

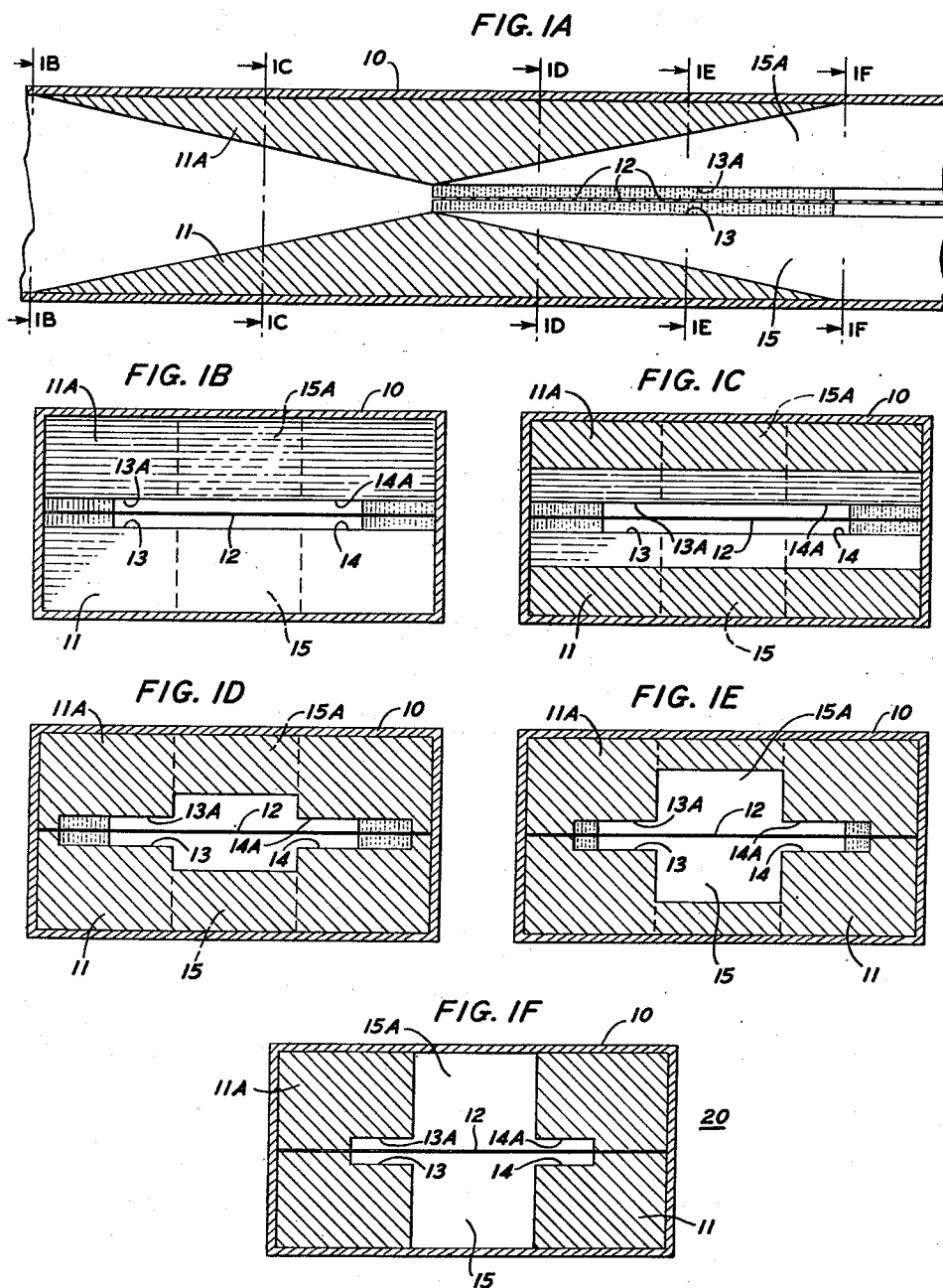
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J. R. PIERCE ET AL
BACKWARD WAVE TUBE

