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SPATIAL HARMONIC TRAVELING WAVE TUBE

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FIG. 1

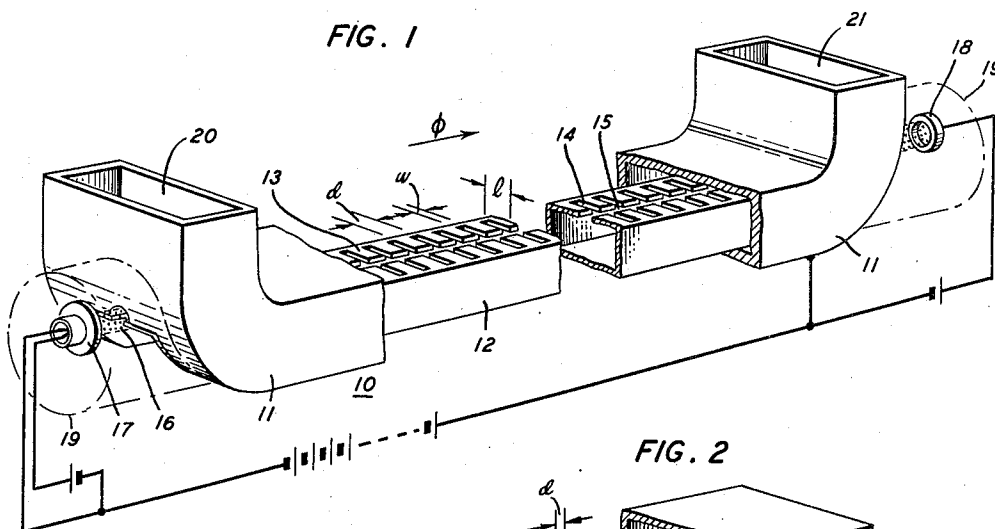


FIG. 2

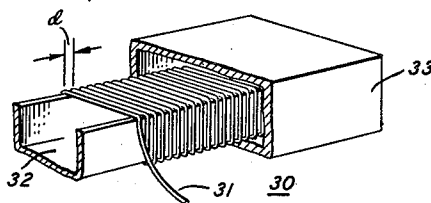
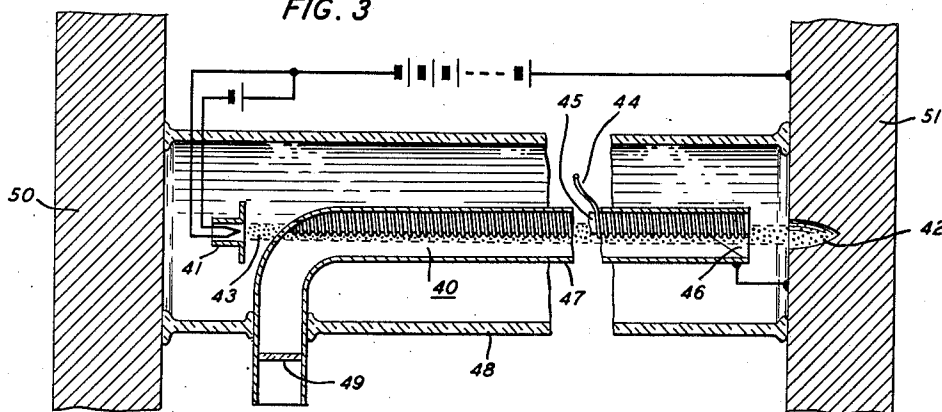


FIG. 3



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SPATIAL HARMONIC TRAVELING WAVE TUBE

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7 Claims. (Cl. 315—3.5)

This invention relates to microwave devices and more particularly to such devices of the so-called traveling wave type.

The principal object of this invention is to simplify the structure of a wave guiding circuit useful for amplification or generation of electromagnetic waves at millimeter wavelengths.

Another object is to achieve broad band amplification in traveling wave tubes without sacrificing gain and ease of construction.

