top of the hollow interior. The spaces between adjacent fins **13** form the slots **11**. The bottom edges of the fins **13** contain three spaced longitudinal slots **12** which extend for substantially the whole length of the tube.

Just to the left of the fin **13** farthest to the left in Fig. 1, is an end slot **14**. This slot is slightly shallower and narrower than the remaining slots **11** for improved matching. To the left of slot **14** is a short connecting section **15**, a cross section, taken along the line 1C—1C, being shown in Fig. 1C. The connecting section is of the same cross section as the between-the-slot cross section of Fig. 1A, except that the sections of the fin between longitudinal slots **12** extend to the bottom of the opening to provide a radio frequency short at the end of the wave guiding path.

To the left of connecting section **15**, block **10** has a hollow interior of rectangular cross section to provide space for a cathode **16** and a control grid **17**. An accelerator grid **18** also occupies part of the space to the left of connecting section **15**, comprising a flat molybdenum plate of rectangular cross section with a central screened rectangular aperture. The molybdenum plate is flush against the right-hand end of the open space and the aperture is aligned with passage **15** and fins **13**. The aperture and the previously described end section determine the shape of an electron stream which is projected past fins **13**, the shape being approximately that shown by the dotted outlines **19** in Figs. 1A and 1B.

An oxide coated nickel cathode **16** is located in the left-hand portion of the open space. Cathode **16** is rectangular in cross section and its oxide coated surface faces to the right and is aligned with the aperture in the plate comprising accelerator grid **18**. Cathode **16** has a hollow interior and contains a heating coil **20** which will be described later.

Control grid **17** is located between cathode **16** and accelerator grid **18**. It comprises a thin molybdenum plate with a rectangular screened aperture which is also aligned with the aperture in the plate comprising accelerator grid **18**. The manner in which both cathode **16** and control grid **17** are supported will also be described later.

Just to the right of the fin **13** farthest to the right in Fig. 1 is an end slot **21** which corresponds to slot **14** on the left. A short connecting section **22**, corresponding to section **15** on the left, extends between slot **21** and a rectangular hollow portion at the right-hand end of block **10** which contains a collector electrode **23**. Collector **23** is a flat rectangular molybdenum plate and is aligned with section **22** and fins **13** to intercept the electrons which are projected past fins **13**. The manner in which collector **23** is supported will be described later.

At the upstream end of the tube (that is, near the electron gun), end slot **14** is connected to output wave guide **24** by a tapered wave guide **25**. Wave guide **24** is of standard rectangular cross section and its long dimension is normal to the plane of the drawing. Wave guide **25** is also of rectangular cross section, and is tapered to act as an impedance transformer. A short distance below the base of rectangular guide **25**, block **10** terminates in a flat circular face which projects somewhat from the rest of block **10**.

An annular slot **27** opens on the flat circular face of block **10** and surrounds guide **25**, serving as a radio frequency choke. The interior of block **10** is sealed off by a glass window **28**, which is separated slightly from the face of block **10** and situated directly below guide **25**. Window **28** is held in place by a molybdenum cup **29** which surrounds the projecting portion of block **10** and is brazed to block **10** outside of chock **27**.

The end of wave guide **24** is enlarged to fit over the raised portion of block **10** and make contact with block **10** without touching molybdenum cup **29**. Except for a circular flange which surrounds cup **29**, guide **24** is terminated in a flat circular face which is parallel to the face of block **10** and is located just below it on the other side of glass window **28**. The rectangular interior of guide **24** is aligned with guide **25** and is similarly surrounded by an annular slot **30**, which serves as a radio frequency choke.

