July 19, 1960 A. KARP 2,945,981

MAGNETRON-TYPE TRAVELING WAVE TUBE

Filed June 13, 1955 4 Sheets-Sheet 1

FIG. 1

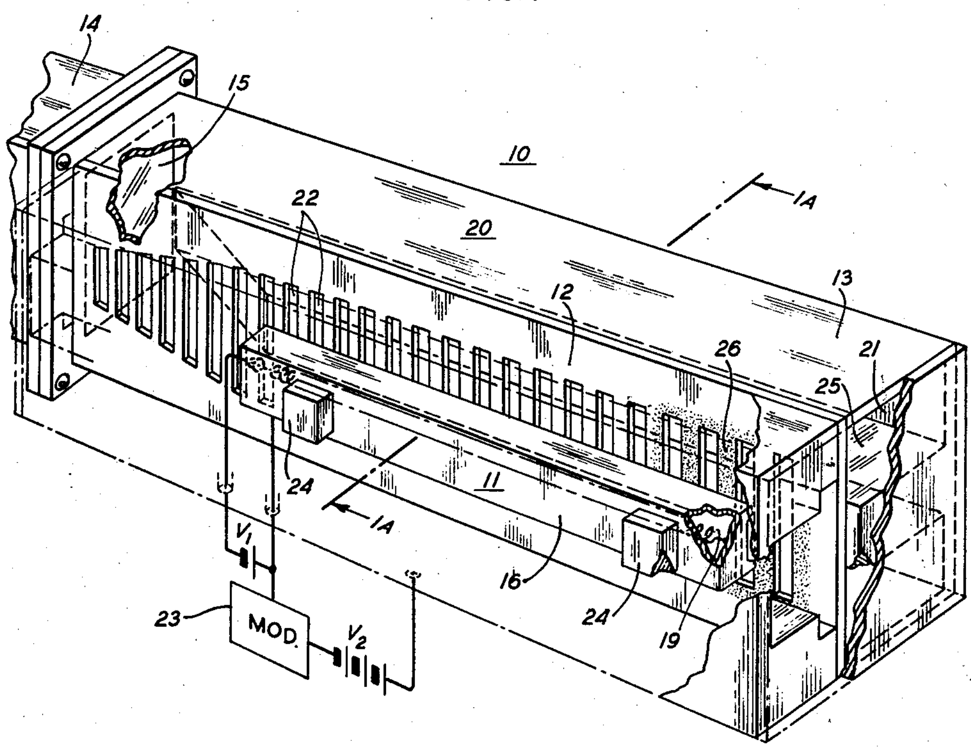

FIG. 1A

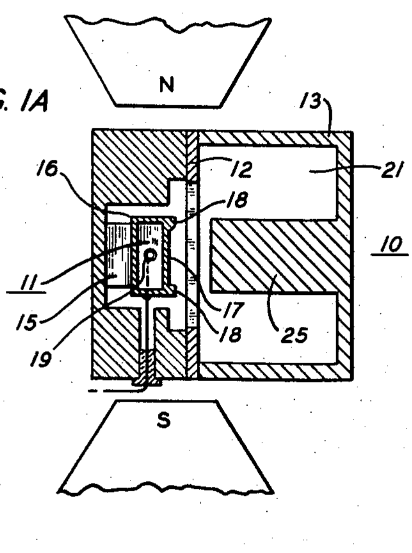

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FIG. 2

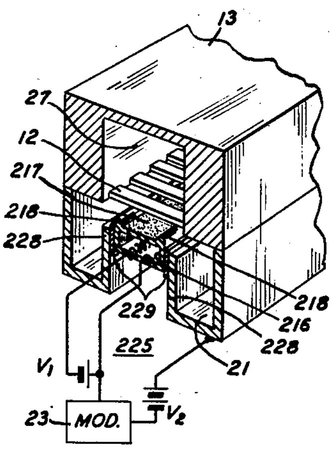


FIG. 3

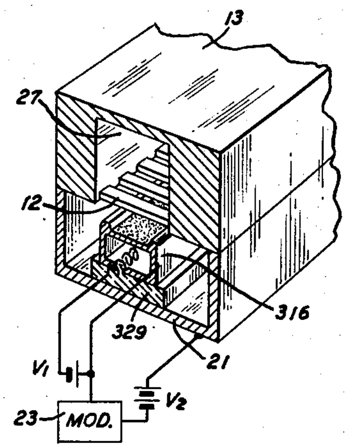


FIG. 4

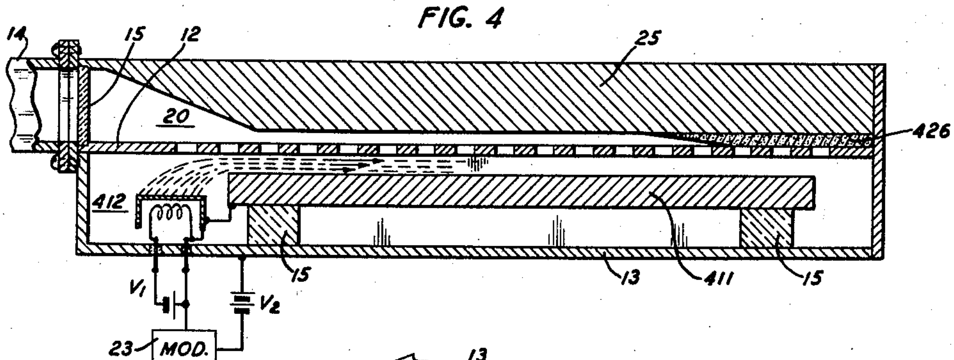
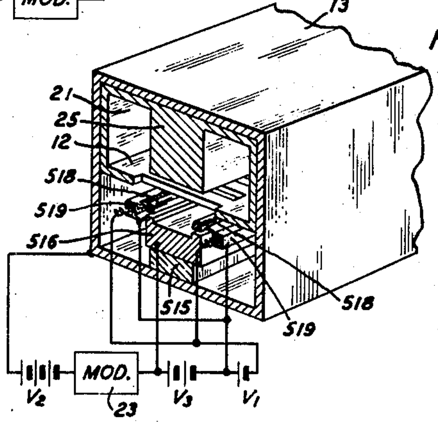


FIG. 5



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MAGNETRON-TYPE TRAVELING WAVE TUBE