2,824,256

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2 Sheets-Sheet 1



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2 Sheets-Sheet 2

FIG. 2

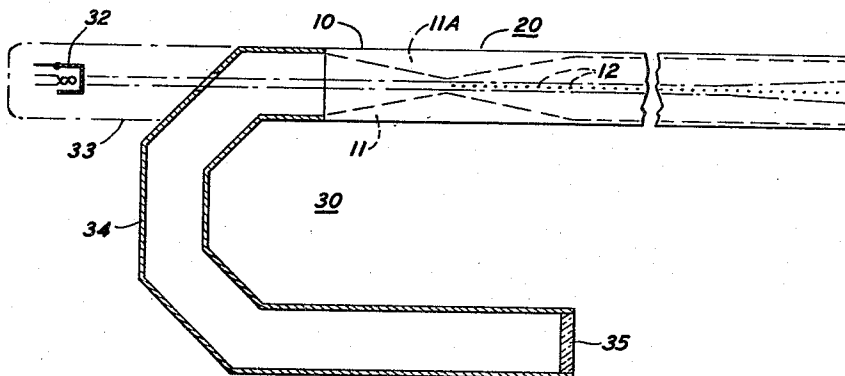


FIG. 3

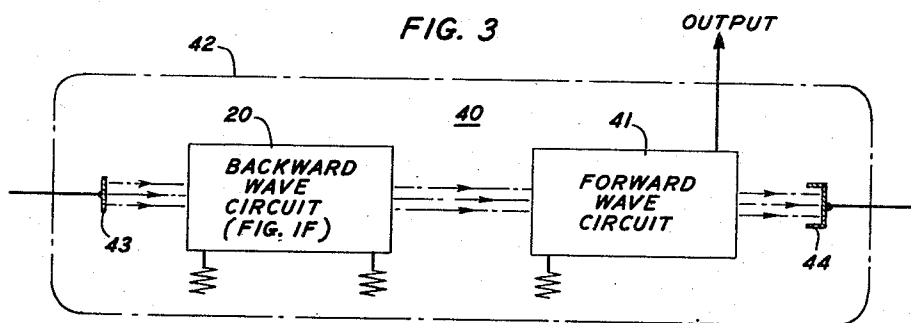


FIG. 4

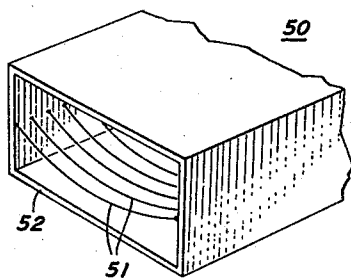
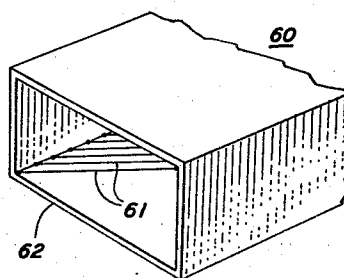


FIG. 5



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1

2,824,256

BACKWARD WAVE TUBE

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7 Claims. (Cl. 315—3.5)

This invention relates to devices which employ the interaction between a traveling electromagnetic wave and an electron beam over a plurality of operating wavelengths. Such devices are now generally termed traveling wave tubes.

An important class of traveling wave tubes is one in which the electron beam interacts with an electromagnetic wave which is propagating along an interaction circuit in a direction opposite to that of the electron flow past the circuit. Such operation is termed backward wave operation. In backward wave operation the electromagnetic wave is made to propagate along an interaction circuit of a kind which sets up electric field components which have a phase velocity in a direction opposite to that of energy propagation, and the velocity of the electron beam is made substantially equal to that of a selected one of such components for interaction therewith with a consequent amplification of the propagating wave.