At the downstream end of the tube (that is, adjacent collector electrode **23**), the wave guiding path is suitably terminated to minimize internal reflections therefrom. To this end, there is included in each opening formed at this end of the tube between the central fin portion **13** and the sides of block **10** a wedge **31** of ceramic material with suitable lossy material, for example, colloidal graphite. The cross section of the wedge increases in the direction of electron flow and the wedge extends advantageously over several wavelengths of the wave guiding structure. By thus tapering the lossy wedges, a wide band impedance match can be obtained and reflections from this end of the wave guiding path can be substantially eliminated. The provision of dissipative terminations at the downstream end of the wave path to inhibit reflections is an important feature in accordance with the invention. As a result, interference effects between backward and forward traveling waves can be minimized and a more uniform frequency versus output characteristic can be realized. In general internal reflections cannot be completely eliminated since successive slots of the wave guiding structure will contribute some reflection.

It is of course feasible to employ various other arrangements for effecting the broad band termination desired, as for example, coupling to the downstream end of the wave guiding circuit a standard wave guide which is terminated.

The entire tube extends lengthwise between two poles **55** and **56** of an electromagnet which supplies a longitudinal beam focussing magnetic field.

Fig. 1D shows a section of the tube taken through cathode **16**, along the line 1D—1D, illustrating the manner in which cathode **16** is supported and the manner in which it is heated. As shown, one end of heating coil **20** is embedded in cathode **16**. The other end of coil **20** is attached to a tungsten rod **38**. Cathode **16** is attached to another parallel tungsten rod **39**, both rods extending out of the tube, to the right in Fig. 1D, and out normal to the plane of the drawing in Fig. 1. A copper sleeve **40** surrounds rods **38** and **39** and fits tightly into the side wall of block **10**, forming a passage out of the tube. A short molybdenum sleeve **41** is brazed to the end of sleeve **40** and a glass cap **42** is sealed to the end of sleeve **41**. Rods **38** and **39** extend through the end of glass cap **42**. A heater potential source **43** is connected between rods **38** and **39**, causing cathode **16** to be heated and its oxide coated face to emit a stream of electrons.

As shown in Fig. 1, control grid **17** is attached to a tungsten rod **44** which extends upwardly out of the tube. A copper sleeve **45** fits tightly into the top wall of block **10** to form a passage out of the tube. A short molybdenum sleeve **46** is brazed to the end of sleeve **45** and a glass cap **47** is sealed to the end of sleeve **46**. Rod **44** extends through the end of glass cap **47** and is connected to the positive terminal of a biasing voltage supply **48**, the negative terminal of which is connected to rod **39**, as shown in Fig. 1D. It should be noted that while Fig. 1 shows a connection from the negative terminal of voltage supply **48** passing through the left end wall of the tube, such a representation is only schematic and is for the purpose of depicting a complete circuit. The actual connection is to the end of rod **39** as shown in Fig. 1D.

The collector electrode **23** at the right-hand end of the tube is attached to a tungsten rod **49** which extends through an opening in the top of block **10**. A copper sleeve **50** surrounds rod **47** and fits snugly into block **10** to form a passageway out of the tube. A short molybdenum sleeve **51** is brazed to the end of sleeve **50**, and a glass cap **52** is sealed to the end of molybdenum sleeve **51**. Rod **47** extends through the end of glass cap **52** and is connected to the positive side of a battery **53**.

The negative side of battery **53** is connected directly to copper block **10**, which is also grounded. The negative side of voltage supply **53** is also connected to the positive terminal of a main beam accelerating voltage supply **54** which is made variable. The negative terminal of voltage supply **54** is connected to the negative terminal of voltage supply **48**. For operation as a frequency modulator, modulating signals from an appropriate modulating source **57** are inserted in series with the steady beam voltage to vary the velocity of electron flow along the wave guiding path for modulating the oscillatory frequency as a function of the modulating signals.

