Aug. 23, 1966 M. M. MANN 3,268,761

TRAVELING-WAVE TUBE SLOW-WAVE STRUCTURE INCLUDING MULTIPLE HELICES INTERCONNECTED BY SPACED CONDUCTIVE PLATES

Filed April 3, 1963 3 Sheets-Sheet 1

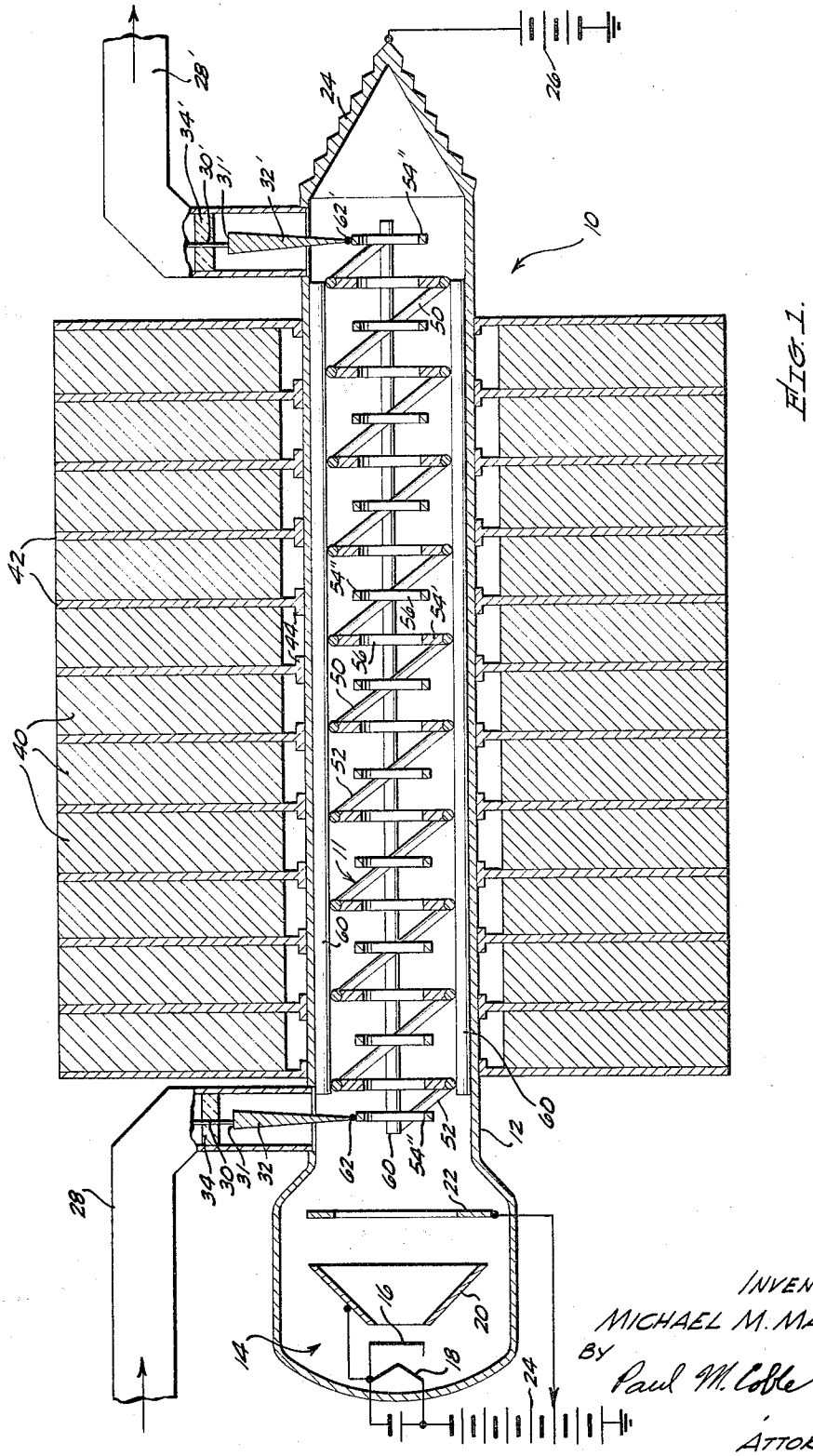


FIG. 1.