In a copending application Serial No. 422,613, filed April 12, 1954, by A. Karp and W. C. Yocom there is described a traveling wave tube which incorporates an interaction circuit well adapted for backward wave operation, particularly because of the ease with which it can be fabricated in a form suitable for use at millimeter wavelengths. This interaction circuit comprises a linear array of straight wirelike elements extending between the narrow side walls of a hollow wave guide which is provided with a central ridge extending axially therealong in the direction of the linear array. In this circuit, the central ridge in the wave guide acts to increase the cutoff wavelength of the guide whereby the length of each wire element is shorter than the one half the cutoff wavelength of the guide. Such a circuit when propagating a signal whose wavelength is slightly longer than twice the length of the wires is found to establish relatively strong axial electric field components which have a phase velocity in the direction opposite to that of wave propagation and so are conducive to backward wave operation. If the axial electric field associated with the propagation of the wave along the circuit is developed as a sum of a Fourier series of which each component is traveling with a different phase velocity, the phase velocity of the backward traveling component with which interaction is most profitably made is found to involve a $(2\pi - \theta)$ term where θ is the phase difference between adjacent wires with progress in the direction of the electron flow. This component is generally termed the first negative spatial harmonic.

Operation with such negative spatial harmonic components is found to possess certain limitations. In general, it would be preferable to interact with the fundamental component of a Fourier series representation of the wave since the impedance of the circuit is higher for such a fundamental component, with a consequent improvement in the efficiency of operation.

An object of the present invention is to improve the efficiency of traveling wave tubes operating in a backward wave mode.

2

A related object is to secure such improvement by a more efficient interaction circuit.

To such ends, a feature of the invention is an interaction circuit which comprises a plurality of wire-like elements extending transversely across a wave guide in an axial linear array, characterized in that each of the wire elements has a length which is longer than one half the characteristic cutoff wavelength of the wave guide. This end is advantageously achieved by modifying the geometry of the guide to reduce its characteristic cutoff wavelength. To this end, the wave guide is ridged at regions opposite the ends of the wires. This may be viewed, alternatively, as a reduction in the capacitance at the center of the wires relative to the capacitance at their ends or as the addition of an inductance at the two ends of the wires.

In a preferred embodiment of the invention, the wave guide is ridged opposite the ends of the wires both below and above the wires. This results in an interaction circuit when comprises a wave guide having a substantially "cruciform" interior in which a plurality of wire elements extend in a linear array between a pair of side walls.

Each circuit of this kind is found to have associated with the propagation therealong of a wave in one direction an axial electric field component with a phase velocity in the opposite direction which in a Fourier series representation of the axial electric field of the wave involves simply θ where θ is, as before, the phase shift between adjacent wires with progress in the direction of electron flow. Such a component represents the fundamental of the Fourier series representation of the wave, and as such it is the strongest of the various components, and the one susceptible of optimum efficiency of interaction with the beam. This circuit may be characterized, in an alternative, as having a negative phase constant just above the resonant frequency of the wires, a phase constant which becomes less negative as the frequency rises.

The invention has special application to backward wave oscillators. In such oscillators, an electron beam is projected past an interaction circuit conducive to backward wave operation. Oscillations are set up by the regenerative action of the electron beam which travels oppositely to the wave and transfers energy from regions of high wave energy level upstream along the circuit to regions of lower wave energy level downstream along the circuit. The terms "upstream" and "downstream" are used here and hereinafter to denote relative separation along the path of electron flow from the electron source. In the most common form of backward wave oscillator the oscillatory wave energy is abstracted by means of an output connection at the upstream end of the circuit where the oscillatory wave is a maximum while the downstream end of the circuit is made substantially reflectionless to minimize the effect of wave energy reflected from the output connection. In an alternative form, the modulations set up on the electron beam by interaction with the oscillatory backward traveling wave may be used to induce a corresponding wave in a suitable coupling element.

