Feb. 3, 1959 R. H. WINKLER 2,872,650

WAVEGUIDE

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Fig. 1

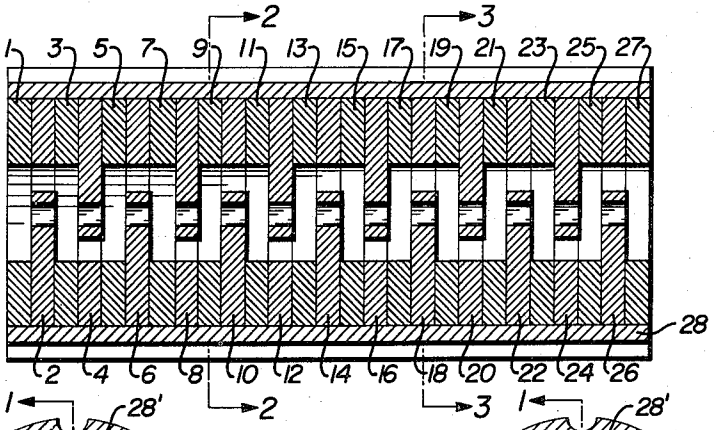


Fig. 2

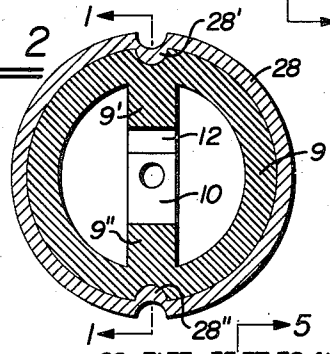


Fig. 3

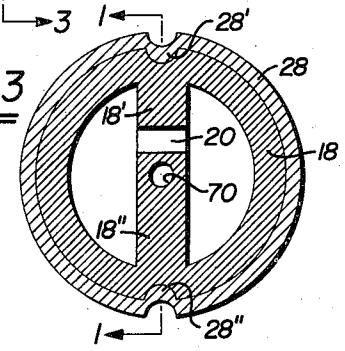


Fig. 4

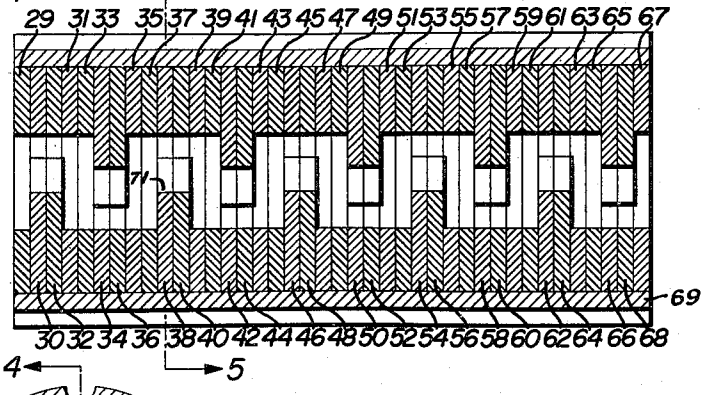
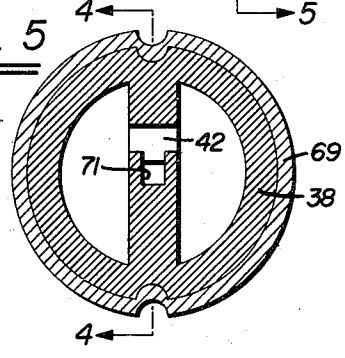


Fig. 5



INVENTOR.
Richard H. Winkler
BY Lippincott & Smith
Attorneys

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WAVEGUIDE

Richard H. Winkler, Palo Alto, Calif., assignor, by mesne assignments, to Monogram Precision Industries, Inc., Culver City, Calif., a corporation of California

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This invention relates to waveguides for transmitting electromagnetic waves, and in particular to improved waveguide structures, useful in traveling-wave tubes and the like, for transmitting electromagnetic waves at low velocities.

In traveling-wave tubes and the like, including traveling-wave tubes used as backward-wave oscillators, a slow-wave structure must be provided for transmitting electromagnetic waves at low velocities such that the phase velocity of the wave at a selected frequency or frequency band is substantially equal to the velocity of electrons in an electron beam. For such purposes, a variety of slow-wave structures have been proposed including helices and various waveguide structures. The present invention relates to waveguides that are particularly useful as slow-wave structures in traveling-wave tubes and the like, including backward-wave oscillators, although it should be understood that the improved waveguides herein disclosed are not limited to such use, but may also be used in other places and for other purposes.

