April 27, 1965 E. A. ASH 3,181,090

DELAY LINE FOR TRAVELLING WAVE TUBE

Filed Oct. 27, 1960 4 Sheets-Sheet 1

FIG. 1.

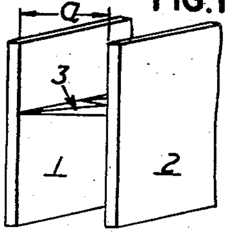

FIG. 2.

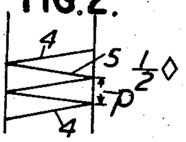

FIG. 3.

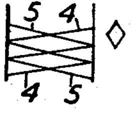

FIG. 6.

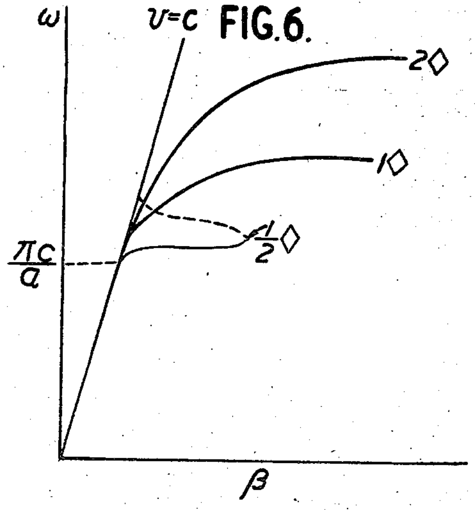

FIG. 4.

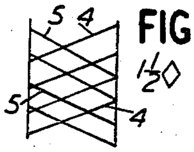

FIG. 5.

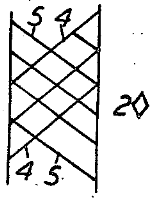

FIG. 7.

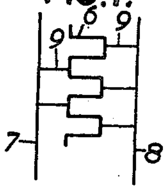

FIG. 8.

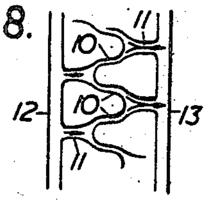

FIG 9

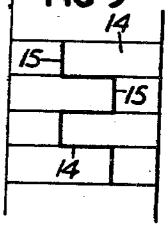

FIG. 10.

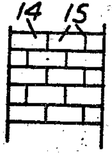

FIG. 11.

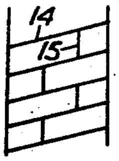

FIG. 12.

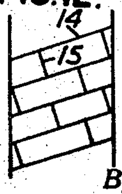

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FIG. 13.