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

Fig. 1A shows an axial longitudinal section of an arrangement including a slow wave circuit in accordance with the invention and a rectangular wave guide coupling connection at one end thereof, Figs. 1B through 1F are sections taken along lines BB, CC, DD, EE, and FF, respectively, of the arrangement shown in Fig. 1A;

Figs. 2 and 3 each illustrate backward wave type oscillators wherein there is incorporated a slow wave circuit of the kind shown in Fig. 1; and

Figs. 4 and 5 are views taken in transverse cross section of alternative forms of slow wave circuits in accordance with the invention.

With reference now more particularly to the drawings, the interaction circuit arrangement shown in Figs. 1A through 1F comprises a hollow wave guide 10, advantageously of copper, which initially is of rectangular cross section and of standard dimensions for the operating band of wave-lengths. As shown, the vertical dimension of the wave guiding passage is gradually decreased with travel from left to right, by the tapered conductive inserts 11 and 11A which extend longitudinally along the guide and serve as a mode converter for transforming the transverse electric mode characteristic of propagation in the rectangular wave guide to one suitable for propagation by the slow wave circuit. The inserts 11 and 11A are positioned in mirror symmetry relative to an axial plane parallel to the broad walls of the guide. In Fig. 1B, it is seen that each of the inserts extends across the full width of the wave guiding passage. At a point along the wave guide 10 at which the vertical dimension of the wave guiding passage has been appreciably reduced, each of a plurality of wirelike conductive elements 12, advantageously of ribbon type, stretches across the width of the wave guiding passage forming a linear array extending axially along the wave guide in the plane of symmetry of the two insert members. This linear array advantageously begins at the point where the vertical dimension of the wave guiding passage is least. Beyond the point where the linear array of wires begins, each of the insert members is grooved. The two inserts are advantageously grooved in a manner which continues to make the plane of the wires a plane of mirror symmetry. It will be convenient to describe in detail only the groove in insert member 11. Its groove is stepped, having a central portion 15 of uniform width equal advantageously to approximately one half the length of the wires along the uniform main portion of the array and two symmetrically stepped end portions, which may be viewed as ledges 13 and 14 in the side walls. Along a transition region the depth of the central portion 15 of the grooving increases gradually with axial distance, thereby increasing gradually the separation of the central portion of the wires from the bottom surface of the wave guide. Over this transition region the vertical separation of the stepped portions 13, 14 from the ends of the wire elements remains substantially uniform but the width of such portions decreases gradually in a manner effectively to shorten the free lengths of the wire elements. In the main portion beyond the transition region, the geometry of the circuit remains uniform. In a similar manner the insert 11A is grooved to form a central groove 15A between stepped portions 13A and 14A. A comparison of Figs. 1B through 1F illustrates the manner of transition from a hollow rectangular wave guide to a slow wave circuit in accordance with the invention. The overall length of the transition region advantageously is at least several operating wavelengths long to minimize reflections in the course of the mode conversion.

The arrangement described is adapted either for transferring wave energy supplied to the rectangular wave guide to the slow wave circuit or for transferring wave energy from the slow wave circuit to the rectangular wave guide. Of course, the slow wave circuit can be provided with a rectangular wave guide connection at each end in an analogous manner.

As shown in Fig. 1F, which is a transverse section of the fully developed form of the slow wave circuit, each of the wire elements 12 is loaded at its ends with respect to the center portion by ledges 13A and 14A symmetric with respect to ledges 13 and 14, respectively. From the standpoint of the entire length of each wire, the central grooves 15 and 15A may be viewed as reducing the capacitance of the central portion relative to the two end portions. Alternatively, from the standpoint of only the

central portion of the length of each wire, the portions extending beyond into the side ledges may be viewed as the addition of inductive loading. Viewed in either fashion, the net effect is to reduce the cutoff wavelength of the wave guide to a value less than the resonant wavelength of the entire length of the wires. It is less important that the depths of central grooves 15 and 15A be similar inasmuch as such dimensions are relatively immaterial provided they are sufficient. However, to preserve the symmetry, such dimensions are here shown equal. The interior of the wave guiding passage of this kind will for purposes of brevity be characterized as cruciform in cross section. A circuit of this kind would be coupled to a rectangular wave guide by a transition region which includes a pair of symmetrically positioned mode conversion members of the kind described above. It may be desirable, for special applications, to have the loading asymmetric, in which case the spacing of ledges 13A and 14A from the wire elements may be different from that of ledges 13 and 14 and/or the ledges may be of different widths.