The dimensions that a waveguide is required to have depend upon the waveguide configuration and the operating frequency range for which it is designed. In other words, a waveguide of a given size and configuration has a cut-off frequency that is the lowest frequency at which the waveguide will transmit electromagnetic waves. Obviously, the cut-off frequency must be lower than the lowest frequency at which the waveguide is designed to operate. In general, a decrease in the cut-off frequency requires an increase in the waveguide dimensions, and consequently there is a minimum size for a waveguide of a given configuration that is to transmit electromagnetic waves having frequencies within a desired frequency range.

In traveling-wave tubes and the like, it is usually necessary to provide a magnetic field through the waveguide to assist in confining an electron beam or beams. The magnetic field may be provided by an electromagnet or by a permanent magnet structure. For magnet economy and for other reasons it is desirable that the transverse dimensions of the waveguide be as small as is practicable, and in particular that the waveguide be adapted to fit inside a cylinder of minimum size. Accordingly, an object of this invention is to provide improved waveguides having exceptionally small transverse dimensions relative to the frequency of electromagnetic waves that are to be transmitted by the waveguide.

Simple tubular waveguides are not suitable for use as slow-wave structures in traveling-wave tubes and the like, since the phase velocity of electromagnetic waves transmitted by such waveguides is very great, usually greater than the speed of light. Consequently, waveguides that are to be used as slow-wave structures must be loaded or iterated structures of relatively complex configuration. Heretofore the manufacture of such structures has been difficult and costly. Accordingly another object of this invention is to provide improved slow-wave

structures that can be manufactured simply and inexpensively.

Different waveguides that are to be used at different frequency ranges may have similar configurations, but in general they must differ from one another with respect to at least one of the waveguide dimensions. Consequently, it has generally been true heretofore that substantially complete retooling is necessary for the manufacture of each different waveguide size or design that is to operate at a different frequency range. As a result the economies of large scale production have not been fully achieved in waveguide manufacture, and the cost of waveguides has been high. Accordingly, still another object of this invention is to provide improved waveguides that can be manufactured for operation at different frequency ranges with little if any retooling or change in manufacturing procedures.

Other objects and advantages of the invention will appear as the description proceeds.

Briefly stated, in accordance with certain aspects of this invention, an improved waveguide consists essentially of a hollow circular cylinder, two diametrically opposed longitudinal ridges within the cylinder, each ridge having a substantially rectangular cross-section, and two pluralities of teeth equally spaced along the length of respective ones of the two ridges. It will be understood that a tooth is a projection having one end only attached to the waveguide ridge and having another end and sides that are substantially unattached. Thus a tooth is to be distinguished from a partition extending completely across a waveguide from one side to the other. Preferably each tooth is equal in width to the ridge that it is attached to. The two pluralities of teeth extend radially transverse to the cylinder from one toward another of the ridges, and are interleaved or interdigitated, with the teeth of one plurality alternating with the teeth of the other plurality along the length of the waveguide to form a tortuous open-sided serpentine passage extending lengthwise of the cylinder between the interdigital teeth. The waveguide is an iterated slow-wave structure that transmits electromagnetic waves of certain frequencies with low phase velocities.

For a given cross-sectional area, such a waveguide has a lower cut-off frequency than that of a conventional ridged waveguide with uniform ridges, and has a much lower cut-off frequency than that of a simple cylindrical waveguide. Consequently the improved waveguide is of exceptionally small size in comparison with other waveguides designed to operate in the same frequency range. Furthermore, the improved waveguide is substantially as high as it is wide, so that it can be fitted inside a circular cylinder of exceptionally small diameter.

The small size of the improved waveguide, and the relatively low phase velocity of electromagnetic waves transmitted thereby, makes this waveguide especially useful in traveling-wave tubes and the like, since a magnetic field can be produced through the waveguide with exceptionally small magnets. The small size of the improved waveguide also makes its use advantageous in other applications where space and weight requirements are severe.

In accordance with certain other aspects of this invention, the improved waveguide consists essentially of a stack of metal wafers or laminations, which may be manufactured inexpensively by punching the wafers from sheet metal with suitable dies. A ridged waveguide with interdigital teeth can be made by using only two wafer shapes, so that all of the required wafers can be punched with only two dies.

One set of identical wafers is of generally annular shape with an interior tooth and an interior stub diametrically opposed to each other, while the other set of

identical wafers is of generally annular shape with two diametrically opposed interior stubs. The wafers are stacked together with the teeth and stubs alined in a common diametric plane to form a hollow cylinder with two longitudinal ridges carrying interdigital teeth. The stack of wafers can be fitted into a tube or cylinder that can also serve as the envelope, or a portion of the envelope, of an evacuated structure such as a traveling-wave tube.