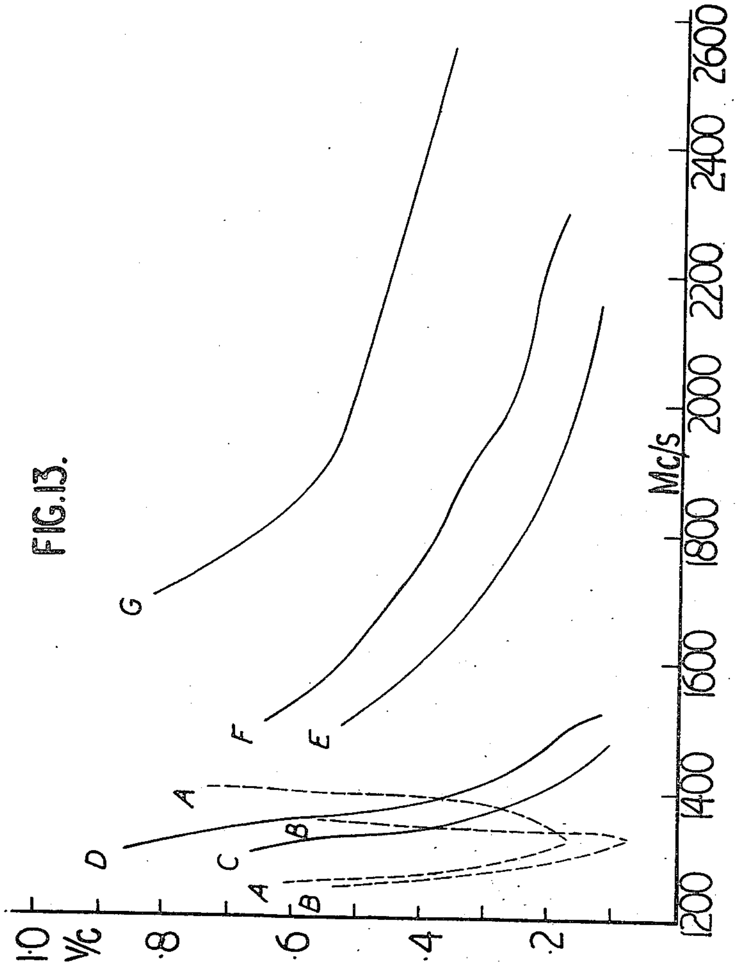

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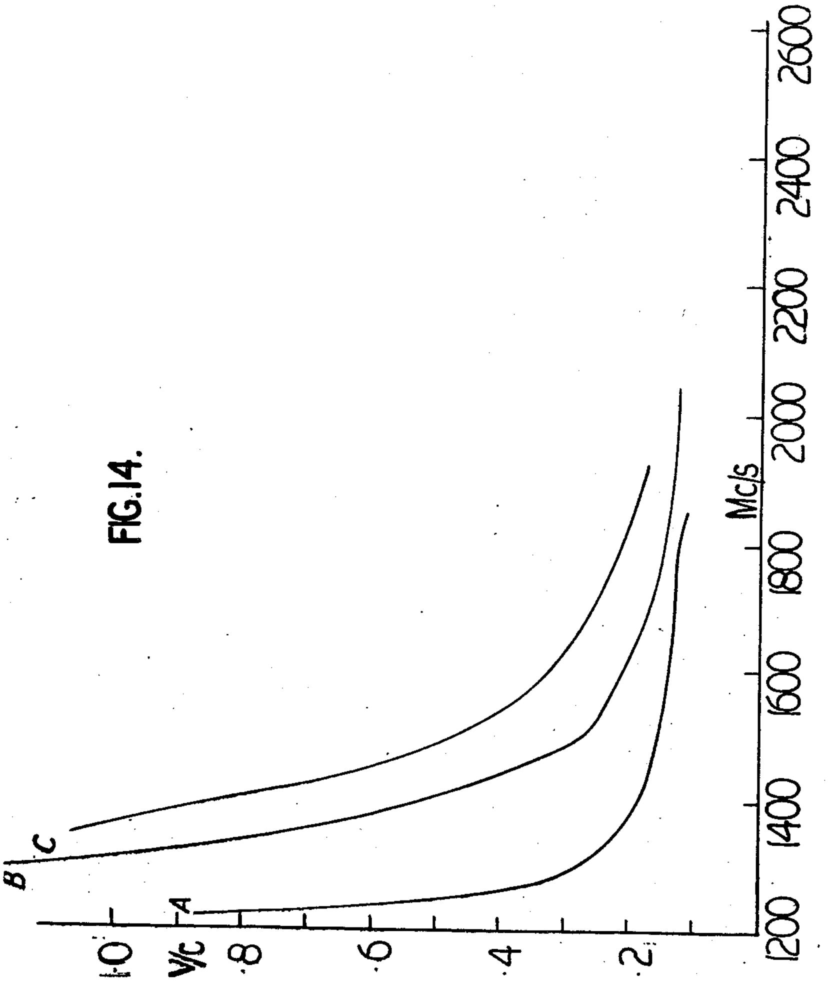
FIG.14.



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DELAY LINE FOR TRAVELLING WAVE TUBE

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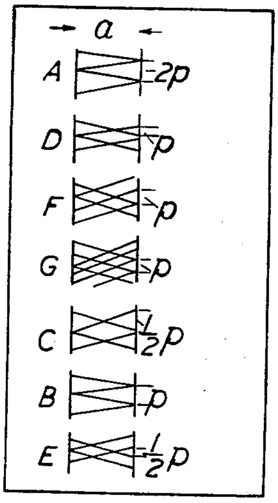
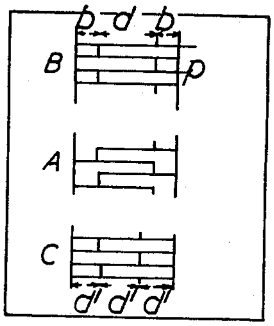


FIG. 13a.

FIG. 14a.