Microwave devices of the so-called traveling wave type which cause the transfer of energy from an electron stream to an electromagnetic wave propagating along the circuit offer one particular advantage not found in other amplifying devices, namely, useful amplification over a very broad band of frequency. Since this band width, expressed as a percentage of the operating frequency, is relatively fixed, it is desirable to raise the frequency of operation as much as possible to a value where, for example, a band width of ten percent covers many thousands of megacycles. Unfortunately, however, as the frequency of operation is increased various difficulties are encountered. For example, a helix such as is commonly used in traveling wave tubes for propagating a "fast" electromagnetic wave has been employed in a tube operating at roughly 50,000 megacycles but the amplification of the tube is so limited and the helix is so difficult to manufacture because of its microscopic size that such a structure is not very satisfactory. An alternative approach to these problems has been suggested by S. Millman in an article "A spatial harmonic traveling wave amplifier for six millimeters wavelength," appearing in the Proceedings of the Institute of Radio Engineers, volume 39, page 1040, September 1951.

The present invention makes use of the spatial harmonic principle of operation and for a comprehensive exposition thereof the reader is referred to the above-mentioned article. Briefly though, it may be said that this principle consists essentially in causing an electron stream interacting with an electromagnetic wave to interact only at given intervals. This is accomplished by beaming the electron stream in electrical proximity to a series of regularly spaced discontinuities along which a wave is propagating. These discontinuities are chosen so that there exists between them a component of electric field parallel to the direction of electron flow and so that no such component exists in the region over them. By adjusting the velocity of the electron stream, a given electron can be made to reach each interval between discontinuities at a time when the electric field intensity here is the same as it was in the preceding interval when this electron arrived there. The electrons can thus be synchronized in phase with any wave which propagates along these discontinuities with a component of phase velocity parallel to the electron flow equal to the velocity of the electrons plus a velocity such that the electric field rotates any multiple of ± 360 degrees between successive interaction intervals.

In accordance with the present invention, an electron stream is beamed in coupling relation to the electric field existing in the vicinity of a series of regularly spaced discontinuities of basically simple construction positioned within a conductively bounded wave guiding path. These discontinuities, which can be made more uniformly and much more easily than structures used for a similar purpose heretofore, are, in one specific embodiment, formed by a plurality of slot-like openings perforating a thin sheet while in a second embodiment they are formed by parallel spaced turns of wire having slot-openings between them. A more complete understanding, however, of the nature and the objects of this invention may be gained from the following description thereof given in connection with the accompanying drawings of several illustrative embodiments. With reference to the drawings in general:

Fig. 1 is a perspective view of an embodiment of a spatial harmonic wave guiding circuit in accordance with the invention comprising a rectangular wave guide surrounding a raised hollow rectangular ridge in the surface of which there are a plurality of regularly spaced slot-like openings;

Fig. 2 shows in perspective view a section of a second embodiment of a spatial harmonic wave guiding circuit similar to that of Fig. 1 but in which the discontinuities are formed by parallel turns of a wire wrapped upon a U-shaped channel; and

Fig. 3 is a side section of a backward traveling wave oscillator in which a circuit similar to that shown in Fig. 2 is a component part.

Referring now more particularly to the drawings, there is shown in Fig. 1, by way of example for purposes of illustration, a wave guiding circuit 10 adapted to propagate an electromagnetic wave therethrough past a series of slot-resonators formed by slot-like openings in a conducting surface so that the wave may interact with an electron stream beamed in coupling relation to these resonators. Wave energy, which may have a phase velocity along the circuit greater than the speed of light, may then extract energy from the electron stream traveling in the same direction as the wave with a velocity, for example, of one-twentieth the speed of light.

Wave circuit 10 comprises a rectangular wave guide 11 surrounding a hollow rectangular ridge 12 which is centered along the bottom wall of the guide and which may be brazed or soldered to it. In the upper surface 13 of this ridge, which is parallel to the upper and lower surfaces of the guide surrounding it, there are a plurality of slot-like openings 14 which are regularly spaced a distance d apart along the direction of wave propagation. These openings, together with the metal between them, form slot-resonators lying transverse to the direction of wave propagation. They are of width w and have a length l which makes them one-quarter wavelength resonant at the upper cut-off frequency of the circuit. The lower cut-off frequency of guide 11 is lowered somewhat along its center length by ridge 12 and an increase in the operating band width is thereby obtained. The amount that this lower cut-off frequency is altered depends upon the relative dimensions of the ridge and its surrounding wave guide, but a ridge of outside measurements roughly equal to five-eighths the inside measurements of its associated guide is satisfactory. The wall thickness of ridge 12 is not critical but it should be thin compared to the free space wavelength of operation. Longitudinal slit 15, which is cut in wall 13 perpendicular to openings 14, provides a convenient passage for electron stream 16, past the series of slot-resonators. This slit has negligible electrical effect upon the action of the slot-resonators and it may be eliminated if not wanted by placing, for example, the two sections of wall 13 together. Its use, however, is desirable since it serves additionally to prevent the

metal between openings 14 from buckling out of the plane of wall 13 when this wall is unevenly heated.