It is characteristic of an intermittent type circuit of the kind shown in Fig. 1 that an electron stream can be made to interact with a backward traveling wave. For such interaction, the velocity of the electron stream is adjusted so that in the time that an electron traverses the distance between the slots where the interacting field component is high, the backward wave travels an integral number of wavelengths less substantially this same distance. In a more quantitative sense, the intermittent wave circuit shown can be considered a filter type iterative circuit. If there is set up in the circuit a wave which travels along the circuit in a direction opposite to the electron flow, interaction may be had with this wave if the electron speed is made substantially equal to

$$\frac{\omega d}{2\pi n-\beta}$$

where ω is the angular frequency of the backward traveling wave, d is the average length along the path of electron flow of one filter section, n is an integer, and β is the phase displacement per section of the backward wave. When this condition is met, a given group of electrons interacts with like portions of the backward wave at successive interaction intervals. Such operation is generally characterized as spatial harmonic. The presence of relatively longer intervening regions of low field serves to shield the electrons from out-of-phase components of the wave.

In the operation of the oscillator of the invention, when the electron stream is turned on and the stream current is made to exceed a certain starting current, noise components therein tend to excite a backward traveling wave which acts in the manner of the wave described in the analysis above, and, accordingly, there results a growing backward traveling circuit-wave which is associated with forward traveling space charge waves or density modulations on the beam. This association results in electronic feedback. More simply, the operation can be described as follows. At a given time, that portion of the excited wave at a particular slot **11** where the longitudinal electric field component of the wave is high acts on the group of electrons in the vicinity of the slot and velocity modulates and bunches the electrons correspondingly. This bunched electron group moves downstream and at succeeding slots interacts with that portion of the excited wave then at these slots. If the relative velocities of the stream and excited wave are as described, the group of electrons will "see" the same phase of the excited wave at the successive slots, and, accordingly, the electron stream will be periodically velocity modulated and bunched as it moves downstream, while the excited backward traveling wave will similarly grow in amplitude as it proceeds upstream along the wave guiding path. It can be seen that instead of a conventional single closed loop for energy circulation, there are here a multiplicity of closed loops for energy circulation, each comprising a downstream path of travel for oscillatory energy in the form of space charge waves along the electron stream between pairs of slots and a return upstream path for oscillatory energy in the form of a backward wave traveling along the circuit between the same pairs. Moreover, these loops for circulating energy exist not only between pairs of successive slots but also between any two slots.

By utilization of a wave guiding circuit which is dispersive, varying the beam velocity can be made to vary the frequency of maximum gain. In particular, if the beam velocity is varied continuously, the frequency of maximum gain varies accordingly. However, for stable oscillations at the frequency of maximum gain, it is necessary that the phase shift around each of the circulating loops remain an integral number of 2π radians, as this frequency of maximum gain varies. It can easily be shown with reference to Fig. 1 that the phase change from the yth slot to the xth slot moving along with the excited circuit wave in the backward direction, plus the phase change from the xth slot to the yth slot moving with the electron beam in the forward direction is an integral multiple of 2π if the velocity of the electron flow and the phase velocity of the circuit wave satisfy the condition that a given group of electrons see a corresponding phase of the electric field of the wave at each slot. Quantitatively, this means that the time needed by an electron of velocity u to travel the distance d between two slots should be equal to the time taken by the wave of phase velocity v to travel and integral number of whole wavelengths along the wave guiding structure λ_g minus the distance d, or that:

$$\frac{d}{u}=\frac{n\lambda_g-d}{v} \quad (1)$$

where n is an integer. The phase shift in radians along the electron path from one slot to the next is, therefore,

$$\frac{\omega d}{u}$$

where ω is the angular frequency of oscillations. The phase shift in radians along the circuit is

$$\frac{\omega d}{v}$$

The total phase shift is then

$$\frac{\omega d}{u}+\frac{\omega d}{v} \quad (2)$$

By substituting in Equation 2 the value of

$$\frac{d}{u}$$

given by Equation 1, there is obtained

$$\omega\left(\frac{n\lambda_g-d}{v}\right)+\frac{\omega d}{v}=\frac{n\lambda_g\omega}{v}=2n\pi \quad (3)$$

since

$$\frac{\lambda_g\omega}{v}$$

is equal to 2π from the definitions of the various terms. Accordingly, the condition for oscillations on the phase shift around the closed loops remains automatically satisfied even though the velocity of the electron stream is varied. As a result of this operation, continuous tuning over very wide frequency ranges can be achieved merely by varying the beam voltage, which is provided, for example, by the variable voltage supply **54** to vary the beam velocity.