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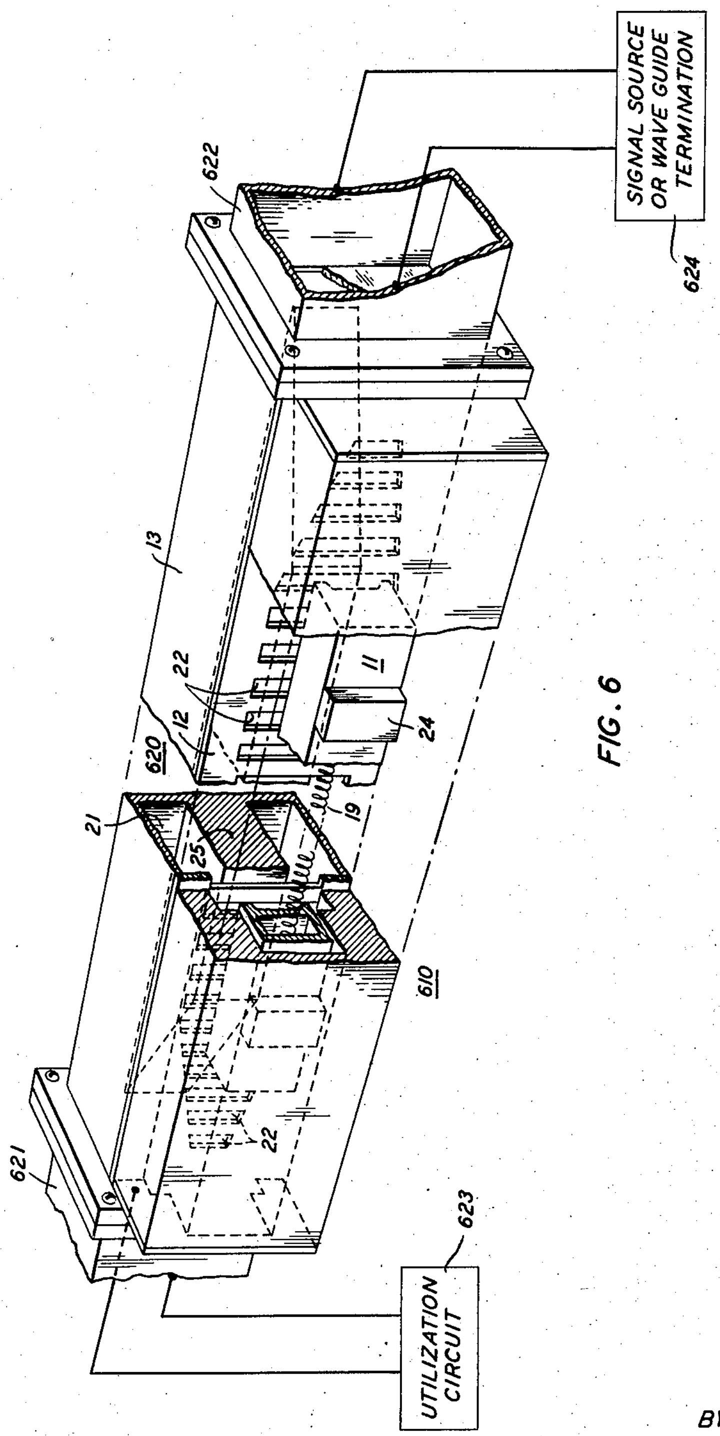

FIG. 6

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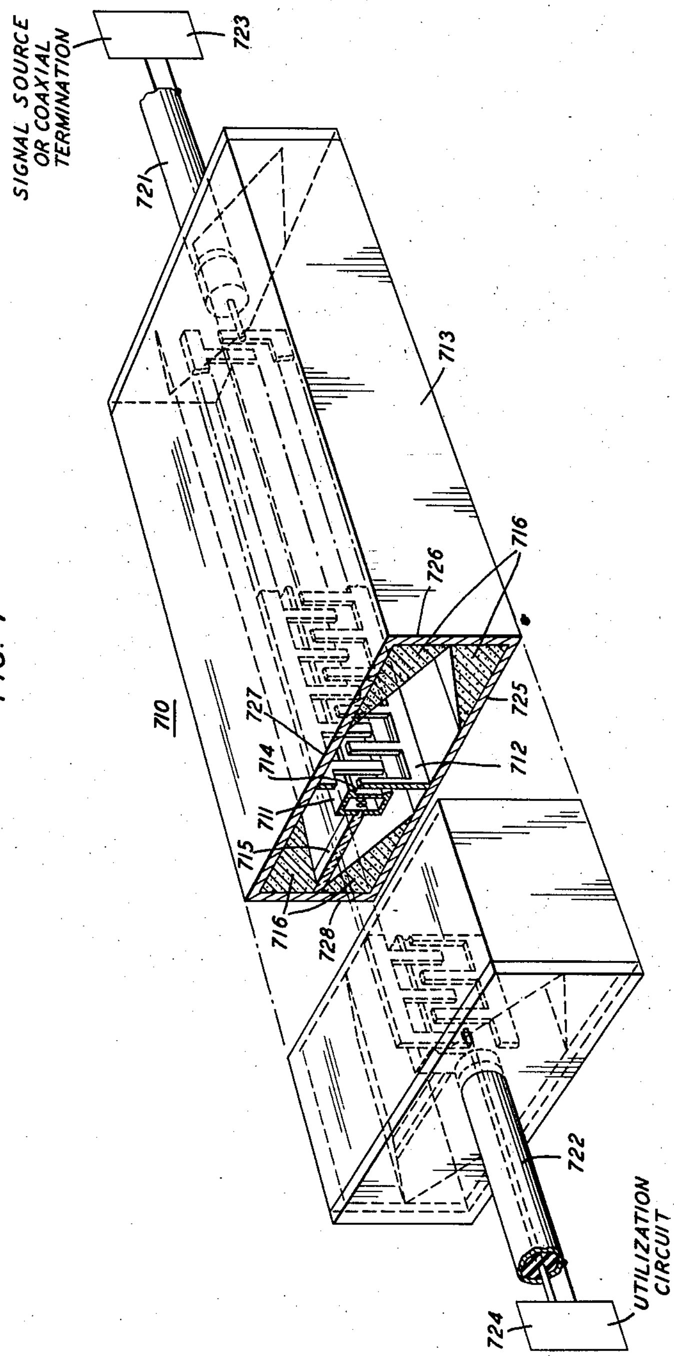

FIG. 7

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MAGNETRON-TYPE TRAVELING WAVE TUBE

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19 Claims. (Cl. 315—3.5)

This invention relates to high frequency electronic devices and more particularly to those devices of the traveling wave type.

This application forms a continuation-in-part of my application Serial No. 328,625, filed Dec. 30, 1952, which describes a novel form of slow wave circuit especially suited for use in traveling wave tubes of the colinear type in which the electron beam passes along a wave propagating circuit parallel to the flux lines of a beam-focusing field. In one aspect the present invention relates to the combination of a circuit of the kind described in the parent application with other necessary elements to form a traveling wave tube of the crossed-field type in which the electron beam passes through a region of crossed electrostatic and magnetostatic fields. It has been found that circuits of the type described have particular advantage in a crossed-field device in that they afford a solution to operating problems of such devices which have not heretofore been solved. In a broader aspect, however, the present invention relates to the use, in crossed-field type tubes, of slow wave circuits whose effective interaction impedance increases with increases in frequency.

Traveling wave tubes of two distinct types have received considerable attention recently in an effort to obtain efficient high frequency amplifiers and oscillators capable of operating over very wide frequency bands.

The first type, which is referred to herein as the "colinear" type, utilizes the principle of kinetic energy interchange between a moving electron beam and a traveling electromagnetic wave wherein the beam, the component of the traveling wave interacting therewith, and the electric or magnetic field used for focusing the beam are all parallel; hence the term "colinear."

The second type, referred to herein as the "crossed-field" or magnetron type, utilizes the principle of potential energy interchange between electrons of a moving electron beam and a traveling electromagnetic wave. Tubes of this type are characterized in that they employ both an electric and a magnetic field, the two fields being perpendicular; hence the term "crossed-field" type. In tubes of this type an electron beam is projected along a path in a direction perpendicular to both fields. The electron beam in moving through the perpendicularly disposed electric and magnetic fields is focused by the combined action of these fields to pass in coupling proximity with a component of a traveling wave. The effect of the variations in electric field intensity of the propagating wave causes the electron beam to be bunched and the bunches to move toward regions of lower electric field potential, thereby giving up energy to the propagating wave for amplification thereof.