Electron gun 17 and collector electrode 18 are aligned with respect to circuit 10 so that the electron stream flows along the axis of slit 15 through the openings in the lower wall of guide 11 provided for this purpose. Non-magnetic envelopes 19, surrounding these electrodes, together with windows (not shown) in ends 20 and 21 of guide 11 and the metal walls thereof, form an air-tight enclosure.

The curved ends of guide 11 provide a simple and effective means of impedance matching between the length of circuit 10 which includes ridge 12 and the input and output wave guides which may be attached at ends 20 and 21 respectively. Ridge 12 may be inserted through openings in the lower wall of the guide and soldered or brazed in place so that the curvature of this wall will provide an effective tapering of the ridge height. The inside dimensions of wave guide 11 are preferably chosen so that it will propagate a transverse electric wave in the fundamental mode with the electric field perpendicular to the upper and lower walls of the guide. The conducting elements of circuit 10 are preferably made of the same metal such as copper or silver plated molybdenum.

A parallel extending magnetic field is provided for focusing the electron stream. A single line of magnetic flux ϕ , parallel to electron stream 16, is shown in Fig. 1 to indicate the orientation of this field relative to circuit 10. The elements for generating this field have not been shown in order to simplify the drawing but any appropriate means may be used such as magnet poles 50 and 51 shown in Fig. 3.

In operation, a transverse electric wave is preferably applied to circuit 10 by some appropriate means, such as a wave guide of the same dimensions as guide 11. As this wave propagates from the gun end 20, of the circuit to the collector end, it is amplified by spatial harmonic interaction with the electron stream. This spatial harmonic phenomenon may best be understood by a consideration of the following abbreviated mathematical analysis adapted specifically to the structure shown in Fig. 1 but applicable to spatial harmonic action in general.

If z is the direction of wave velocity in the wave guide, then in the vicinity of recurrent discontinuities in the guide the z component of a traveling wave may be written

$$E_z = F(z) e^{j\omega t} \quad (1)$$

in which ω is the radian frequency and

$$F(z) = \sum_{n=-\infty}^{n=\infty} A_n \exp \left[-j(2\pi n + \theta) \frac{z}{d} \right] \quad (2)$$

where d is the distance between successive discontinuities which here are the slots 14, n is an integer and θ is the phase delay in radians from one discontinuity to the next and is given by

$$\theta = \frac{2\pi d}{\lambda_g} \quad (3)$$

where λ_g is the guide wavelength of the fundamental wave corresponding to $n=0$ in Equation 2. Assuming the amplitude of E_z to be constant at the edge of the discontinuities or slots, and denoting it by E_0 , A_n may be written

$$A_n = \frac{E_0}{d} \int_{-\frac{w}{2}}^{+\frac{w}{2}} \exp \left[j(2\pi n + \theta) \frac{z}{d} \right] dz = \frac{2E_0}{2\pi n + \theta} \sin \left[(2\pi n + \theta) \frac{w}{2d} \right] \quad (4)$$

where w is the width of a slot 14. Substituting in Equation 1

$$E_z = E_0 \sum_{n=-\infty}^{n=\infty} \frac{2 \sin \left((2\pi n + \theta) \frac{w}{2d} \right)}{2\pi n + \theta} \exp \left(j \left[\omega t - (2\pi n + \theta) \frac{z}{d} \right] \right) \quad (5)$$

From this last equation it can be seen that near the slot discontinuities in the wave guide there appears to be an infinite number of spatial harmonic components of the fundamental wave, each traveling at a different phase velocity given by

$$\frac{\omega d}{(2\pi n + \theta)}$$

in which n is an integer between $-\infty$ and $+\infty$. Setting $n=0$ we see that the fundamental wave travels in the positive z direction with a phase velocity of

$$\frac{\omega d}{\theta}$$

For $n=1$, a wave appears to travel in the positive z direction with a velocity of

$$\frac{\omega d}{(2\pi + \theta)}$$

which is less than the velocity for the fundamental wave. Similarly for other positive values of n . For $n=-1$, there appears to be a wave traveling in the positive z direction with a phase velocity

$$\frac{\omega d}{(-2\pi + \theta)}$$

which is negative since fundamental phase displacement θ between successive slots is less than 2π . Thus for each negative integer n there corresponds a wave having negative phase velocity, or, in other words, a backward traveling wave. The group velocity of all spatial harmonic waves, it should be remembered, is always in the direction of power propagation and is the same for all, including those which have negative phase velocity.