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Filed April 3, 1963 3 Sheets-Sheet 2

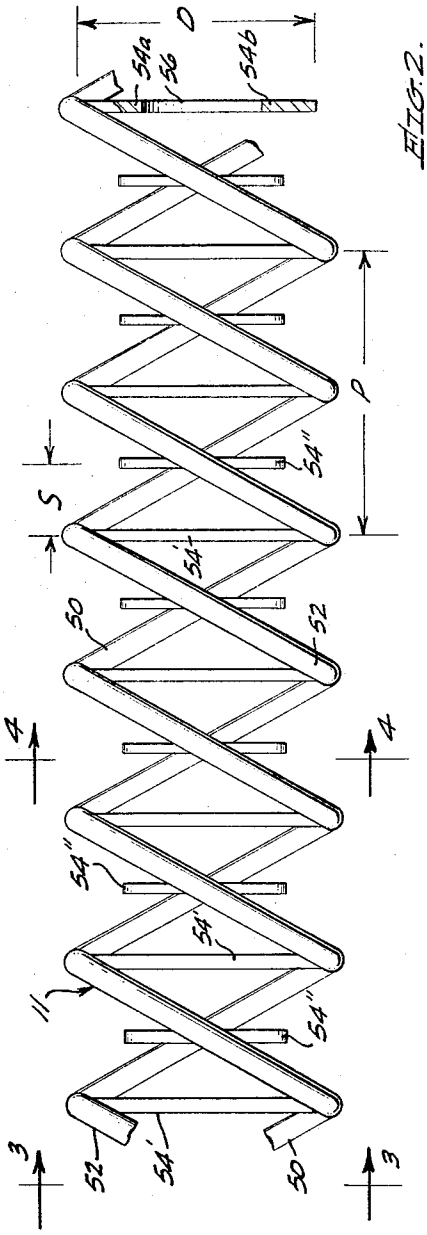


FIG. 2.

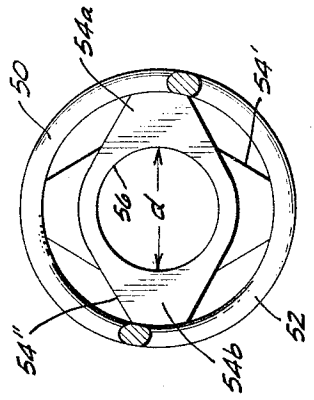


FIG. 4.

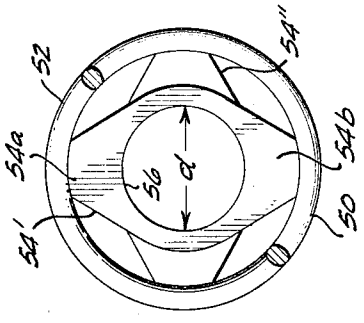


FIG. 3.

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TRAVELING-WAVE TUBE SLOW-WAVE STRUCTURE INCLUDING MULTIPLE HELICES INTERCONNECTED BY SPACED CONDUCTIVE PLATES

Filed April 3, 1963 3 Sheets-Sheet 3

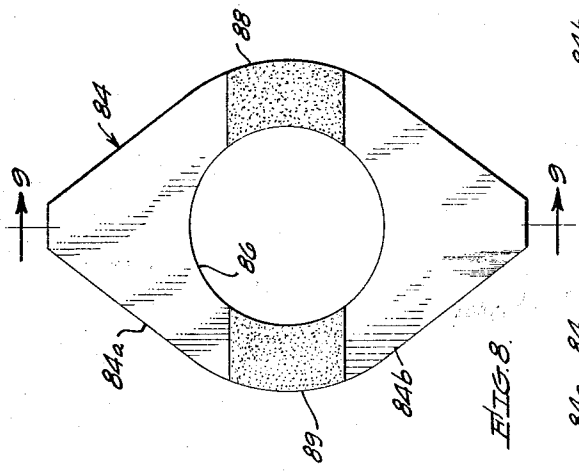


FIG. 8.