In the backward wave oscillator 30 shown in Fig. 2, the slow wave circuit 20 is of the kind shown in Figs. 1A through 1F. As discussed above, it includes a plurality of wire elements 12 extending transversely across a wave guide 10 having a wave passage therethrough which is substantially cruciform in cross section. The wires form a linear array which extends along the axis of the guide. The slow wave circuit is coupled to a section of hollow wave guide of rectangular cross section by way of a transition region which is formed by a pair of insert members 11, 11A for effecting the necessary mode conversion.

For providing an electron beam for flow past the wave circuit, an electron gun, shown schematically simply as the cathode 32, is positioned beyond one end of the circuit within an evacuated enclosure represented by the broken line 33. The beam is projected past the circuit under the impetus of accelerating forces provided by a potential difference applied between the cathode and the slow wave circuit. A suitable aperture is provided in the wall of the wave guide 10 for entrance of the beam into the wave guiding passage. The electrons advantageously flood the region surrounding the linear array of wires. To minimize transverse excursions of electrons as they flow past the linear array, the tube is advantageously completely immersed in a strong, axial magnetic field. Such a field may be established either by a permanent magnet or an electromagnet. In the interest of simplicity, a showing of such flux producing equipment has been omitted from the drawing. In a tube of this kind, it is unnecessary to provide a separate collector electrode at the end of the slow wave circuit but instead the beam is there permitted to diverge by the insertion of permeable material which results in a distortion therealong of the focusing field and so is collected by the walls of the wave guide.

In this embodiment, as in the usual form of backward wave oscillator, the oscillatory wave is abstracted at the upstream end of the slow wave circuit. To this end, the upstream end of the slow wave circuit is coupled to a rectangular wave guide section 34 which serves as the output coupling connection. It facilitates immersion in an axial magnetic field if transverse dimensions of the coupling connection are minimized and so the rectangular wave guide section is provided with a pair of right angle bends. A pressure tight glass window 35 is provided at the end of this section by way of which output energy may be supplied to a rectangular wave guide connection.

In an oscillator of this kind, it is usually unnecessary to take any special precautions to make the downstream end of the slow wave circuit reflectionless. It is sufficient merely to extend the length of the slow wave circuit beyond the point at which the electron stream is first al-

lowed to diverge so that the loss inherent in the slow wave circuit provides the necessary absorption of any incident wave energy.

The operation is of the kind familiar to a backward wave oscillator. Noise components in the electron stream set up noise waves which propagate upstream in the slow wave circuit. By appropriate choice of the velocity of the beam, interaction in a backward wave mode is had with the one of such waves of a desired frequency, and oscillations result at such frequency when the beam current and the coupling efficiency are sufficiently high. Accordingly, the frequency of oscillations is tuned by changes in the velocity of the beam which, in turn, is controlled by the accelerating voltage applied between the cathode and circuit. By modulating this voltage with signal information, a frequency modulated output wave can be achieved. In particular, the interaction is most efficient in an operating band of frequencies at which the wavelength is slightly shorter than twice the length of the wire elements along the smooth portion of the slow wave circuit.