In the vicinity of the guide wall between slots, that is the metal region between slots 14, the electrons see substantially no z component of electric field, while when passing over a slot opening they see a strong z direction electric field. This alternate passage from drift space to interaction space is analogous to a stroboscopic light flashing on a patterned wheel, the duration of each flash corresponding to the time the electrons are in the reaction space over the slot opening, the interval between flashes corresponding to the time it takes an electron to go from one slot center to the next and the angular velocity of the wheel corresponding to the phase velocity of the fundamental spatial harmonic of the traveling wave. For a given wheel velocity there will be a stroboscopic frequency at which the wheel appears stationary and this apparent non-rotation of the wheel corresponds to synchronism between a spatial harmonic of the wave and the electrons. In this synchronous condition a single electron "sees" the same field vector as it passes each slot opening and therefore the requirement for electromagnetic-wave electron-stream interaction is met by, in effect, "fooling the electrons."

By assuming that the group velocity of the wave propagating down the guide is opposite to the velocity of electron flow, it can be seen, following the above analogy, that the electrons can be synchronized with a spatial harmonic of the wave having a negative phase velocity relative to the group velocity. When such conditions actually exist in a spatial harmonic tube, electromagnetic power flows from the collector end to the gun end of the tube. This mode of operation, useful for amplification up to a critical value of beam current, is likewise useful for obtaining oscillations beyond this critical value since the necessary feedback path for sustaining the oscillations is then automatically provided by the electron stream.

From an inspection of Fig. 1, it is apparent that somewhere between the condition where the slot spacing d equals slot width w , in which case there is substantially no interaction between the electromagnetic wave and the electron stream, and the condition where width w of the slot opening is zero, in which case the interaction is like-

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wise zero, there must be some ratio of slot width to slot spacing which gives optimum interaction if there is to be any net gain. Now, it can be shown that the electron velocity V_e required for synchronization is given by

$$V_e = \frac{\omega d}{(2\pi n + \theta)} \quad (6)$$

where ω is the radian frequency, d the center to center slot spacing, n an integer, and θ the fundamental phase displacement between slots, usually

$$\frac{\pi}{3} \text{ to } \frac{\pi}{2}$$

It can further be shown that the amplification of the electromagnetic wave interacting with the electrons is proportional to

$$\text{Gain} = K \frac{\sin^2 \left[\frac{(2\pi n + \theta)w}{2d} \right]}{\frac{(2\pi n + \theta)w}{2d}} \quad (7)$$

where K is a proportionally constant and where w is the width of a slot opening. By differentiating this last equation with respect to

$$\frac{w}{d}$$

and setting the result equal to zero, the gain is seen to be maximum when

$$\frac{w}{d} = \frac{2.33}{(2\pi n + \theta)} \quad (8)$$

As mentioned previously, practical values of θ may be roughly between

$$\frac{\pi}{3} < \theta < \frac{\pi}{2}$$

and so, from Equations 6 and 8, w is easily determined for a given electron velocity V_e , a given value of n and a given frequency of operation.

The slot spacing and dimensions in the circuit shown in Fig. 1 may be chosen according to Equations 6 and 8 for synchronization of the electron stream with either forward or backward traveling spatial harmonic waves. The number of slots used will depend upon the gain desired but approximately 100 are sufficient for ordinary gain requirements. It should be understood that a structure designed for a particular mode of spatial harmonic operation at a given frequency and with an electron stream having a certain velocity may be used additionally to obtain interaction between waves having the same or slightly different frequencies and electron streams having greatly different velocities. The following dimensions, which are given merely for the purpose of illustration, have been found satisfactory in a circuit built according to the design shown in Fig. 1 for synchronization between the first forward spatial harmonic wave and an electron stream having a velocity equivalent to approximately 1300 volts: length $l = 0.220\lambda_0$, distance $d = 0.086\lambda_0$, width $w = 0.025\lambda_0$, and width of slit $15 = 0.065\lambda_0$, where λ_0 is the free space wavelength at the center frequency of operation.