Some advantages of the crossed-field type of operation are increased efficiency, high power operation, linear modulation characteristics when used as an oscillator, and a reduction in severity of the beam focusing problem since a constant magnetic field is required only over a relatively short space. In a colinear type traveling wave tube, the electron beam, in giving up kinetic energy to the traveling wave, suffers a decrease in average velocity and therefore falls out of synchronism with the traveling wave. In a crossed-field device, however, since no kinetic energy interchange takes place, the electron beam can be maintained in synchronism with the traveling wave along its entire length. Hence, a crossed-field device is inherently more efficient.

A mode of operation in traveling wave tubes which is becoming increasingly more important today in backward-wave operation. In operation of this kind an electromagnetic wave is propagated in a direction opposite to the direction of electron flow. The wave traveling in a direction opposite to the electron flow has components traveling in the direction of electron flow which interact with the electron beam for amplification of the wave. Although the advantages of crossed-field type operation over the more conventional colinear type operation are generally known, efforts directed toward the use of backward-wave operation in a crossed-field device have not been wholly successful. In particular, when previous crossed-field devices were designed to operate as backward-wave amplifiers, the amplifiers were inherently unstable. This instability is particularly pronounced when the beam current of the amplifier is increased in an attempt to realize high power operation. Furthermore, when previous crossed-field devices were designed to operate as backward-wave oscillators the oscillators tended to oscillate only at a single low frequency. Efforts to sweep the frequency of oscillation of such oscillators, particularly with high beam current operation, have not been successful.

A principal object of the present invention, therefore, is to achieve stable operation in crossed-field type backward-wave amplifiers and linear frequency sweeping of crossed-field backward-wave oscillators over an extremely broad frequency band.

It has been found that the reason for instability in crossed-field backward-wave devices is the presence of multivelocity components in the electron beam, that is, different electrons in the beam traveling at different speeds. Moreover, it is now understood that a multivelocity beam is inherent in a crossed-field device when the beam current is increased in an effort to obtain reasonably high power operation. The reasons for this will be discussed hereinafter. The present invention, therefore, is based on the appreciation of the causes of instability in these devices and the avoidance of such instability by appropriate design of wave propagating circuits to be used in such devices, whereby the multivelocity beam is not only tolerated but used to advantage. In particular, it has been found that the interaction impedance vs. frequency characteristics of the wave propagating circuits used heretofore in crossed-field backward-wave devices have precluded obtaining stable operation with high current beams. It is now understood that stable operation over an extremely broad frequency band can be obtained in crossed-field backward-wave devices by the use of a traveling wave circuit whose effective interaction impedance vs. frequency characteristics, unlike those of previous circuits, are such that its effective interaction impedance increases monotonically with frequency over the entire range of frequencies below the highest operating frequency.

Accordingly, a principal feature of the present invention is a backward-wave crossed-field tube which includes a wave propagating circuit whose effective interaction impedance increases monotonically with frequency at all frequencies below the highest frequency of operation. A circuit having such interaction impedance characteristics may be obtained in either of two ways. The first way involves utilizing a circuit whose interaction impedance inherently increases monotonically with frequency. The second way involves modification of a known circuit whose interaction impedance curve normally has a peak at some low frequency, and therefore has a region where the interaction impedance decreases with frequency. Such a circuit is modified by introducing frequency sensitive attenuation so that the low frequency impedance peak is eliminated and therefore the desired interaction impedance characteristics obtained.

In one embodiment of the present invention, electrons are emitted along the length of a cathode and pass through a region of crossed electric and magnetic fields in coupling relation to a high frequency electric field existing in the vicinity of a series of regularly spaced discontinuities of basically simple construction positioned in one wall of a conductively bounded wave guide. These discontinuities may be formed by slot-like openings through one wall of a rectangular wave guide. Alternatively, they may be formed by parallel wires positioned transversely across an opening in one wall of a rectangular wave guide, or by successive turns of a wire wrapped in a helical fashion around a rectangular wave guide having a section of one of its walls removed. In this embodiment the effective interaction impedance inherently increases monotonically with frequency.

In a second embodiment of the present invention, an electron stream is emitted along the length of a cathode and passes through a region of crossed electric and magnetic fields in coupling relation to a high frequency electric field existing in the vicinity of a series of regularly spaced discontinuities formed by an interdigital-type structure. In this embodiment lossy material is provided along the interdigital structure. The lossy material is positioned on either or both sides of the interdigital structure and tapered such that the amount of lossy material increases with an increase in distance away from the structure. In this embodiment the interaction impedance curve of the circuit, before the lossy material is provided therealong, would normally have a low frequency peak. In the presence of the lossy material, however, the effective interaction impedance of the circuit increases monotonically with frequency.

A more complete understanding of the nature and objects of this invention can be obtained from the following description read in connection with the accompanying drawings of several illustrative embodiments thereof in which:

Fig. 1 is a perspective view partially cut-away of one embodiment of the present invention for use as a crossed-field backward-wave oscillator having an electron emissive sole plate;

Fig. 1A is a cross-sectional view taken through line 1A—1A of Fig. 1;

Figs. 2 and 3 are fragmentary perspective views of modifications of the embodiment of Fig. 1;

Fig. 4 is a longitudinal section of a modification of the embodiment shown in Fig. 1 wherein electron emission is provided by an injection from a cathode separate from the sole plate;

Fig. 5 is a fragmentary perspective view of a further modification of the embodiment of Fig. 1 wherein electron emission is provided by side injection from electron guns adjacent the sole plate;

Fig. 6 is a further modification of Fig. 1 for use either as a crossed-field backward-wave amplifier or oscillator; and

Fig. 7 is a perspective view of the second embodiment of the present invention for use either as a crossed-field backward-wave amplifier or oscillator.

Before describing the various embodiments of the present invention in detail it will be helpful to discuss briefly the cause of instability in a crossed-field backward-wave amplifier. In such a device a constant voltage difference is maintained between an anode, which forms part of a wave propagating circuit, and a sole plate which is spaced from and extends parallel to the anode along its length. Magnetic means are provided for establishing a constant magnetic field perpendicular to the electric field. It is known that an electron moving in a region of crossed electric and magnetic fields will travel at a speed v which is equal to $E \times H$, where E and H are the strengths of the electric and magnetic fields, respectively. Moreover, it can be appreciated that an electron beam projected through a crossed-field region will affect the strength of the electric field in the region of the beam. The effect is negligible for fine low-density electron beams but becomes appreciable for wide high-density beams. When a high current beam is used as is generally desirable for obtaining high power operation, or, more particularly, when a high current beam is used in a closely defined region as is required for high frequency operation, a non-uniform electric voltage gradient will result across the beam width. This amounts to a non-uniform value of E, and a consequent non-uniform value of v, across the beam width. Therefore the speed of each electron in the beam will be a function of its position in the beam, the electrons close to the anode traveling at a faster speed than the electrons close to the sole plate. It is inherent therefore in crossed-field operation when a high current beam is used in a region closely confined between two closely spaced electrodes that the different electrons over any cross-section of the beam will be traveling at different speeds.