Such a swept oscillator is adaptable to a variety of uses. In particular, by superimposing modulating voltages derived from a source **57** of signal information on the steady beam voltage, there can be achieved frequency modulation in accordance with the signal information of a base frequency corresponding to the steady beam voltage. It is of course possible to employ various other arrangements to vary the beam velocity past the wave guiding structure in accordance with modulating information.

For optimum results, it is desirable to provide as good a termination at the downstream end of the wave guiding path as possible. Accordingly, the dissipative blocks inserted there are designed to minimize reflections over the entire band of wavelengths which are likely to propagate along the wave guiding structure. In this way, there are prevented oscillations due to reflected forward waves which might otherwise interfere with the desired backward oscillatory wave. Moreover, this expedient also tends to improve the uniformity as a function of frequency of the output level of backward oscillations.

It is also desirable to provide a uniform transition at the upstream end between the output wave guide and the wave guiding circuit for uniform output over the frequency band of interest.

In general, the circuit structure should have a high impedance effectively constant and a low circuit loss over a wide frequency band when supporting a backward mode of propagation. Additionally, the circuit should be easily matched to conventional output circuits over a wide frequency band.

Various other forms of wave guiding circuits can similarly be employed for propagating the backward wave. It is generally advantageous to utilize a wave guiding structure designed to favor interaction with a cylindrical electron beam in order to benefit by greater uniformity of electron velocity, lower magnetic focussing fields and lower cathode loading. Fig. 2 shows schematically an oscillator **60** wherein there is incorporated a ribbon helix type of wave circuit which can be advantageously employed in cooperation with a cylindrical beam. The various tube elements are enclosed in an evacuated tubular envelope **61** which preferably is of a non-magnetic metal such as copper. At one end of the envelope there is positioned the electron source **62** which is shown schematically (for simplicity in the drawings) as a cylindrical electron emissive cathode. At the opposite end of the envelope there is disposed the target electrode **63** which defines with the electron source a longitudinal path of electron flow. Conventional magnetic focussing is employed to minimize radial components of electron flow. Beam accelerating voltage is provided by the beam voltage source **70**. Along the path of electron flow there extends the wave circuit which comprises a ribbon conductor **64** helically wound or otherwise fashioned, for example, to have a distance around one turn substantially equal to one half the average wavelength in the frequency band planned for operation. The electron source preferably is adapted to provide a hollow cylindrical beam whose flow is parallel and contiguous to the broad dimension of the ribbon conductor and coaxial with the helix. This particular embodiment is designed to have the stream flow past the inner surface of the ribbon helix, although it is feasible to have the flow past the outer surface, or past both surfaces simultaneously. Output waves are derived for utilization at the upstream end of the wave circuit in accordance with one feature of the invention. To this end, a wave guide **65**, which is of standard rectangular cross section with its long dimension normal to the plane of the drawing and which forms by way of the vacuum-tight glass window **66** a continuation of transmission path to suitable utilization apparatus, is coupled to the upstream end of the helix wave circuit for abstracting wave energy therefrom in the manner well known in the art of abstracting wave energy from a helix wave circuit. One convenient technique for achieving a suitable wave circuit of this kind is to groove a hollow metallic cylinder along a suitable helical path. In particular, the wave circuit shown is of this construction. A thin-walled cylinder **67** of length sufficient to extend from the output wave guide to a point short of the target electrode is grooved as shown along a helical path **69** which thereafter becomes the gaps between helix turns. For a more uniform transition between helical wave circuit and the wave guide output, at the upstream end the pitch of the helical grooving is tapered, in the manner well known in the art for improving helix terminations. Downstream beyond this tapered end, the pitch of the helical grooving becomes uniform at a geometry for providing wave phase velocities suitable for interaction with convenient beam velocities. In according with an important feature of the invention, internal reflections at the downstream end of the wave circuit are to be inhibited. To this end, there is provided at the downstream end of the wave circuit a suitable dissipative termination, which for example, as shown comprises a cylindrical ceramic block **68** which surrounds the downstream end of the helix circuit and is apertured for passage of the electron flow in a truncated right circular cone having its base at the upstream end of the block and coated along its inside surface with suitable lossy material.