Fig. 3 shows schematically an alternative form of backward wave oscillator 40. Herein an interaction circuit 20 of the kind previously described is employed primarily to modulate an electron beam in accordance with an oscillatory wave. Thereafter such beam modulation is made to induce an oscillatory wave into a slow wave circuit 41 positioned downstream with respect to the backward wave circuit. The slow wave circuit 41 is one especially adapted for operation in a forward wave mode. Since a wide variety of forms of such a forward wave circuit is known, it is here shown schematically. Typically, such a forward wave circuit may be a wire or ribbon helix. For operation at millimeter wavelengths, the forward wave circuit may advantageously be of the form described in the aforementioned Karp-Yocom application, comprising a linear array of wire elements positioned in a wave guide which is provided with a central ridge. The general principles and advantages of a backward wave oscillator of this kind are described in a co-pending application Serial No. 392,946 filed November 18, 1953, by H. Heffner and R. Kompfner.

Within an evacuated enclosure shown as the broken line 42, at opposite ends an electron gun 43 and a collector electrode 44 serve to define a path of flow of an electron beam. Suitable equipment (not shown) is used to minimize transverse components of flow. Positioned upstream along the path of flow is a slow wave interaction circuit of the kind shown in Figs. 1A through 1F which provides backward wave type interaction with the electron flow. The characteristics of this circuit are made to be such that a backward traveling oscillatory wave is induced in this circuit in the manner characteristic of the oscillator described above. In this instance, the slow wave circuit 20 is terminated in its characteristic impedance at both ends so that the oscillatory wave set up therein is absorbed with minimum reflection. However, concomitant with the growth of this oscillatory wave in the slow wave circuit, there results a corresponding modulation of the electron beam. Such beam modulation may be viewed as the growth of space charge waves on the electron beam. Such space charge waves grow with progress in the direction of electron flow past the slow wave circuit 20 and subsequently induce a forward traveling wave in the slow wave circuit 41 of a frequency corresponding to the wave set up initially in the backward wave circuit 20. The circuit 41 is designed so that the forward induced wave interacts with the electron beam in the manner characteristic of forward wave type traveling wave amplifier. The amplified wave is abstracted at the downstream end of circuit 41. The upstream end of circuit 41 preferably is terminated. Alternatively, the circuit 41 may be designed to have nonreciprocal attenuation characteristics, low in the forward direction, high in the backward direction. It is important that the cir-

cuit 41 be designed not to oscillate independently in a backward wave mode if the full advantages of this form of oscillator are to be realized.

The principles of the invention may be embodied in alternative forms of slow wave circuits. Various expedients are possible for arranging that in a linear array of wire-like elements extending along a wave guide, each of the elements be capacitively loaded less at its ends than in the center whereby the length of each element becomes longer than half the cutoff wavelength of the guide.

In the circuit 50 shown in Fig. 4, a plurality of curved wire elements 51 extend in a linear array between the narrow side walls of a rectangular wave guide 52.

In the circuit shown in Fig. 5, a plurality of wire elements 61 extend in a linear array between opposite vertices of a rectangular wave guide 62.

It is to be understood that the various embodiments described are merely illustrative of the general principles of the invention. Various arrangements may be devised by workers skilled in the art without departing from the spirit and scope of the invention. For example, the slow wave circuits which form the principal feature of the invention may be provided with coupling connections at their two ends and utilized in traveling wave amplifiers of the backward wave type.

What is claimed is:

1. In a backward wave oscillator, means for forming an electron beam, an interaction circuit positioned along the path of flow of said beam comprising a hollow wave guide substantially cruciform in cross section in which between a pair of surfaces extends transversely a plurality of axially spaced wirelike conductive elements in a linear array, and a coupling connection to the upstream end of said interaction circuit comprising a hollow wave guide of rectangular cross section coupled to said interaction circuit by way of a mode converting member.

2. In a backward wave oscillator, means for forming an electron beam, a backward wave mode interaction circuit positioned upstream along the path of flow comprising a hollow wave guide substantially cruciform in cross section in which between a pair of surfaces extends transversely a plurality of wirelike conductive elements in an axial linear array, means for making the two ends of said circuit substantially reflectionless, a forward wave mode interaction circuit positioned downstream along the path of flow, and means for extracting output wave energy from the downstream end of said forward wave mode circuit.