Keeping in mind the fact that a multivelocity electron beam is inherent in crossed-field operation at high frequencies when high beam currents are used, consideration must be given to the nature of a circuit for use in backward-wave operation. Such a circuit is characterized in that it can propagate a wave having frequency components over a wide frequency range, and further, that the phase velocity of each component traveling in a backward or negative direction (that is, opposite to the direction of electron flow) is a direct function of its frequency. A situation therefore obtains where the circuit is capable of propagating many frequency components, and therefore components at various phase velocities, and the beam likewise has many velocity components. If then, amplification of a particular frequency component of the wave is desired, the multivelocity beam is adjusted so that some velocity component thereof equals the velocity of the particular frequency component to be amplified. Disadvantageously, however, other frequency components will be initiated and amplified whose velocity equals various other velocity components of the beam. Moreover, if the gain is greater for some other frequency component the amplifier will tend merely to oscillate at the frequency of highest gain. Likewise, if the device is intended to be an oscillator, rather than an amplifier, the oscillator will tend merely to oscillate at the frequency of highest gain and no frequency sweeping can be obtained.

In the past, traveling wave circuits of the inter-digital type were generally used in crossed-field backward-wave devices. In circuits of this type a very sharp peak in the interaction impedance curve normally occurs at some low frequency. This represents the frequency of highest gain, and therefore the circuit tends to oscillate at this frequency.

The present invention solves these problems so as to obtain both stable operation in crossed-field backward-wave amplifiers and linear frequency sweeping over a wide frequency range in crossed-field backward-wave oscillators. The solution involves the use in such an amplifier or oscillator of an interaction circuit whose effective inter-action impedance increases monotonically with frequency. Hence, the effective interaction impedance will be less for the wave components having slower phase velocities, as the slower phase velocities correspond to lower frequencies. With such a circuit a multivelocity beam is adjusted so that its highest velocity component travels at the same speed as the frequency component of the wave to be amplified. For all slower wave components the effective interaction impedance, and therefore the gain, will be less; hence the device will not tend to oscillate at a lower frequency.

It can be appreciated, since the lower velocity components of the beam are spaced further from the interaction circuit than the higher velocity components, that a circuit whose effective interaction impedance is substantially constant with frequency will give satisfactory operation. In such an arrangement the effective gain will be greatest for the closest beam component and therefore the device will amplify the frequency component which corresponds in velocity to the fastest velocity component of the beam. In the case of an oscillator this frequency of oscillation can be swept linearly with time by varying the beam accelerating voltage linearly with time. A crossed-field backward-wave device having an interaction circuit whose effective interaction impedance is substantially constant with frequency (rather than decreasing with frequency) is therefore within the scope of the present invention. It is, however, desirable to employ an interaction circuit whose effective interaction impedance increases with frequency so that the effective gain increases sharply with frequency. In such a case all the lower frequency components which might be initiated by the multivelocity beam have considerably less gain than the frequency which corresponds to the highest velocity component of the beam. The advantage in reducing the level of these undesired components as much as possible is, of course, that the possibility of interference by these components with the desired output is thereby minimized.

Referring now more particularly to the drawings, Figs. 1 and 1A show, for purposes of illustration, a traveling wave tube **10** for use as a crossed-field backward-wave oscillator. The tube comprises a sole plate **11**, which additionally serves as a cathode, and an anode **12**, of highly conductive material such as copper, positioned within an evacuated envelope **13**. The term sole plate as used herein designates an electrode which extends along a substantial portion of the length of the anode. It is spaced apart from the anode, generally being parallel thereto, and is maintained at a voltage different from the anode voltage for establishing an electrostatic field in the region between the sole plate and anode. When the sole plate furnishes the electrons required for interaction it is also referred to as the cathode. Envelope **13** is preferably made of copper or other suitable nonmagnetic conductive material. It is provided at one end with a section of rectangular wave guide **14** for coupling wave energy from the tube. A wave guide window **15**, of glass or other suitable material, is provided between envelope **13** and wave guide **14** for maintaining the desired evacuated conditions.

Cathode **11** is supported within envelope **13** by electrically insulating blocks **24** and includes a hollow conductive member **16** having one surface **17** thereof coated with electron emissive material along its length. Parallel to the emissive surface **17** and extending along the length of sole plate **11** are side rails **18** which serve as beam forming electrodes for preventing the electrons from spreading out in the direction shown as vertical in Fig. 1A. A cathode heater **19** is positioned within hollow member **16**. One end of the heater is connected to the hollow member **16** which is electrically connected to one side of heater voltage supply V_1 and the other end is connected by suitable lead-in wire to the other side of voltage supply V_1.

Anode **12** serves as a wall of a ridged rectangular wave guide **21**, the remainder of the guide being formed by a portion of envelope **13** and conductive ridge **25**. The anode together with the remainder of wave guide **21** forms a spatial harmonic wave guiding circuit **20** in which a series of recurrent discontinuities, recurring along the direction of propagation, is formed by a succession of discrete transverse slot-like openings **22** therethrough. The inside dimensions of wave guide **21** with its ridge are chosen so that, prior to the cutting of slots **22**, a transverse electric wave will propagate therethrough with its electric field perpendicular to anode-wall **12**. Ridge **25**, which is centered along the wall opposite to anode-wall **12**, serves primarily to broaden the useful operating frequency bandwidth of the circuit, but is not essential otherwise. The discrete transverse slots **22**, which, together with the metal separating them, form slot-resonators, perforate anode-wall **12**, and are regularly spaced along this wall parallel to each other in a series extending parallel to the direction of flow of the electron stream and the flow of wave power. The length of each of these slots is a little less than one-quarter of a free space wavelength at the upper cut-off frequency of the circuit and this length is the principal factor in determining this frequency. The end group of slots are gradually tapered in length over a distance until their length is at least halved and ridge **25** is tapered to zero height over the same or greater distance. The amount and distance of both tapers, however, may be varied according to the quality of impedance match desired.

Anode **12** is electrically connected to envelope **13**, which is maintained at reference or ground potential. Also connected to envelope **13** is the positive terminal of voltage source V_2. The negative terminal of source V_2 is connected through a voltage modulation source **23** to cathode **11** for maintaining a suitable direct current voltage between the cathode and anode. This direct current voltage establishes an electrostatic field between the cathode and anode along the length of the cathode. Permanent magnets, shown in Fig. 1A, provide a steady magnetic field perpendicular to the electrostatic field along the region between the cathode and anode.

In operation, electrons emitted from the cathode **11** are directed by the crossed electric and magnetic fields to pass longitudinally toward the right-hand end of tube **10** along the region between the cathode and anode. The electrons tend to follow a scalloping or cycloidal path, but because of a dense cloud of electrons which forms above the emissive cathode the scalloping is minimized and the resulting electron path is substantially longitudinal. In passing in coupling proximity to a wave propagating along spatial harmonic circuit **20**, the electrons become bunched and the bunches move toward the anode. These bunches serve both to amplify the wave passing along the circuit and to form a feedback path for backward-wave oscillation. A discussion of this type of operation can be found in an article by H. Heffner in the Proceedings of the I. R. E., pages 930 to 937. After giving up their energy to the propagating wave, the electrons become collected by anode **12** thereby forming a completed circuit between the cathode and anode. In order to avoid reflection of any wave energy which appears at the downstream or right-hand end of tube **10**, the wave propagating circuit **20** may either be terminated in its characteristic impedance or loaded with appropriate lossy material at that end. In Fig. 1 the circuit is loaded by a coating of lossy conductive material **26**, such as nickel or iron, on the bars of metal separating the last few slots of anode **12**. Such termination at the downstream end is generally not required unless wave energy is reflected at the upstream tube-to-wave guide connection. In the absence of such reflection the signal level at the downstream end of the circuit will be substantially zero.