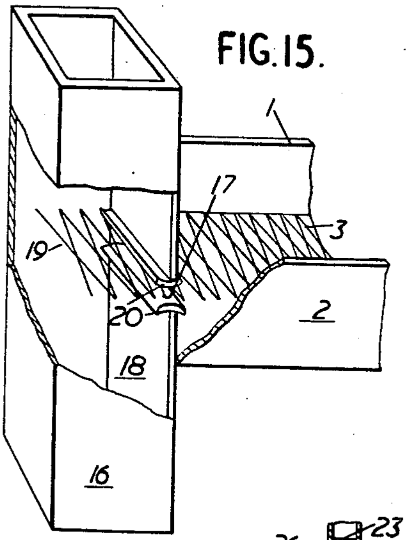
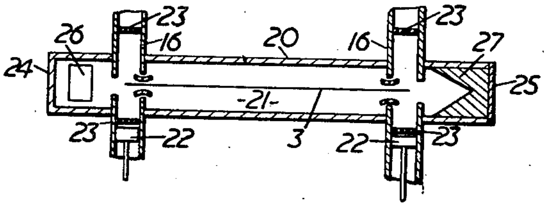


FIG. 15.

FIG. 16.



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United States Patent Office

3,181,090
Patented Apr. 27, 1965

3,181,090
DELAY LINE FOR TRAVELLING WAVE TUBE

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Filed Oct. 27, 1960, Ser. No. 65,304
Claims priority, application Great Britain, Nov. 30, 1959, 40,545/59
7 Claims. (Cl. 333—31)

The present invention relates to slow wave structures such as are incorporated in travelling wave tubes and backward wave oscillators.

The conventional helix slow wave structure has many known disadvantages for tubes of the highest frequencies, particularly from the point of view of manufacturing difficulties. An alternative slow wave structure, of which there are several variants, consists, basically, in a ladderlike arrangement of half wave resonators, in the form of bars or wires, stretched between parallel plane conducting side walls. A perfectly symmetrical arrangement of this type does not propagate over a finite band of frequencies, but may be made to propagate by introducing some asymmetry in the geometrical arrangement which will make the magnetic and electric couplings between adjacent resonators unequal. The present invention may be regarded, in one aspect, from the viewpoint of this asymmetrical class of slow wave structure. According to the present invention there is provided a slow wave structure which will propagate radio frequency waves over a frequency band whose width exceeds four percent of the mid-band frequency comprising a pair of parallel plane conducting walls and a grating joining the two side walls along the length of the structure in a plane perpendicular to the side walls with the side walls extending above and below the plane of the grating, and in which the grating is composed of intersecting conducting strands arranged to form a regular pattern of staggered apertures.

Many possible patterns of grating may be used, some more advantageously than others from the point of view of either mechanical construction or of bandwidth. In general it may be taken that for travelling wave amplifier or backward wave oscillator use, a frequency band less than 4% of the midband frequency is of little value. At present we prefer one of two general types of grating pattern: in the first, the pattern is of diamonds, produced by the intersection of two oppositely inclined sets of equidistant parallel strands, with, as a special case, what may be called a "half diamond" pattern, where the oppositely inclined strands intersect only at the side walls.

The other preferred pattern, which may be regarded as derived from a "meander line," has a zig-zag conducting path extending from end to end of the slow wave structure in between the side walls and supporting strands join this meander line at regular intervals to the side walls.

A variant of the meander line structure is produced by a set of equidistant parallel strands stretched from side wall to side wall at right angles to them and shorter strands, parallel to the side walls, each joining an adjacent pair of the transverse strands and off-set from one another so as to form a pattern of apertures similar to the conventional arrangements of bricks in a wall, there being normally a fraction of a whole brick terminating each row. This last mentioned variant can be regarded as a version of the diamond pattern in which the diamonds are distorted into rectangles.

The slow wave structures of the invention have mechanical and electrical characteristics which render them particularly suitable for use either for comparatively low frequency, high power, tubes or for millimetre wave tubes.

Unlike the helix, no insulation is required between the slow wave structure and surrounding parts. The dispersion characteristics are such as would be suitable for a slow wave structure used in conjunction with a high voltage electron beam, while the strands of a structure can be made in the form of hollow pipes so that it is eminently suitable for use in a high power low frequency travelling wave tube. On the other hand, small gratings can readily be produced by photo-etching techniques, and the structures exhibit strong spatial harmonic components in their propagation characteristics; they are thus very suitable for use as slow wave structures at the shortest wavelengths, for example in a backward wave oscillator at millimetre wavelengths.