Fig. 2 shows in perspective a portion of the center section of a spatial harmonic circuit 30 similar to that shown in Fig. 1. Here the slot-resonators are formed by parallel turns of wire 31 which lie substantially transversely across the top of supporting U-shaped channel 32. The pitch with which this wire is wrapped around the channel determines the slot spacing d while this pitch, together with the wire diameter, determines the width of the opening between turns. The length across the top of the channel of the turns of wire 31 in the absence of a longitudinal slit equivalent to slit 15 in Fig. 1 is such that these turns, together with the openings between them, are half-wave resonant at the upper cut-off frequency of

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the circuit. Wave guide 33, which surrounds the wire wound channel or ridge, may be identical to guide 11 in Fig. 1, although it is not necessarily so. As in Fig. 1 this ridge is fastened along the bottom wall of the guide and is centered between the side walls thereof. An electron gun and collector electrode (not shown), similar to those shown in Fig. 1, may be used with circuit 30 to beam an electron stream just over and just under the turns of wire 31. Means (not shown) for producing a magnetic field aligned with the axis of the electron stream may be similar to those shown in Fig. 3.

It is not necessary that wire 31 be of any particular cross section, but it is preferably round, as shown, or ribbon-shaped, having a thickness less than its width. The thickness of this wire is not critical but as with the thickness of ridge walls in circuit 10, it should be much smaller than a free space wavelength at the frequency of operation. For mechanical stability the wire should preferably be wrapped tightly around channel 32, although, alternative to this, lengths of wire may be laid across the channel opening and firmly fastened in position by a frame or by other appropriate means.

Any one of these wire structures is particularly adapted to backward spatial harmonic wave operation since the ratio of space between the wires w to wire spacing d can readily be made to satisfy Equations 6 and 8 for negative integers. A ratio of

$$\frac{w}{d} = \frac{1}{2}$$

has been found suitable in these structures for synchronization of the electron stream with the first backward wave. A smaller ratio in the vicinity of one-third should be used with the first forward wave.

The operation of wave guiding circuit 30 is substantially the same as that of circuit 10 in Fig. 1 and it is only necessary to mention here that for backward spatial harmonic amplification, wave energy should be fed into the collector end of the circuit and extracted from the gun end thereof.

It should be understood that none of the wave guiding circuits described in the foregoing is limited to spatial harmonic wave amplification since any one of these structures, if it has the requisite dimensions, may be used for the generation of wave energy by either conventional or by backward wave operation. Conventional oscillations may be obtained in any amplifier simply by returning a sufficient portion of the output energy to the input of the amplifier and the operation of such an arrangement is so well known that more of a description here would be superfluous. The generation of backward wave oscillations, on the other hand, is a recent development in the art and, in view of the importance of the present invention in this regard, a brief description of a backward wave oscillator is appropriate.

Fig. 3 is a side view illustration of a backward wave oscillator in which a circuit 40, substantially the same as circuit 30, is the wave propagating element. This circuit is aligned with respect to electron gun 41 and collector cavity 42 so that electron stream 43 flows just over and just under the turns of wire 44 wrapped around channel 45. At the collector end of the circuit, lossy material 46 is positioned within guide 47 on either side of channel 45 in order to minimize reflection of wave energy at this point. Any wave energy which may be returned from the output connection at the gun end by impedance mismatches is thereby substantially reduced and its unwanted interference with energy propagating in the opposite direction is mostly eliminated. At the gun end of the circuit oscillating wave energy is extracted from the circuit by a continuation of guide 47 which is bent downward for impedance matching as explained previously. An appropriate opening is provided in the curved section of the top wall of the guide for the passage of electron stream 43. Guide 47 is sealed through envelope 48 and this en-

velope, together with window 49 in the guide, and magnet poles 50 and 51, forms an air-tight enclosure surrounding the electron stream. Opening 42 in pole piece 51 is shaped approximately as shown in order to reduce secondary emission from this pole which serves additionally as a collector electrode. All the elements in the region between pole pieces should be non-magnetic so that the magnetic field may be made to focus the electron stream along an axis with which the field is aligned.