The spatial harmonic circuit formed by the regularly apertured anode-wall **12** together with wave guide **21** is characterized in that its effective interaction impedance increases monotonically with frequency. Thus the highest frequency component with which the beam is capable of interacting will enjoy the highest gain and oscillation will result at that frequency. Because the phase velocity of the negative space harmonic component along circuit

20 increases with frequency, the highest frequency component with which the beam can interact corresponds to the highest velocity component of the beam. Oscillation therefore occurs at the frequency which corresponds to the highest velocity component of the beam. The frequency of oscillation can be varied by varying the speed of the beam, which, in turn, varies the speed of its highest velocity component. The speed of the beam can be varied in any desired fashion by applying an appropriate modulating signal from modulator **23**. By linearly varying the voltage applied by modulator **23** the frequency of oscillation will be linearly swept.

It can be appreciated that the present invention is particularly adapted for use in a crossed-field backward-wave oscillator which employs a cathode consisting of a sole plate having an electron emissive surface along all or a substantial portion, of its length. Such a cathode, because of its extensive emissive surface, generally provides a high current, and hence, a multivelocity beam. Cathodes of this type find particular advantage where high power operation is required. The present invention, however, is not restricted to tubes which include cathodes of this type but extends to the use of any cathode which employs space charge limited emission. Such emission is also characteristic of the various other cathode arrangements to be described hereinafter and invariably provides a multivelocity beam in crossed-field operation.

Figs. 2 and 3 are modifications of the embodiment of Figs. 1 and 1A, wherein an electron emissive surface is provided along the conductive ridge of rectangular wave guide **21**. Component parts of these figures which correspond to parts already described with reference to Figs. 1 and 1A have been designated with like reference numerals. In each of these embodiments a spatial harmonic wave guiding circuit is formed by regularly slotted anode **12** together with ridged wave guide **21**. As in Figs. 1 and 1A the ridged guide is dimensioned so that, prior to the cutting of slots **22**, a transverse electric wave can propagate therethrough with its electric field perpendicular to anode-wall **12**. Also, in each of the modifications, region **27** along the anode **12** on the opposite side from the conductive ridge is dimensioned small enough to be non-progagating at all frequencies of operation, so that no wave energy will be found in this region other than that contained in the fields immediately surrounding the slots. In Fig. 2, ridge **225** comprises a hollow conductive member **216** having one surface **217** which is electron emissive over a substantial portion of its length and side rails **218** which serve as beam forming electrodes. Hollow conductive member **216** serves as both the cathode and sole plate, as well as being part of ridge **225**. Voltage source V_1 supplies the cathode heater voltage by a suitable connection to the cathode heater located within tubular member **216**. The tubular member is spaced by strips of electrical insulating material **229** from conductive members **228**, which form the sides of ridge **225**. As in Fig. 1, voltage source V_2 maintains an appropriate direct current voltage between anode **12** and cathode **216**, and means for varying this voltage is provided by modulator **23**.

In Fig. 3, hollow conductive member **316** serves as both the cathode and sole plate, as well as being the conductive ridge of wave guide **21**. It has an electron emissive surface along a substantial portion of its length, beam forming side rails, and a cathode heater, as described with reference to Fig. 2. Conductive cathode member **316** is spaced apart from the remainder of wave guide **21** by a strip of electrical insulating material **329**, so that the anode and cathode member can be maintained at different direct current potentials. The thickness of insulated strip **329** has been exaggerated for emphasis, but, in practice, can be made any suitable size for providing the desired insulation. It is understood that the modifications of Figs. 2 and 3 are shown merely as fragmentary views of modifications of the oscillator of Fig. 1

and, in operation, each of these arrangements would be terminated at one end, enclosed in an evacuated envelope, and provided with means for establishing a constant magnetic field, as described with reference to Figs. 1 and 1A.

Fig. 4 is a modification of the crossed-field backward-wave oscillator of Figs. 1 and 1A, like component parts being designated with like reference numerals. In this modification a sole plate **411** extends along a substantial portion of the length of the series of slots in anode **12**, and cathode **412** (shown schematically) supplies electrons which pass longitudinally between anode **12** and sole plate **411**. As in Fig. 1 an electrostatic field is maintained between the anode and the sole plate, and a steady magnetic field is provided perpendicular to the electrostatic field in that region. Unlike that in the tube shown in Fig. 1, however, the sole plate of this modification is not electron emissive. In this modification electron emission is derived from cathode **412** which is separate from the sole plate. Cathode **412** emits a high current stream of electrons and hence a wide multi-velocity beam is formed in the crossed-field region. The velocity of the various electrons across the beam width are represented by the vectors shown, the velocity being roughly proportional to the length of the vector. Circuit **20** is terminated by a section of lossy dielectric **426**, such as silicon carbide in porcelain or aquadag coated ceramic, in close proximity with the last few slots at the downstream end of anode **12**.

Fig. 5 shows a further modification of the tube shown in Figs. 1 and 1A, and in this modification electron injection is provided by electron guns shown schematically. In this modification a spatial harmonic circuit is formed by regularly slotted anode **12** together with the remainder of rectangular wave guide **21**. Wave guide **21** herein is not integral with envelope **13**. This is merely a detail of construction which is a matter of choice. Sole plate **516** is positioned along the length of anode **12** and spaced apart from conductive envelope **13** by insulating spacers **515**. Means for establishing an electrostatic field between the sole plate **516** and anode **12**, and for varying that field, are provided by voltage source V_2 and modulator **23**, respectively. A steady magnetic field is established perpendicular to the electrostatic field by suitable magnetic means (not shown). Electron guns for projecting electrons into the region of crossed electric and magnetic fields include two cathodes **519**, each having a surface of electron emissive material along its length, and side rails **518** which serve as accelerating anodes. The side rails are conductively connected to sole plate **516** by supporting members (not shown) at various points along their length. Voltage source V_3 maintains the cathodes **519** at a voltage negative with respect to the voltage of the sole plate so that electrons supplied by the cathodes are accelerated through the slot in side rails **518** into the crossed-field region. These electrons form a multivelocity beam which passes longitudinally along the region between the sole plate and anode. Side rails **518** preferably extend along sole plate **516** in close proximity to anode **12** to form substantially a small dimensioned enclosure below the slots of anode **12**. This precludes the leakage of wave energy into the lower half of envelope **13** of Fig. 5.

Typical values of voltages V_2 and V_3 are ten thousand volts and one hundred volts, respectively. Although V_2 is shown as a steady direct current voltage it is understood that this voltage may be supplied intermittently as, for example, by a succession of high voltage pulses.