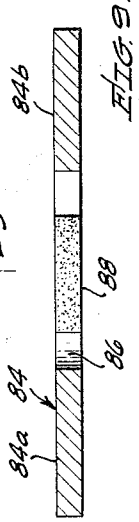


FIG. 9.

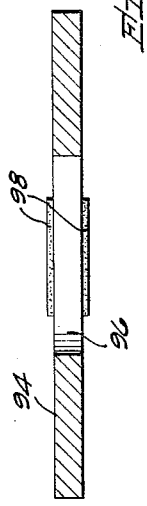


FIG. 10.

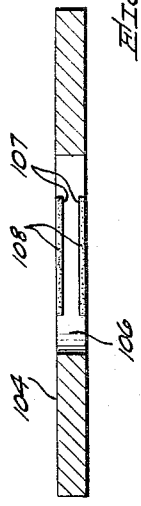


FIG. 11.

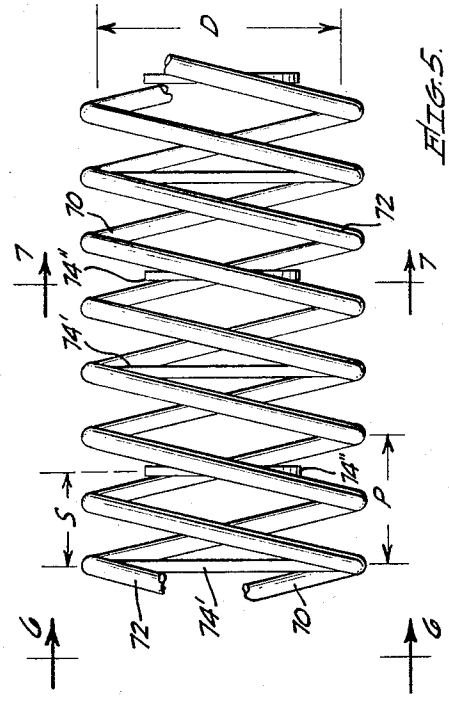


FIG. 5.

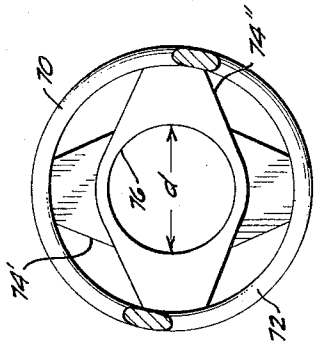


FIG. 7.

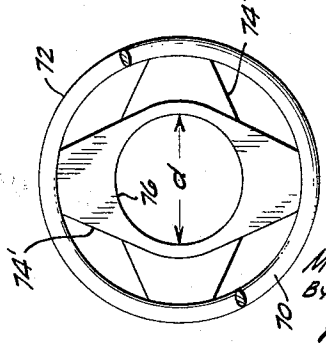


FIG. 6.

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United States Patent Office 3,268,761 Patented August 23, 1966

3,268,761

TRAVELING-WAVE TUBE SLOW-WAVE STRUCTURE INCLUDING MULTIPLE HELICES INTERCONNECTED BY SPACED CONDUCTIVE PLATES

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Filed Apr. 3, 1963, Ser. No. 270,300
21 Claims. (Cl. 315—3.6)

This invention relates generally to traveling-wave tubes, and more particularly relates to a novel traveling-wave tube slow-wave structure which achieves high power operation while maintaining a high interacton impedance, high efficiency, and wide bandwidth.

In traveling-wave tubes a stream of electrons is caused to interact with a propagating electromagnetic wave in a manner which amplifies the electromagnetic energy. In order to achieve such interaction, the electromagnetic wave is propagated along a slow-wave structure which is disposed along and about the electron stream path. The slow-wave structure provides a path of propagation for the electromagnetic wave which is considerably longer than the axial length of the structure, and hence, the traveling-wave may be made to effectively propagate at nearly the velocity of the electron stream. Interactions between electrons in the stream and the traveling-wave cause velocity modulation and bunching of the stream electrons, the net result being a transfer of energy from the electron stream to the wave traveling along the slow-wave structure.