The operating frequency or frequency range of such a waveguide can be changed simply by changing the thickness of the wafers, so that different waveguides for use at different frequencies or frequency ranges can be made with the same dies simply by punching the wafers from sheet metal stock of different thicknesses. In the event that a desired wafer thickness is greater than the maximum thickness of sheet metal stock that is available and can be punched conveniently, composite wafers can be made simply by stacking two or more identical wafers together.

The invention will be better understood from the following detailed description taken in connection with the accompanying drawing, and its scope will be pointed out in the appended claims. In the drawing,

Fig. 1 is a longitudinal section of a waveguide embodying principles of this invention;

Fig. 2 is a transverse section taken along the line **2—2** of Fig. 1, the plane of Fig. 1 being indicated in Fig. 2 by the line **1—1**;

Fig. 3 is a transverse section taken along the line **3—3** of Fig. 1, the plane of Fig. 1 being indicated in Fig. 3 by line **1—1**;

Fig. 4 is a longitudinal section of another waveguide embodying principles of this invention, showing an alternative construction; and

Fig. 5 is a transverse section taken along the line **5—5** of Fig. 4, the plane of Fig. 4 being indicated in Fig. 5 by line **4—4**.

Referring now to Figs. 1, 2 and 3 of the drawing, the improved waveguide consists essentially of a stack of axially alined metal wafers identified in the drawing by reference numerals **1** through **27**. The odd-numbered wafers **1** through **27** are arranged in alternation with even-numbered wafers **2** through **26**, as shown. All of the odd-numbered wafers **1** through **27** are identical to wafer **9**, which is best shown in Fig. 2. Wafer **9** is of a generally annular shape, and has a central circular aperture containing two diametrically opposed radial stubs **9'** and **9''**, as shown. The stubs are generally rectangular in shape, and have a length smaller than the radius of the aperture. All of the even-numbered wafers **2** through **26** are identical to wafer **18**, which is best shown in Fig. 3. Wafer **18** is of a generally annular shape, and has a central circular aperture containing a radial stub **18'** and a radial tooth **18''** diametrically opposed to each other, as shown. The tooth has a length larger than the radius of the aperture. Wafer **18** is identical in size and shape to wafer **9**, except for the substitution of tooth **18''** for stub **9''**.

The metal wafers **1** through **27** are stacked together in axial alinement, with the stubs and teeth alined in a common diametric plane. The annular portions of the wafers form a hollow cylinder, and the stubs form two diametrically opposed interior longitudinal ridges having substantially rectangular cross sections. The teeth of the even-numbered wafers extend transverse to the cylinder from one toward the other of the two ridges. Odd-numbered wafers alternate in position with even-numbered wafers, so that the teeth are equally spaced apart along the length of the waveguide. Alternate ones of the even-numbered wafers are inverted, as is best shown in Fig. 1, to form interdigital teeth that extend transverse to the waveguide in diametrically opposite directions. The stack of wafers may be enclosed within and held in position by a cylindrical envelope or tube

28, or they may be fastened together by any other suitable means. For example, the wafers may be brazed or soldered together to form an integral waveguide structure.

Tube **28** may be a portion of the evacuated envelope for a traveling-wave tube or the like. The wafers may be of any material having good electrical conductivity, although a highly conductive metal such as copper or silver is generally employed so that the waveguide may transmit electromagnetic waves with little attenuation. If desired, each wafer may consist of two or more different metals, such as silver plated over copper punchings. After assembly of the stack of wafers, the inside of the waveguide may, if desired, be coated with a thin layer of highly conductive metal such as silver. Certain of the wafers, for example wafers **11** through **15** near the middle of the waveguide, may be of lossy material such as iron, or may be coated with a lossy material, to provide an attenuator section that attenuates the transmitted waves.

Tube **28** may be of metal, glass, or any other suitable material. Preferably, the outside circumference of each wafer is substantially circular, so that the stack of wafers has a substantially cylindrical outside surface, and tube **28** fits snugly around the outside surface of the stack to hold the wafers securely in place. To prevent angular misalinement of the wafers, the outside surface of each wafer may have two slots or key channels that receive longitudinal internal ribs or keys **28'** and **28''** pressed, rolled or otherwise formed in tube **28**, as shown in the drawing.