The invention will be further described with reference to the accompanying diagrammatic drawings in which:

FIG. 1 represents a perspective view of one end of a slow wave structure according to the invention;

FIGS. 2 to 5 illustrate plan views of the grating of FIG. 1, each showing a different diamond pattern of apertures;

FIG. 6 shows, qualitatively, dispersion characteristics of diamond-apertured structures of the invention;

FIGURE 7 illustrates a meander line pattern of grating according to the invention;

FIG. 8 illustrates a modification of the arrangement of FIG. 7 suitable for water cooling;

FIG. 9 illustrates a "brick wall" variant of the meander line structure of FIG. 7;

FIGS. 10 to 12 illustrate respective variants of the arrangement of FIG. 9;

FIGS. 13 and 14 show measured dispersion characteristics of variously dimensioned diamond and meander line structures respectively illustrated in FIGS. 13*a* and 14*a*;

FIG. 15 illustrates a means of coupling a slow wave structure according to the invention to a hollow rectangular waveguide; and

FIG. 16 illustrates an embodiment of a slow wave structure according to the invention in a travelling wave tube.

In all its variants the slow wave structure of the present invention comprises, as indicated in FIG. 1, a pair of plane parallel side walls 1 and 2, indicated as spaced apart a distance *a*, with a conducting grating 3 joining the walls in a plane perpendicular to them and running the length of the structure. The strands of the grating are arranged to produce an array of intersecting conductors forming a regular pattern of staggered apertures. A typical type of pattern is indicated in FIGS. 2 to 5, in all of which there are two sets of equidistant parallel strands stretching from side wall to side wall, the two sets making equal and opposite angles with the normals to the side walls, and in which, except for the extreme end strands of the pattern, each strand is joined at its ends to respective strands of the other set.

Mention has been made above of the resonator type of slow wave structure in which an array of similar half wave resonators in stretched between a pair of parallel side walls. By inclining the resonators to the walls an asymmetry in coupling of the electric and magnetic fields of adjacent resonators is produced and propagation can occur over a limited bandwith. A bandwidth of such a single sheet structure of parallel resonators is, however, very small. A marked improvement in bandwidth is obtained if a second sheet, having its resonators equally and oppositely inclined to the side walls, is placed above or below the first sheet. From one point of view of the arrangement of FIG. 1 the patterns of FIGS. 2 to 5 can be regarded as being derived from the double sheet structure just mentioned, in which the spacing between the two sheets is reduced to zero. The propagation characteristics however are quite different from that in the case of the two sheets of simple parallel half wave resonators. From another point of view the patterns of FIGS. 2 to 5 can be regarded, in part, as planar versions of the contrawound helix; the propagation constants are here much more akin, but are by no means equivalent. Thus structures according to the present invention show prominent spatial or Hartree harmonics, while that illustrated in FIG. 2 has also a fundamental backward mode which the contrawound helix does not possess. The side walls are essential constituents of the slow wave structure and determine the low frequency cut-off of the propagation characteristics.

In the pattern of FIG. 2 one set of equidistant parallel strands **4** stretches from side wall to side wall and is joined at its ends by respective strands **5** of a similar set, strands **4** and **5** being oppositely inclined to the walls. In FIG. 2 the strands of the two sets intersect only at the side walls and so produce a pattern or triangles which, compared with the other patterns of FIGS. 3 to 5, can be regarded as being a pattern of half diamonds, as indicated by the symbolic legend to the right of the figure.

In FIG. 3 the strands **4** and **5** of the respective two sets intersect one another once intermediate the side walls so as to produce full diamond-shaped apertures between the walls. This pattern we refer to as a single diamond pattern, a complete diamond reaching from side wall to side wall, as represented by the single diamond symbol to the right of the figure.

With each strand of one set intersected twice by strands of the other set, we obtain the one and a half diamond pattern of FIG. 4, while with three intersections of each strand the two diamond pattern of FIG. 5 is obtained.