An additional modification of the tube of Figs. 1 and 1A is shown in Fig. 6. Component parts of this modification which correspond to parts already described are designated with like reference numerals. In the present modification traveling wave tube **610** is capable of operating either as an oscillator or an amplifier. As in the tube of Fig. 1 a spatial harmonic circuit **620** is formed by regularly slotted anode **12** together with the remainder of ridged wave guide **21**. Unlike Fig. 1 however, ridged wave guide **21** of the present modification forms part of a through wave transmission path, being coupled at one end to wave guide **621** and at the other end to wave guide **622**. A wave guide window is provided at both ends of envelope **13** for maintaining evacuated conditions within the envelope. The length of the slots **22** in anode **12** and height of ridge **25** are appropriately tapered at both ends for obtaining an adequate impedance match between circuit **620** and each of the wave guides. A sole plate **11**, also serving as cathode, is positioned along a substantial portion of the series of slots in anode **12**. Means for establishing a difference in potential between the cathode and anode, and for varying the difference in potential therebetween have not been shown. Such means, as well as means for establishing a steady magnetic field perpendicular to the electrostatic field, have been shown in Figs. 1 and 1A.

For operation as a backward-wave oscillator wave guide **622** is terminated in its characteristic impedance as shown diagrammatically by block **624**, and operation is substantially as described with reference to the oscillator shown in Fig. 1. Wave energy derived from tube **610** is coupled via wave guide **621** to a utilization circuit **623**. For operation as a backward-wave amplifier, wave energy to be amplified is supplied by a source represented diagrammatically by block **624** and coupled via wave guide **622** to tube **610**. In passing from right to left through this tube, in a direction opposite to the electron beam flow in the tube, the wave is amplified by the now well known process of backward-wave amplification. In the process the fastest electrons in the beam are maintained in synchronism with a negative space harmonic of the traveling wave for interaction therewith, whereby a transfer of energy from the beam to the wave acts to amplify the wave. The amplified wave energy is then coupled via wave guide **621** to suitable utilization means **623**.

A second embodiment of the present invention is shown in Fig. 7. In this embodiment traveling wave tube **710** may be used as a crossed-field backward-wave oscillator or amplifier. Tube **710** comprises cathode **711** and anode **712** spaced apart within evacuated envelope **713** of copper or other nonmagnetic conductive material. Anode **712** is an interdigital type structure suitably dimensioned for propagating a traveling wave therealong for interaction with electron flow from cathode **711**. The interdigital type structure normally has the phase velocity of its fundamental spatial component directed oppositely to the direction of wave propagation, that is, opposite to the direction of power flow. In backward-wave operation in such a structure, therefore, interaction is normally with the fundamental rather than with harmonics thereof. The fundamental in such a case is referred to as a negative component of the wave, since electron flow is directed oppositely thereto, but it is not properly referred to as a negative spatial harmonic. The anode is joined to the envelope which is maintained at reference or ground potential. Cathode **711**, having an electron emissive surface **714**, is electrically insulated from envelope **713** by insulating support member **715**, so that said cathode can be maintained at an appropriate negative voltage. Various other types of supporting structures of insulating material may be used, as will be apparent to one skilled in the art. The voltage difference maintained between the anode and cathode establishes an electrostatic field in the region therebetween. Perpendicular to the electrostatic field in the region between the anode and cathode is maintained a steady magnetic field by magnetic means, not shown. In the presence of these crossed electric and magnetic fields, electrons emitted from surface **714** move longitudinally along the region between the cathode and anode, in a direction depending upon the direction of the magnetic field. Assuming the direction to be from left to right in Fig. 7, the electrons will interact with a negative component of an electromagnetic wave whose group velocity is directed from right to left. The interdigital array along anode **712** is coupled at one end to coaxial line **721** and at the other end to coaxial line **722**. Loss is provided for a wave traveling along the interdigital array of anode **712** by lossy material **716**. The lossy material is positioned on both sides of the interdigital array, which forms a part of the slow wave propagating circuit, and is tapered to increase in width away from the array. The use of loss in this way is to be distinguished from the use of loss in forward-wave traveling wave amplifiers in which loss is inserted along an intermediate portion of the wave circuit to attenuate reflected wave components arising from mismatches at the end terminations. In particular, in the present instance, the loss is spaced away from the circuit along substantially its entire length in a manner to attenuate resonances set up by the side closures associated with the wave circuit. Such tapered lossy material will afford frequency sensitive attenuation to a wave traveling along the circuit.

In the absence of lossy material **716** the interdigital structure **712** exhibits a high peak of effective interaction impedance at a low frequency which is the resonant frequency of the cavities formed by the envelope **713** of conductive material on either side of structure **712**. At this frequency, the wave impedance is high and the amplitude of the backward-wave is at its maximum. This represents the frequency of highest gain for the circuit. Hence, low velocity components of a multi-velocity beam will tend to initiate and amplify wave components at this frequency irrespective of the speed of the beam. Crossed-field backward-wave amplifiers therefore tend to oscillate at this frequency and crossed-field backward-wave oscillators also tend to oscillate at this frequency despite efforts to change the frequency of oscillation by varying the speed of the electron beam. Such a phenomena in oscillators has been called "sticking." To avoid this problem, lossy material **716** is arranged so that the impedance looking into the cavities formed by envelope **713** is substantially the impedance of free space. This eliminates the resonant frequency impedance peak which the circuit exhibits in the absence of the lossy material. Moreover, since the electromagnetic fields of a wave propagating along the interdigital array fringes out further at lower frequencies, the loss distribution shown will selectively reduce the gain at the lower frequencies, so as to give an effective interaction impedance which increases sharply with frequency.

Other means may be substituted for providing an impedance substantially equal to that of free space across the boundaries of anode **712** at wave guide walls **725** and **727**. One method is to remove conductive walls **726** and **728** and substitute therefore transparent or absorbing material. This acts to eliminate the cavity resonance thereby eliminating the low frequency interaction impedance peak. A second method is to increase the width of wave guide walls **725** and **727** in a direction transverse to anode **712**. The width of these walls must be made several wavelengths at the operating frequency. Preferably, the width is made a quarter wavelength at a frequency which is less than one-third of the lowest frequency of operation. Resonances at frequencies below this frequency will not give rise to the difficulties set forth above, since the electrical length of the circuit for such low frequencies will not be sufficient to provide a substantial gain. With wave guide walls of such width, the walls **726** and **728** may be of any desired material. Although these arrangements will serve to eliminate the low frequency peak in the effective interaction impedance curve, the preferred arrangement is the loss distribution shown in the tube of Fig. 7 since such an arrangement gives rise to an effective impedance curve which rises more sharply with frequency, as well as eliminating the low frequency effective interaction impedance peak.

In operation as an oscillator, coaxial wave guide 721 is terminated at its characteristic impedance, as shown diagrammatically by block 723, and operation is substantially as described with reference to the oscillator shown in Fig. 1. Wave energy derived from tube 710 is coupled via coaxial line 722 to a utilization circuit 724. In operation as a backward-wave amplifier, wave energy to be amplified is supplied by the source represented diagrammatically by block 723 and coupled via coaxial line 721 to tube 710. In passing from right to left through the tube, in a direction opposite to the direction of the electron flow in the tube, the wave energy is amplified and passes via coaxial line 722 to utilization circuit 724.