3. In a backward wave oscillator, an interaction circuit comprising a hollow conductive wave guide having a wave path therethrough whose cross section is substantially cruciform, and a plurality of wirelike elements extending between an opposite pair of surfaces of said wave guide in a linear array parallel to the axis of the wave guide, the successive elements of the array extending parallel to each other and being spaced apart in the direction of wave propagation along said wave guide.

4. In a device which utilizes the interaction between an electron beam and a negative spatial component of an electromagnetic wave for amplifying the wave, means for forming an electron beam and for projecting said beam along a predetermined path, and a slow wave circuit along said path for propagating an electromagnetic wave in coupling relation with said electron beam, said slow wave circuit comprising a hollow conductive wave guide positioned to surround the beam path along a substantial portion of the length of the path and characterized in that the inner surface of the guide defines a wave path which in cross section is substantially cruciform in shape, a plurality of wirelike elements extending from opposite points of the inner surface of the wave guide to form a linear array along the beam path, successive elements of the array extending parallel to each other and being spaced apart in the direction of the beam path.

5. In a device which utilizes the interaction between

a charged particle beam and an electromagnetic wave for amplifying the wave, means for forming a beam of charged particles and for projecting said beam along a predetermined path, and a slow wave circuit for propagating an electromagnetic wave in coupling relation with said beam, said slow wave circuit comprising a conductively bounded wave guiding path and a succession of wirelike elements extending across said path, successive elements of the succession extending parallel to each other and being spaced apart in the direction of wave propagation along said path, said slow wave circuit being characterized in that the cross section of its conductively bounded wave guiding path includes a first region having a predetermined transverse dimension and a second region having a larger transverse dimension measured in the same direction as said predetermined transverse dimension and further characterized in that the succession of wirelike elements extends across said wave path in the region of its larger transverse dimension.

6. In a device which utilizes the interaction between a charged particle beam and an electromagnetic wave for amplifying the wave, means for forming a beam of charged particles and for projecting said beam along a predetermined path, and a slow wave circuit for propagating an electromagnetic wave in coupling relation with said beam, said slow wave circuit comprising a conductively bounded wave guiding path and an array of wirelike elements extending across said path, successive elements of the array extending parallel to each other and being spaced apart in the direction of wave propagation along said path, said slow wave circuit being characterized in that the cross section of its conductively bounded wave guiding path includes a first region having a predetermined transverse dimension and a second region having a transverse di-

mension measured in the same direction as said predetermined transverse dimension equal to approximately twice the transverse dimension of the first region and further characterized in that the array of wirelike elements extends across said wave path along said second region.

7. In a device which utilizes the interaction between an electron beam and a spatial component of an electromagnetic wave for amplifying the wave, means for forming an electron beam and for projecting said beam along a predetermined path, a slow wave circuit along said path for propagating an electromagnetic wave in coupling relation with said electron beam, and coupling means connected at one end of said slow wave circuit for extracting wave energy therefrom, said slow wave circuit comprising a hollow conductive wave guide positioned to surround the beam path along a substantial portion of the length of the path and characterized in that the inner surface of the guide defines a wave path which in cross section is substantially cruciform in shape, a plurality of wirelike elements extending from opposite points of the inner surface of the wave guide to form a linear array along the beam path, successive elements of the array extending parallel to each other and being spaced apart in the direction of the beam path.

References Cited in the file of this patent

UNITED STATES PATENTS

2,441,574	Jaynes	May 18, 1948
2,457,601	Ring	Dec. 28, 1948
2,698,398	Gintzon	Dec. 28, 1954
2,708,236	Pierce	May 10, 1955
2,745,984	Hagelbarger et al.	May 15, 1956
2,746,036	Walker	May 15, 1956