It is possible, by increasing the number of intersections, to produce further diamond patterns in which any number of complete diamonds or of complete diamonds plus a half diamond, joined end to end, fit in the transverse dimension of the slow wave structure. As the number of intersections is increased, however, the thickness of the strands reduces the open area of the grating occupied by apertures.

The dispersion characteristics of the diamond structures of the present invention are illustrated qualitatively in the Brillouin plot of FIG. 6. Here the angular frequency ω of the propagated waves is plotted as ordinate against the phase constant β as abscissa. Three curves are shown, namely those typical of the half-diamond, one-diamond, and two- diamond patterns respectively. All have the same lower cut-off frequency, denoted by the ordinate $\pi c/a$, where c is the velocity of light and a is the separation between the conducting planes **1** and **2** of FIG. 1. At this cut-off frequency the phase velocity is equal to the velocity of light, so that the curves intersect the straight line $v=c$ passing through the origin as indicated in FIG. 6, v being the velocity of propagation along the line. In the Brillouin plot the velocity of propagation $v=\omega/\beta$ while the group velocity is equal to

$$\frac{d\omega}{d\beta}$$

the slope of the curve. For the half-diamond structure the dispersion curve of the Brillouin plot is of low slope and is characterised by a branch, shown dotted, in which the slope is negative—i.e. the group velocity is oppositely directed to the phase velocity; thus the half-diamond structure exhibits a fundamental backward mode of propagation. The other patterns of FIGS. 3 to 5 do not have a fundamental backward mode of propagation, but all exhibit strong first spatial harmonic modes. For these harmonic modes the phase constant β is simply related to the phase constant in the fundamental mode, so that the Brillouin plots are generally similar to those for the fundamental modes. As the number of diamonds across the pattern is increased, so there is an increase in the upper frequency cut-off of the slow wave structure. As the pitch p between adjacent wires (FIG. 2) is increased, in any of the patterns, the velocity of propagation is increased, the velocity increase being nearly proportional to the increase in pitch (except near the cut-off frequencies).

The characteristic impedance of the slow wave structures is high, and, although the bandwidth of, for example, the half-diamond structure, is somewhat low, the product of bandwidth and impedance of the circuit turns out to be near the optimum for use in a travelling wave amplifier.

Mention has been made above of the mechanical difficulty which may be encountered when an attempt is made to increase the number of diamonds across the width of the slow wave structure. This may be overcome, to a large extent, by modifying the pattern so as to obtain, for example, an equivalent arrangement of rectangles, such as illustrated in FIG. 9. These modified structures can also be regarded as derived from a meander line stretching from end to end of the slow wave structure. In FIG. 7 there is shown a pattern in which a rectangular zig-zag continuous conductor **6** stretches from end to end of the structure midway between the sidewalls **7** and **8**. The conductor **6** is supported at each bend by a conducting stub **9** joining the meander line to the respective adjacent side walls of the structure.

The arrangement of FIG. 7 can be compared to the half-diamond structure of FIG. 2, and its propagation characteristics are generally similar.

There is no need for the meander line to be of strictly rectangular shape; the bends may be rounded and, as is illustrated very diagrammatically in FIG. 8, the grating may be made of hollow piping rather than fine strands. In FIG. 8 a sinous piping **10** replaces the meander line **6** and the struts **9** are replaced by further pipes **11** which join the piping **10** to hollow side walls **12** and **13**. Cooling liquid is pumped into the side wall **12** and flows through the piping network to the opposite hollow wall **13**.

The pattern of FIG. 7 may be modified by arranging that the side struts extend from wall to wall. We then obtain a pattern such as that of FIG. 9. In FIG. 9 the struts **9** become portions of a set of parallel equidistant strands **14** stretching normally between the side walls, and a set of short strands **15** is arranged parallel to the side walls with each strand **15** joining two adjacent strands of the set **14**, adjacent strands **15** being staggered so that the pattern of apertures resembles that of the conventional brick-built wall, each row containing one and a half bricks. In the drawing the strands **15** and the portion of the strands **14** between them has been thickened to show the correspondence with the meander line **6** of FIG. 7. On the other hand, comparison with FIG. 4 shows that the pattern of FIG. 9 can be regarded as a modified one and a half diamond structure, to which it has similar propagation characteristics. More than one strand **15** can be placed between adjacent strands **14**, as for example is illustrated in the FIG. 10, which would correspond to a two and a half diamond structure. Alternatively the pattern of FIG. 10 can be regarded as a double meander line structure in which two meander lines such as **6** of FIG. 7 can be traced out side by side.