When the current density of the electron stream in the arrangement shown in Fig. 3 exceeds a certain critical value, oscillations may suddenly begin at a frequency which is determined by the stream velocity. Wave energy, originating at the collector end of circuit 40, flows toward the output end thereof where it is led off through window 49 to an appropriate output connection. As this energy passes along the wire wound ridge within guide 47 it is amplified by interaction between the backward traveling spatial harmonic of itself which is synchronized with the electron stream and the electron stream. This interaction, at the same time, causes a bunching of the electron stream. This bunching in turn causes an increase in wave energy which in turn causes a bunching of the electron stream and so on. Thus the feedback energy necessary to sustain oscillations is automatically returned to the circuit by the electron stream. Since the frequency of oscillation is determined principally by the electron velocity for a given wave guiding structure and since this velocity is easily varied electrically over a wide range, the frequency may be modulated at a high rate and with a very broad band width.

The invention described herein is not limited solely to the embodiments shown since it may include spatial harmonic wave guiding structures of other than rectangular cross section. Furthermore, the input and output connections described above in connection with the drawing may be replaced by equivalent means without altering the nature of this invention. Lastly, it will be apparent to those skilled in the art that the dimensions of the wave guiding circuits shown in the accompanying drawing may be selected over a wide range without departing from the spirit or scope of the invention as set forth.

What is claimed is:

1. In a microwave device, means for forming and projecting an electron stream for interaction with an electromagnetic wave propagating parallel to the axis of said stream and with higher phase velocity than the velocity of the stream, conductively bounded rectangular wave guiding means adapted to propagate an electric wave therethrough, and iterative filter means positioned asymmetrically within said guiding means parallel to the direction of wave propagation, said filter means including a conductively bounded hollow rectangular member the lateral dimension of which is less than the lateral dimension of said wave guiding means, one wall of said member being perpendicular to the orientation of the wave electric field and in which there are a plurality of substantially transverse slot-like openings regularly spaced in the direction of wave propagation.

2. In a microwave device, means for beaming an electron stream along a path, and conductively bounded wave guiding means adapted to propagate therethrough in a direction parallel to said path an electromagnetic wave for interaction with said electron stream, said wave guiding means including a wave guide surrounding a raised hollow ridge one surface of which is formed by a plurality of transverse slot-resonators regularly spaced in the direction of wave propagation said ridge having a lateral dimension less than the lateral dimension of said wave guiding means.

3. In a microwave device, means for beaming an elec-

tron stream along a path, and conductively bounded wave guiding means adapted to propagate therethrough in a direction parallel to said path an electromagnetic wave for interaction with said electron stream, said wave guiding means including a rectangular wave guide surrounding a hollow rectangular ridge one surface of which is formed by a thin conducting sheet perforated by a plurality of transverse slot-like openings regularly spaced in the direction of wave propagation, the surfaces of said ridge adjacent said thin sheet being spaced from the walls of said wave guiding means.

4. In a microwave device, means for beaming an electron stream along a path, and conductively bounded wave guiding means adapted to propagate therealong in a direction parallel to said path an electromagnetic wave for interaction with said electron stream, said wave guiding means including a rectangular wave guide surrounding a hollow rectangular ridge one surface of which is formed by parallel spaced turns of wire lying substantially parallel to the direction of wave propagation, the surfaces of said ridge adjacent said one surface being spaced from the walls of said guiding means.

5. In a traveling wave tube, means for beaming an electron stream along an axis, and conductively bounded wave guiding means adapted to propagate therethrough an electromagnetic wave for interaction with said electron stream, said wave guiding means including a length of wave guide whose ends are bent out of line from the electron path and whose center section surrounds a raised hollow ridge having in one surface thereof a plurality of slot-resonators lying transverse to the direction of wave propagation and regularly spaced apart in this direction, the lateral dimension of said ridge being less than the lateral dimension of said wave guide.

6. A traveling wave tube comprising means for beaming an electron stream along a fixed path, an air-tight envelope surrounding said means, and wave propagating means adapted to cause interaction between said electron stream and an electromagnetic wave propagating through said wave propagating means in a direction parallel to said fixed path, said wave propagating means including a rectangular wave guide asymmetrically surrounding a hollow rectangular ridge whose surface perpendicular to the electric field is formed by a plurality of slot-resonators lying substantially transverse to the direction of wave propagation and regularly spaced apart in this direction, the surfaces of said ridge adjacent said slotted surface being spaced from the walls of said wave guiding means.

7. In a microwave device, means for propagating therethrough an electromagnetic wave at a speed less than the speed of light said means including a raised hollow ridge having in a surface thereof a plurality of slot openings lying substantially transverse to the direction of wave propagation and spaced apart in that direction, and a rectangular wave guide asymmetrically surrounding said ridge, the lateral dimension of said ridge being less than the lateral dimension of said wave guide.

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