It will be noted from the drawing that the stack of wafers forms a waveguide consisting essentially of a circular cylinder with two diametrically opposed longitudinal ridges within the cylinder. The even-numbered discs have portions extending transverse to the cylinder that form two pluralities of transverse teeth alternating and interdigitaled with each other. Teeth of the first plurality, formed by portions of wafers **4**, **8**, **12**, **16**, **20**, and **24**, extend downward from the top longitudinal ridge, while teeth of the second plurality, formed by portions of wafers **2**, **6**, **10**, **14**, **18**, **22** and **26**, extend upward from the lower longitudinal ridge. The teeth are spaced apart by the odd-numbered wafers so that a tortuous serpentine passage extends between the teeth along the length of the waveguide and repetitively crosses the longitudinal axis of the waveguide.

The improved waveguide has an exceptionally low cut-off frequency relative to its transverse dimensions, and therefore it may be of exceptionally small size for operation within a given frequency range. Furthermore, it occupies a substantially cylindrical space and has a height that is substantially equal to its width, so that it may be fitted inside a cylindrical envelope **28** of minimum diameter. Furthermore, the waveguide is capable of transmitting electromagnetic waves at relatively low phase velocities suitable for traveling-wave tubes and the like. The small size of the waveguide makes it relatively easy to provide a magnetic field through the waveguide, by means of either a magnet coil wound about tube **28** or a permanent magnet structure.

The frequency range of the waveguide depends, among other things, upon the spacing of the interdigital teeth, and therefore depends on the thickness of the wafers. Consequently, waveguides for operation at different frequency ranges may be made simply by punching the wafers from different thicknesses of sheet metal stock. Consequently, large volume production techniques can advantageously be employed for economical manufacture, even though a variety of different waveguides must be made for operation at different frequency ranges. The odd-numbered wafers are not necessarily of the same thickness as the even-numbered wafers, the thickness and other dimensions of the wafers being determined by the

designer in accordance with the purposes for which the waveguide is to be used.

In the event that a particular design may require greater spacing between the interdigital teeth than can conveniently be provided by a single wafer thickness, two or more identical wafers may be stacked together to form, in effect, a single composite wafer. A waveguide constructed in this manner is shown in Figs. 4 and 5. In Fig. 4, the odd-numbered wafers **29** through **67**, which are all identical, are stacked together in groups of two as shown. Similarly, the even-numbered wafers **30** through **68** are stacked together in groups of two, and the wafers are assembled in the stack so that groups of two odd-numbered wafers alternate with groups of two even-numbered wafers. As a result, the spacing between the interdigital teeth is twice as great as it would be if the same wafers were alternated in the manner shown in Fig. 1.

Many other arrangements are possible, and it is not necessary that each group of even-numbered wafers contain the same number of wafers as a group of odd-numbered wafers. Stated in more general terminology, there are first and second pluralities of wafers stacked together in axial alinement in a repetitive sequence of wafers of the first plurality and wafers of the second plurality. The stack of wafers may be contained within and held in position by a cylindrical envelope or tube **69** in a manner similar to the construction hereinbefore described in connection with Fig. 1.

In a traveling-wave tube, an electron beam must be provided in interacting relation with electromagnetic waves transmitted by the waveguide. Preferably, the electron beam passes through the waveguide substantially along its longitudinal axis, and means should be provided for conveying the electrons through the interdigital teeth.

In the embodiment illustrated by Figs. 1 through 3 of the drawing, this is accomplished by providing a hole **70** through the tooth of each even-numbered wafer, as shown. Hole **70** is located at the diametrical center of the wafer so that all of these holes are in linear alinement after the waveguide is assembled. Consequently, there is an unobstructive passage for the electron beam along the longitudinal axis of the waveguide. As electrons pass between successive interdigital teeth, interaction between the electrons and the electromagnetic waves amplifies the waves in a well known manner; provided that the electron velocities are substantially equal to the phase velocity along the waveguide axis of electromagnetic waves transmitted by the waveguide.

In the embodiment illustrated by Figs. 4 and 5 of the drawing, a slot **71** is cut into the free end of each interdigital tooth, as shown. Slots **71** extend through the diametrical centers of the even-numbered wafers, and thus provide an unobstructed passage for an electron beam along the longitudinal axis of the waveguide.

The longitudinal ridges in the waveguide serve several useful purposes. The most important of these, particularly in a traveling-wave tube used as a backward-wave oscillator, is that they make the serpentine passage between the interdigital teeth flatter than it would be without the ridges. This in turn, increases the rate of change of the phase velocity with changes in frequency of the electromagnetic waves. Since a backward-wave oscillator is usually tuned by adjusting the electron velocities, for example by adjusting the voltage between the waveguide and the cathode of an electron gun supplying the beam, the constructions herein described provide tuning over a wider frequency range with a given range of voltage adjustment. The ridges also strengthen the interdigital teeth by providing mechanical support at the roots of the teeth.