It is understood that the above-decribed arrangements are merely illustrative of the application of the general principles of the invention. Various other arrangements may be devised by one skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. In a device which utilizes the interaction between an electron beam and an electromagnetic wave to amplify the wave, a slow wave circuit for propagating an electromagnetic wave therealong in a predetermined direction, said slow wave circuit including a conductively bounded wave guide, one wall of which has a plurality of discrete slot-like openings extending therethrough and spaced apart in a series parallel to the direction of wave propagation, means for forming an electron beam for flow along a path in coupling relation to a negative component of an electromagnetic wave propagating along the slow wave circuit, means for forming a magnetic field perpendicular to the path of the beam along a major portion of its length, and means for forming an electric field in a direction perpendicular to said magnetic field along a major portion of the length of said slow wave circuit.

2. In a device which utilizes the interaction between an electron beam and an electromagnetic wave to amplify the wave, a slow wave circuit for propagating an electromagnetic wave therealong in a predetermined direction, said slow wave circuit including a conductively bounded wave guide having a raised conductive ridge along one of its walls and a plurality of discrete openings extending through a wall of said wave guide opposite said ridged wall, said openings spaced apart in a series parallel to the direction of wave propagation, means for forming an electron beam for flow along a path in coupling relation to the wave propagating along said slow wave circuit, the beam passing along said path in a direction opposite to the direction of wave propagation, means for forming a magnetic field perpendicular to the path of the beam along a major portion of its length, and means for forming an electric field in a direction perpendicular to said magnetic field along a major portion of the length of said slow wave circuit.

3. In a device which utilizes the interaction between an electron beam and an electromagnetic wave to amplify the wave, a slow wave circuit for propagating an electromagnetic wave therealong in a predetermined direction, said slow wave circuit including a sheet-like conductive member having a plurality of discrete openings extending therethrough and spaced apart in a series parallel to the direction of wave propagation, means for forming an electron beam for flow along a path in coupling relation to a negative component of an electromagnetic wave propagating along said slow wave circuit, means for forming a magnetic field perpendicular to the direction of wave propagation along a major portion of the length of the slow wave circuit, and means for forming an electric field in a direction perpendicular to said magnetic field along a major portion of the length of said slow wave circuit.

4. An electronic device comprising a wave guide for propagating an electromagnetic wave therealong in a predetermined direction, a section of one wall of said wave guide including a plurality of transverse slot-like openings forming a succession of slot resonators, said succession extending in a direction parallel to the direction of wave propagation; means for forming and projecting an electron stream in a direction opposite to the direction of wave propagation; and means for maintaining said electron stream in coupling relation with said succession of resonators whereby interaction between the electron stream and an electromagnetic wave propagating along said wave guide is obtained, said means including means for forming a magnetic field perpendicular to the direction of wave propagation along a major portion of the length of the succession of slot resonators, and means for forming an electric field in a direction perpendicular to said magnetic field along the major portion of the length of the stream.

5. In a device which utilizes the interaction between an electron beam and an electromagnetic wave for amplifying the wave, a slow wave circuit for propagating an electromagnetic wave therealong in a predetermined direction, said slow wave circuit including a conductively bounded wave guide having a raised conductive ridge along one of its walls and a plurality of discrete openings extending through a wall of said wave guide opposite said ridged wall, said openings spaced apart in a series parallel to the direction of wave propagation, an electron emissive surface extending along a major portion of the length of said conductive ridge for supplying an electron beam for flow along said slow wave circuit, means for forming a magnetic field perpendicular to the direction of wave propagation along a major portion of the length of the series of openings in the region between said series, and means for forming an electric field in a direction perpendicular to said magnetic field along the major portion of the length of said series of openings in the region between said series and said ridge.

6. In a device which utilizes the interaction between an electron beam and an electromagnetic wave for amplifying the wave, a slow wave circuit for propagating an electromagnetic wave therealong in a predetermined direction, said slow wave circuit including a conductively bounded wave guide having a raised conductive ridge along on of its walls and a plurality of discrete openings extending through a wall of said wave guide opposite said ridged wall, said openings spaced apart in a series parallel to the direction of wave propagation, an electron emissive surface extending along the major portion of said conductive ridge for supplying an electron beam for flow along said series of openings, means for electrically insulating the conductive ridge from the remainder of the conductively bounded wave guide, means for maintaining a potential difference between said ridge and the wall of said wave guide having openings therethrough, and means for forming a magnetic field perpendicular to the direction of wave propagation along the major portion of the length of the series of openings in the region between said series of openings and said conductive ridge.

7. In a device which utilizes the interaction between an electron beam and an electromagnetic wave to amplify the wave over a predetermined frequency band, a periodic slow wave circuit for propagating an electromagnetic wave therealong in a predetermined direction, said slow wave circuit characterized in that its effective interaction impedance increases with frequency at all frequencies below the highest frequency of said predetermined frequency band, a sole plate spaced apart from and extending longitudinally along said slow wave circuit, means for establishing a potential difference between said sole plate and said slow wave circuit for forming an electric field therebetween, means for forming a magnetic field perpendicular to said electric field in the region of said electric field, an electron source and ac-

celerating anode positioned for projecting an electron flow into the interspace between the sole plate and the slow wave circuit, the electron source and accelerating anode being disposed to project the electron flow initially in a direction parallel to the magnetic field, and the electric and magnetic fields cooperating to divert the electron flow from its initial direction parallel to the magnetic field to a direction perpendicular to both the electric and magnetic fields in coupling relation to a wave propagating along said slow wave circuit.

8. In a device which utilizes the interaction between an electron beam and an electromagnetic wave for amplifying the wave, a slow wave circuit for propagating an electromagnetic wave therealong in a predetermined direction, said slow wave circuit including a conductively bounded wave guide, one wall of which has a plurality of discrete openings extending therethrough and spaced apart in a series parallel to the direction of wave propagation, means for forming and projecting an electron beam along the path in coupling relation to a negative component of a wave propagating along said slow wave circuit, said means including a sole plate extending along a major portion of said series of openings, at least one conductive side rail extending along the sole plate and having a longitudinally extending slot therein along the major portion of its length, an electron source adjacent said side rail in line with the slot therein for emitting electrons through said slot, means for forming a magnetic field perpendicular to the direction of wave propagation along a major portion of the length of the slow wave circuit in the region between the sole plate and the slow wave circuit, and means for forming an electric field perpendicular to said magnetic field along a major portion of the length of said slow wave circuit in the region between the sole plate and the slow wave circuit.

9. In a device which utilizes the interaction between an electron beam and an electromagnetic wave to amplify the wave, a slow wave circuit for propagating an electromagnetic wave therealong in a predetermined direction, said slow wave circuit including a conductively bounded wave guide, one wall of which has a plurality of discrete openings extending therethrough and spaced apart in a series parallel to the direction of wave propagation, a sole plate spaced apart from said slow wave circuit and extending along the major portion of its length, means for establishing a difference in potential between said sole plate and said slow wave circuit for forming an electric field therebetween, means for forming a magnetic field perpendicular to said electric field in the region of said electric field, and means separate from said sole plate for forming an electron beam and for projecting said beam into said region of crossed electric and magnetic field for flow along a path in coupling relation to the slow wave circuit, said last-mentioned means utilizing space charge limited emission.