In operation, this embodiment resembles that shown in Fig. 1. The ribbon helix provides an intermittent interaction wave guiding path in which when waves propagate along the helix ribbon the gaps **69** between turns are characterized by high axial electric fields whereas the longer regions adjacent the helix turns are characterized by substantially lower axial electric fields. Accordingly, the path of travel for a particular group of electrons will encounter periodic intervals of high interacting field components interspersed with regions of lower interacting field components. As before, the velocity of electron flow is adjusted by means of the voltage supply **70** so that a particular group of electrons will interact at the intervals of high field with corresponding phases of a backward traveling wave. To this end, the velocity of the stream is made such that while an electron traverses the average distance between turns, the backward traveling wave traverses an integral number of wavelengths less the average distance between turns. Accordingly, when the electron beam current reaches a sufficient value, noise components in the stream excite a backward traveling wave which interacts with the electron flow for providing an oscillatory output at the upstream end of the wave guide.

An oscillator of this kind similarly can be adapted for application as a frequency modulator by the insertion in series with the steady beam accelerating voltage **70** of modulating voltages supplied from a suitable information channel.

Figs. 3A, 3B, and 3C show schematically side, top, and end sections of a backward wave oscillator **80** which utilizes an interdigital type wave circuit. The elongated evacuated envelope **81**, for example of rectangular cross section, is of a non-magnetic metal, such as copper. At opposite ends, an electron source **82** and a target electrode **83** therebetween define a longitudinal path of electron flow, which, for example, can be a hollow cylindrical beam. Magnetic focussing is employed to minimize transverse components of electron flow in the manner described above. Beam accelerating potential is supplied by the voltage supply **90** which maintains the electron source at a negative potential with respect to the envelope. For operation as a modulator, provision can be made for applying signals from an appropriate information source for modulating this potential. As in the earlier described arrangements, electromagnetic waves are excited for travel in a direction opposite to that of electron flow along a suitable slow wave guiding structure for interaction with the electron flow. In this case, to serve as a slow wave circuit, there is provided along the path of flow a loaded wave guide **84** which comprises the intermediate portion of the tube loaded by means of two rows or sets **85** of regularly spaced conductive fins or fingers **86** extending in a linear array in an interdigital pattern from the two opposite broad inner surfaces of the envelope. Each row is parallel to and on opposite sides of the tube axis. Each of the fingers extend normal to the path of flow. Two separate rows are used in this instance to provide two parallel circuits as a result of which more efficient use is made of a given tube length. For a broad band match the length of the fins of each row increase at the upstream or output end gradually towards the center section which comprises a multiplicity of fins of uniform length. The dimensions and spacing of the fingers are adjusted to provide phase velocities to backward traveling waves suitable for interaction with electron streams of velocities conveniently realized. The length of each of the fingers along the main region of the circuit is sufficient to have the fingers projecting from one surface interleave with the fingers projecting from the opposite surface for forming longitudinal gaps **91** between successive fingers. Adjacent these regions of finger interleaving along the path of flow, there results a succession of relatively long regions adjacent to the fingers interspersed with the shorter longitudinal gaps between fingers. Accordingly, as in the wave circuits previously described in connection with Figs. 1 and 2, when an appropriate electromagnetic wave propagates along the structure, the longitudinal component of the electric field along the path of flow is made alternatively large and small corresponding, respectively, to the longitudinal gaps between fingers and the longer drift regions adjacent the fingers.