In arrangements otherwise similar to those of FIGS. 7 to 10 it is not essential that the grating pattern be orthogonal to the side walls. Thus in FIG. 11 the strands **14** are inclined to the side walls, the strands **15** remaining parallel to the side walls, so that we now have a staggered pattern of parallelograms corresponding to the one and a half diamond pattern of FIG. 4. In the arrangement of FIG. 12 the strands **15** have also been inclined to the side walls, so that there is no longer a complete analogy with the patterns of FIGS. 2 to 5. The propagation characteristics of an arrangement such as that of FIG. 12 will, however, not be altogether dissimilar to those of the other structures so far described, although the bandwidth will be considerably less than that of the straightforward diamond structures.

Measured dispersion characteristics of several diamond and meander line structures according to the invention are shown in FIGS. 13 and 14 respectively, the size of structure and the frequency range having been chosen purely from the point of view of ease of measurement. In FIG. 13 the ratio v/c of phase velocity to the velocity of light is plotted against frequency in megacycles per second. The curves lettered A to C correspond to the similarly lettered structures illustrated diagrammatically in FIG. 13*a*. In each case the spacing between the side walls, indicated by *a* in FIG. 13*a*, was 12 cm. The distance between adjacent wires is indicated in FIG. 13*a* by the dimension *p*, ½*p*, or 2*p* as the case may be; $p=1$ cm. in all cases.

The curves of FIG. 13 show, as has been discussed previously in connection with FIG. 6, how the bandwidth increases with an increasing number of intersections of the strands and also shows, in curves A and B and in E and F, the somewhat slight increase in phase velocity obtained when the pitch is increased. Thus curves E and F both relate to a one-and-a-half diamond structure but in curve E the pitch is ½ cm. and in curve F 1 cm.

In FIG. 14 the curves A, B and C relate to structures arranged as indicated schematically in FIG. 14*a*. In all these the pitch *p* was 1.7 cms. and the separation between sidewalls 12 cms.; in A and B the dimension *d* was 6 cms. and *b* 3 cms., but in C *b* and *d* were each 4 cms. Structure A has analogies to the half-diamond structure of FIG. 13, B can be regarded as a modified one-and-a-quarter diamond structure, and C as a modification of the one-and-a-half diamond structure.

In connection with the curves of FIGS. 13 and 14 and the experiment structures to which they relate, it is to be emphasized that the absolute values of the frequencies plotted and of the dimensions of the structures given above should not be taken as illustrative of any preferred embodiments of the invention; the frequencies and dimensions were chosen purely from the point of view of convenience in making the measurements involved and in setting up different patterns of grating. Useful design data may, however, be derived from these curves by considering the variation of v/c in terms of the ratio of the frequency of measurement to the lower cut-off frequency, f_c, which, from FIG. 6, is seen to be given by

$$f_c=\frac{c}{2a}$$

and by using, instead of the pitch parameter *p*, a generalised parameter obtained by expressing *p* as a portion of the free space wavelength.

Slow wave structures according to the present invention are very readily coupled to hollow rectangular waveguides. Basically, all that is necessary is to continue the grating a little way beyond the ends of the side walls so that it projects through a slot cut transversely in the broad side of the waveguide. Thus in FIG. 15 a hollow rectangular waveguide is represented at **16** having a transverse slot **17** cut in a broad side **18**. The side walls **1** and **2** of a slow wave structure according to the invention are brought up to the wall **18** so that an extension **19** of the grating **3** projects through the slot **17** about half way into the waveguide. The lips of the slot **17** are provided with curved fins **20** which help to provide a smooth impedance transformation between the waveguide and slow wave structure and also act as chokes preventing radiation through the slot **20**.

FIG. 16 illustrates the use of a slow wave structure according to the invention in a travelling wave amplifier tube. Since there is no need for any insulation in association with the slow wave structure the tube may be of all metal construction having a rectangular envelope **20** whose sides **21** function as the side walls of the slow wave structure with the grating **3** joined between them. The upper and lower walls should be a wavelength or more spaced from the grating **3** so as not to interfere with the performance of the slow wave structure. At each end of the slow wave structure a waveguide **16** is arranged as in FIG. 15 to serve as input and output feeds respectively. The waveguides are represented as having tuning pistons **22** for adjusting the match between slow wave structure and waveguide and are indicated as being hermetically sealed by means of waveguide windows **23**. The waveguides **16** are apertured for passage of an electron beam above and below the grating **3** and are secured to extensions **24** and **25**, respectively, of the envelope **20**. An electron gun **26** is indicated within the end enclosure **24** and an electron collector electrode **27** is represented within the extension **25**.