10. A microwave oscillator comprising a slow wave circuit for propagating an electromagnetic wave therealong in a predetermined direction, said slow wave circuit including a conductively bounded wave guide having a plurality of discrete openings extending therethrough and spaced apart in a series parallel to the direction of wave propagation, means for forming an electron beam for flow along a path in coupling relation to a negative component of the propagating electromagnetic wave, means for forming a magnetic field perpendicular to the direction of wave propagation along the major portion of the length of the slow wave circuit, means for forming an electric field in a direction perpendicular to said magnetic field along the major portion of the length of said slow wave circuit, means for terminating said slow wave circuit in its characteristic impedance, and coupling means for extracting energy from said slow wave circuit.

11. In a device which utilizes the interaction between the electron beam and an electromagnetic wave for amplification of the wave over a predetermined frequency band, a slow wave circuit for propagating an electromagnetic wave therealong in a predetermined direction, said slow wave circuit comprising two parallel-extending metallic surfaces, a first set of rod-like metallic members extending from one of said metallic surfaces, a second set of rod-like metallic members extending from the second metallic surface, the two sets interleaved in an interdigital array in a predetermined direction along the space between the parallel metallic surface, and said parallel surfaces extending from said array in a direction transverse to said predetermined direction of said array a distance of several wave lengths at the operating frequency; means for establishing an electric field perpendicular to the direction of wave propagation along the slow wave circuit in the region of said slow wave circuit, means for establishing a magnetic field perpendicular to said electric field in the region of said slow wave circuit, and means for forming an electron beam for flow in coupling relation with a wave propagating along said slow wave circuit and along a path substantially perpendicular to said crossed electric and magnetic fields.

12. In a device which utilizes the interaction between the electron beam and an electromagnetic wave for amplification of the wave over a predetermined frequency band, a slow wave circuit for propagating an electromagnetic wave therealong in a predetermined direction, said slow wave circuit comprising two parallel-extending metallic surfaces, a first set of rod-like metallic members extending from one of said metallic surfaces, a second set of rod-like metallic members extending from the second metallic surface, the two sets interleaved in an interdigital array in a predetermined direction along the space between the parallel metallic surfaces, and said parallel surfaces extending from said array in a direction transverse to said predetermined direction of said array a distance of one-quarter wave length at a frequency less than one-third that of the lowest frequency of said predetermined frequency band, means for establishing an electric field perpendicular to the direction of wave propagation along the slow wave circuit in the region of said slow wave circuit, means for establishing a magnetic field perpendicular to said electric field in the region of said slow wave circuit, and means for forming an electron beam for flow in coupling relation with a wave propagating along said slow wave circuit and along a path substantially perpendicular to said crossed electric and magnetic fields.

13. In a device which utilizes the interaction between an electron beam and an electromagnetic wave for amplification of the wave over a predetermined frequency band, a slow wave circuit for propagating an electromagnetic wave therealong in a predetermined direction, said slow wave circuit comprising two sets of rod-like metallic members, the members of each set being joined together by a metallic strip and the two sets interleaved to form an interdigital array, and frequency sensitive lossy material positioned along said array, said circuit being characterized in that its effective interaction impedance increases with frequency at all frequencies below the highest frequency of said predetermined frequency band, means for establishing an electric field perpendicular to the direction of wave propagation along the slow wave circuit, means for establishing a magnetic field perpendicular to said electric field in the region of said slow wave circuit, and means for forming an electron beam for flow in coupling relation with a wave propagating along said slow wave circuit and along a path substantially perpendicular to said crossed electric and magnetic fields.

14. In a device which utilizes the interaction between the electron beam and an electromagnetic wave for amplification of the wave over a predetermined frequency band, a slow wave circuit for propagating an electromag-

netic wave therealong in a predetermined direction, said slow wave circuit comprising two sets of rod-like metallic members, the members of each set joined together by a metallic strip and the two sets interleaved to form an interdigital array, and frequency sensitive lossy material positioned along said array for providing attenuation to a wave propagating along said array, the attenuation provided decreasing with frequency, a sole plate spaced apart from an extending longitudinally along said array, means for establishing a potential difference between said sole plate and said array for forming an electric field between said sole plate and said array, means for forming a magnetic field perpendicular to said electric field in the region of said electric field, and means for forming an electron beam and for projecting said beam along said array in a direction perpendicular to the crossed electric and magnetic fields.

15. In a device which utilizes the interaction between the electron beam and an electromagnetic wave for amplification of the wave over a predetermined frequency band, a slow wave circuit for propagating an electromagnetic wave therealong in a predetermined direction, said slow wave circuit comprising two sets of rod-like metallic members, the members of each set being joined together by a metallic strip and the two sets interleaved to form an interdigital array, and lossy material positioned along said array, the amount of said lossy material increasing with distance away from said array; a sole plate spaced apart from and extending longitudinally along said array, an electron emissive surface along a major portion along said array, means for establishing a difference in potential between said sole plate and said array for forming therebetween an electric field, means for forming a magnetic field perpendicular to said electric field in the region of said electric field, and coupling means at one end of said interdigital array for extracting wave energy therefrom.

16. In a device which utilizes the interaction between an electron beam and an electromagnetic wave to amplify the wave over a predetermined frequency band, a periodic slow wave circut for propagating an electromagnetic wave therealong in a predetermined direction, said slow wave circuit characterized in that its effective interaction impedance increases with frequency at all frequencies below the highest frequency of said predetermined frequency band, means utilizing space charge limited emission for supplying electron flow and for projecting said electron flow along a path in coupling relation with a wave propagating along the slow wave circuit and in a direction opposite to the direction of said wave propagation, means for forming a magnetic field perpendicular to the direction of wave propagation along a major portion of the slow wave circuit in the region of the electron path, and means for forming an electric field in a direction perpendicular to said magnetic field along a major portion of the length of said slow wave circuit in the region of the electron path.

17. In a device which utilizes the interaction between an electron beam and an electromagnetic wave to amplify the wave over a predetermined frequency band, a periodic slow wave circuit for propagating an electromagnetic wave therealong in a predetermined direction, said slow wave circuit characterized in that its effective interaction impedance increases with frequency at all frequencies below the highest frequency of said predetermined frequency band, means for forming and projecting an electron beam in a direction opposite to the direction of wave propagation, means for forming a magnetic field perpendicular to the direction of wave propagation along a major portion of the length of the slow wave circuit, and means for forming an electric field in a direction perpendicular to said magnetic field along a major portion of the length of said slow wave circuit.

18. The combination of elements as set forth in claim 17 wherein the means for forming and projecting an electron beam includes an electron emissive surface spaced apart from said slow wave circuit and extending along a major portion of its length.

19. In a device which utilizes the interaction between an electron beam and an electromagnetic wave to amplify the wave or create oscillations over a predetermined frequency band, a periodic slow wave circuit for propagating an electromagnetic wave therealong in a predetermined direction, said slow wave circuit characterized in that its effective interaction impedance increases with frequency at all frequencies below the highest frequency of said predetermined frequency band, means for forming and projecting an electron beam in coupling relation with said electromagnetic wave, means for forming a magnetic field prependicular to the direction of wave propagation along a major portion of the length of the slow wave circuit, and means for forming an electric field in a direction perpendicular to said magnetic field along a major portion of the length of said slow wave circuit.

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