Oscillatory power is abstracted for utilization at the upstream end of the wave circuit by way of an output connection which comprises a conventional rectangular wave guide **87** having its broad dimension parallel to the direction of electron flow. This wave guide connection **87** is provided with a pressure-tight window **88** by way of which output energy may be abstracted for utilization. This wave guide connection makes a right angle bend with the elongated portion of the tube envelope which comprises the wave circuit and, accordingly, a 45 degree deflection plate **89** is provided at the bend in the manner known to the art for diverting the waves traveling longitudinally along the tube to the output wave guide **87**. This plate **89** is provided with a cylindrical aperture **92** for passage therethrough of the electron flow.

As in the arrangements described above, the reflectionless terminations are provided downstream along the wave path to inhibit reflections upstream therefrom. For this purpose, ceramic members **93** suitably coated with lossy material are inserted at the downstream end, arranged obliquely on each side of the linear arrays **85** as shown in Fig. 3B.

In operation, when the electron current exceeds a certain value, noise components in the electron stream excite a wave which travels upstream along the slow wave circuit, growing as a result of interaction with the electron flow. The electron velocity is adjusted so that a particular group of electrons interacts with like portions of the backward traveling wave as it traverses successive gaps between fingers where the longitudinal fields are high. In this case, however, the direction of the longitudinal field between fingers reverses at each successive gap. This is a characteristic well known for such interdigital structures which, in effect, are special forms of folded wave guides. To compensate for the π radians phase reversal between gaps, for interaction the electron velocity is made such that while an electron traverses the average distance between successive gaps, the wave traverses an integral number of half wavelengths less substantially this average distance. In a quantitative sense the velocity of the electrons would be adjusted to be substantially equal to

$$\frac{\omega l}{n\pi-\theta}$$

where ω is the frequency of the backward traveling wave, l is the average distance along the path of electron flow between successive gaps, n is an integer, and θ is the phase displacement of the wave between successive gaps.

However, if this interdigital structure is treated for purposes of analysis as a plurality of iterative filter sections, each section comprising a pair of adjacent fingers and associated gaps, for interaction the velocity of the electron stream is adjusted so that while a given electron travels along the electron path the length of one filter section, the backward traveling wave traverses an integral number of wavelengths less this same length. Quantitatively, for interaction, the velocity of the electron stream should be such that

$$\frac{\omega d}{2n\pi-\beta}$$

where d is the average length of a filter section i.e. the average distance between successive like gaps, and β is the phase displacement per filter section of the backward wave. It can be seen that this relationship is similar to that derived for the wave circuits shown in Figs. 1 and 2.

For operation as a frequency modulator, as described above, modulating signals are superimposed on the beam potential provided by the voltage supply **90** for varying the beam velocity.

Accordingly, it is to be understood that the various embodiments described above are merely illustrative of the general principles of the invention. For example, any of the structures herein disclosed may be used as a microwave amplifier by substituting for the reflectionless terminations shown at the downstream end of the tube a suitable reflectionless input connection for supplying electromagnetic energy to the wave guiding circuit. Various other alternative arrangements can be devised by one skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. Microwave apparatus comprising an electron source and an electrode for producing an electron stream, a source of potential for accelerating the flow of said electrol stream, a wave guiding structure for transmitting electromagnetic waves in a direction opposite to the flow of said electron stream and in interacting relationship therewith, and output means coupled to said wave guiding structure at the end thereof adjacent said electron source for abstracting therefrom electromagnetic wave energy, said wave guiding structure including an elongated envelope having two opposite inner surfaces extending along the path of said electron stream, and a pair of rows of longitudinally spaced conductive elements projecting from said surfaces parallel to and on opposite sides of said path, the elements of each row projecting alternately from the opposite surfaces of said envelope in interdigital relationship to form longitudinal

gaps between successive elements in each row, said gaps being narrower than the dimensions of said elements parallel to said path, said elements being so arranged that each element of each row is positioned transversely opposite an element of the other row and each pair of transversely opposite elements projects from the same surface of said envelope.

2. Microwave apparatus as defined in claim 1 wherein the conductive elements of each row at the end thereof adjacent the electron source are of less length than all the other elements of the same row.

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