It should be understood that this invention in its broader aspects is not limited to specific embodiments herein illustrated and described, and that the following claims are intended to cover all changes and modifications that do not depart from the true spirit and scope of the invention.

What is claimed is:

1. A double ridged waveguide with interdigital teeth on its ridges, comprising an elongate hollow electrically conductive member, two opposed longitudinal electrically conductive ridges within said member, and a plurality of electrically conductive teeth spaced along the length of each of said ridges, the teeth along each ridge extending toward and being interdigitated with the teeth spaced along the opposite ridge, said ridges and said teeth defining an open-sided serpentine passage within said elongate hollow member.

2. A structure for transmitting electromagnetic waves, comprising a hollow cylindrical member, two opposed longitudinal ridges within said member, and a plurality of interdigital teeth spaced along the length of said ridges, said ridges and said teeth defining an open-sided serpentine passage within said hollow cylindrical member.

3. A structure for transmitting electromagnetic waves, comprising a hollow circular conductive cylinder, two diametrically opposed longitudinal conductive ridges within said cylinder, a first plurality of radial conductive teeth spaced along the length of one of said ridges, and a second plurality of radial conductive teeth spaced along the length of the other of said ridges.

4. A structure for transmitting electromagnetic waves, comprising a hollow cylinder, two opposed longitudinal ridges within said cylinder, and two pluralities of teeth spaced along the length of respective ones of said two ridges, each of said teeth extending transverse to said cylinder from one toward the other of said ridges, one plurality of said teeth being interdigitated with the other plurality of said teeth, each of said teeth being substantially equal in width to the ridge that it is attached to, whereby said ridges and said teeth define a substantially open-sided serpentine passage.

5. A structure for transmitting electromagnetic waves, comprising a hollow cylinder, two diametrically opposed longitudinal ridges within said cylinder, said ridges being of substantially rectangular cross-section, and a plurality of transverse interdigital teeth spaced along the length of said ridges, alternate ones of said teeth extending from a first one of said ridges toward a second one of said ridges, other alternate ones of said teeth extending from said second ridge toward said first ridge, said teeth being equally spaced apart one from another to form a serpentine passage extending between the teeth along the length of said cylinder, said cylinder, said ridges and said teeth all being of electrically conductive material.

6. A waveguide comprising a first plurality of identical wafers each having a central aperture with a transverse tooth therein, and a second plurality of identical wafers each having a central aperture without teeth, said wafers being axially alined to form a stack of wafers arranged in a repetitive sequence of wafers of said first plurality and wafers of said second plurality, said teeth being interdigitated to form a serpentine passage extending lengthwise through said stack of wafers.

7. A waveguide comprising a first plurality of identical annular wafers each having an interior stub and an interior tooth diametrically opposed to each other, and a second plurality of identical wafers each having two diametrically opposed interior stubs, said wafers being stacked together in axial alinement in a repetitive sequence of wafers of said first plurality and wafers of said second plurality, said stubs and said teeth being alined to form two ridges with interdigitated teeth.

8. A waveguide comprising a first plurality of identical annular wafers each having an interior stub and an interior tooth diametrically opposed to each other, and a second plurality of identical annular wafers each having two diametrically opposed interior stubs, said wafers being stacked together in axial alinement, wafers of said first

plurality alternating with wafers of said second plurality, said stubs and said teeth being alined in a common diametric plane with alternate ones of said teeth extending in opposite diametric directions, so that said teeth are interdigitated to form a serpentine passage.

9. A waveguide comprising a first plurality of identical annular wafers each having an interior stub and an interior tooth diametrically opposed to each other, and a second plurality of identical annular wafers each having two diametrically opposed interior stubs, said wafers being stacked together in axial alinement, pairs of wafers of said first plurality alternating in sequence with pairs of wafers of said second plurality, said stubs and said teeth being alined in a common diametric plane with alternate pairs of said teeth extending in diametrically opposite directions to form a serpentine passage.

10. A waveguide comprising a first plurality of identical annular metal wafers each having an interior stub and an interior tooth diametrically opposed to each other, a second plurality of identical annular metal wafers each

having two diametrically opposed interior stubs, said wafers being stacked together in axial alinement, wafers of said first plurality alternating in position with wafers of said second plurality, said stubs and said teeth being alined in a common and diametric plane, alternate ones of said teeth extending in diametrically opposite directions, and a cylindrical envelope fitting snugly around the stack of said wafers.

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