In the case of application of the invention to a backward wave oscillator, the arrangement is generally similar to that of FIG. 16 except that the waveguide adjacent the electron collector electrode is omitted and the end portion of the grating **3** adjacent the electron collector electrode is coated with lossy material to provide a reflectionless termination for the slow wave structure.

Although several embodiments have been illustrated in the accompanying drawings, numerous other variants of the invention will occur to those skilled in the art. Although the propagation constants will, in all cases, conform to the general characteristics as described with reference to FIG. 6 and to FIGS. 13 and 14, it does not follow that all structures whose geometry appears to fall within the general geometrical arrangement of embodiments of the invention will necessarily have useful bandwidths; each structure would need to be examined individually to determine the exact shape of the characteristic curves and to determine whether the bandwidth available, at the fundamental mode, falls within the four percent limit which we consider to be requisite for useful application.

It may be mentioned that an experimental backward wave oscillator has been made using a structure similar to C, FIG. 14*a*, scaled down, however, to the 3 cm. band—thus the 12 centimetre width between sidewalls was reduced to 15 millimetres and the pitch between wires reduced accordingly. Oscillations on the first backward mode were obtained, the voltage and frequency characteristics being in good agreement with the figures predicted from "cold" tests.

While the principles of the invention have been described above in connection with specific embodiments, and particular modifications thereof, it is to be clearly understood that this description is made only by way of example and not as a limitation on the scope of the invention.

What I claim is:

1. A slow wave structure which will propagate radio frequency waves over a frequency band whose width exceeds four percent of the mid-band frequency comprising a pair of parallel plane conducting side walls and a grating connecting the two side walls along the length of the structure in a common plane perpendicular to the side walls with the side walls extending above and below the plane of the grating, and in which the grating is composed of continuous intersecting conducting strands arranged to form a regular pattern of staggered apertures, said grating being operable in both amplifier and backward wave tubes.

2. A slow wave structure according to claim 1 in which the strands of the first set are each normal to the side walls and the strands of the second set are perpendicular to those of the first set and arranged to form a brick-like pattern with a fraction of a brick terminating each row.

3. A slow wave structure which will propagate radio frequency waves over a frequency band whose width exceeds four percent comprising a pair of parallel plane conducting side walls and a grating connecting the side walls along the length of the structure in a common plane perpendicular to the side walls with the side walls extending above and below the plane of the grating in which

the grating is composed of a first set of equidistant continuous intersecting conducting strands stretching obliquely from side wall to side wall and a second set of conducting strands similarly arranged at equal and opposite angles of inclination to the side walls, each strand of one set intermediate the end strands of the grating being joined at both ends to the ends of respective strands of the other set, said grating being operable in both amplifier and backward tubes.

4. A slow wave structure which will propagate radio frequency waves over a frequency band whose width exceeds four percent of the mid-band frequency comprising a pair of parallel plane conducting side walls and a grating connecting the two side walls along the length of the structure in a common plane perpendicular to the side walls with the side walls extending above and below the plane of the grating, and in which the grating is composed of a regular continuous zig-zag conducting strand centrally disposed from end to end of the grating and an intersecting conducting strand joined between each bend of zig-zag and the adjacent side wall, said grating being operable in both amplifier and backward wave tubes.

5. A slow wave structure according to claim 4 in which the conducting strand is hollow and the bends of the zig-zag are smoothly rounded to permit the flow of fluid through the hollow conductor.

6. A slow wave structure according to claim 1 in which the grating is composed of a first set of equidistant conducting strands stretching from side wall to side wall and a second set of shorter conducting strands each joining a respective one pair only of the strands of the first set intermediate the ends of the pair.

7. A slow wave structure according to claim 3 in which the strands of the two sets intersect each other only at their ends.

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HERMAN KARL SAALBACH, *Primary Examiner.*

ELI J. SAX, *Examiner.*