A classic form of slow-wave structure is the helix circuit in which a helical conductor is wound coaxially about the path of the electron stream. The helix circuit is noted for its high interaction impedance and its efficient and wide-band operation. However, traveling-wave tubes with helical slow-wave structures are limited in their power handling capabilities.

In an effort to provide traveling-wave tubes which are capable of operating at higher power levels, numerous other forms of slow-wave structures have been developed. Some of the most successful include the disk-loaded circuit, the cloverleaf circuit, the ring-bar circuit, and the folded waveguide circuit. Although these circuits have afforded a substantial increase in power level, they do not equal the helix circuit in bandwidth and efficiency characteristics.

A further development which endeavors to combine the advantages of the helix with those of the higher power circuits is the strapped bifilar helix structure in which a plurality of parallel conductive bars diametrically interconnect the two helices at spacings equal to half the pitch of the helices. In addition to affording higher power operation than the conventional monofilar helix, the strapped bifilar helix achieves superior backward-wave mode suppression.

However, in the continuing search for improved slow-wave structures, it would be desirable to retain the advantages of the strapped bifilar helix circuit, while at the same time providing a circuit with still greater power handling capabilities, higher interaction impedance, greater efficiency, superior spurious mode suppression, and in which lower magnetic focusing fields are required. Accordingly, it is a principal object of the present invention to provide such a slow-wave structure.

It is a further object of the present invention to provide a traveling-wave tube slow-wave structure which, in addition to possessing the advantages set forth above, can be designed to operate with propagating waves having a wide range of phase velocities, thereby allowing interaction with either high or low voltage electron beams.

It is a still further object of the present invention to

provide a simple and reliable high power traveling-wave tube slow-wave structure which, in addition to possessing the high interaction impedance, high efficiency, and wide bandwidth of conventional low power helix structures, also has a greater design flexibility than such prior art structures to ensure operation with large beam diameters.

It is still another object of the present invention to provide a slow-wave structure for a traveling-wave tube which not only inherently acts to suppress modes giving rise to backward-wave oscillations, but which also lends itself to the accommodation of additional devices for the suppression of undesired modes.

In accordance with the objects outlined above, the traveling-wave tube slow-wave structure provided by the present invention comprises a multifilar helix including a plurality of equally spaced individual helical conductors having the same helical diameter and pitch disposed about a common axis. A plurality of electrically conductive cross-piece elements are spaced along the multifilar helix in planes perpendicular to the axis of the helix. Each of the crosspiece elements defines an aperture which encompasses the axis, with the apertures in successive crosspieces being aligned with one another. Each crosspiece element further defines a plurality of portions equal in number to the number of individual helical conductors which extend radially from its aperture to the multifilar helix, with each portion being electrically connected to a different one of the helical conductors. In addition, each radially extending portion in each crosspiece element is angularly displaced with respect to each radially extending portion in the next successive crosspiece element along the axis of the helices.

In preferred embodiments of the invention a bifilar helix is employed, with successive ones of the helix-connecting crosspieces being disposed in quadrature along the bifilar helix at spacings equal to an odd multiple of one quarter of the pitch of the helices. In further embodiments the crosspiece elements are provided with loss means for increasing the electrical resistance to the flow of current through the crosspieces between the helices in order to enhance the suppression of undesired modes.

Other and further objects, advantages, and characteristic features of the present invention will become readily apparent from the following detailed description of preferred embodiments of the invention when taken in conjunction with the appended drawings in which:

FIG. 1 is a longitudinal sectional view illustrating a traveling-wave tube having a slow-wave structure provided according to the principles of the present invention;

FIG. 2 is an enlarged side view of the slow-wave structure of FIG. 1 removed from the tube and partly broken away;

FIG. 3 is a cross-sectional view taken along line 3—3 of FIG. 2;

FIG. 4 is a cross-sectional view taken along line 4—4 of FIG. 2;

FIG. 5 is a side view of a slow-wave structure provided by a further embodiment of the present invention;

FIG. 6 is a cross-sectional view taken along line 6—6 of FIG. 5;

FIG. 7 is a cross-sectional view taken along line 7—7 of FIG. 5;

FIG. 8 is a plan view of a crosspiece for a slow-wave structure provided in accordance with a still further embodiment of the present invention;

FIG. 9 is a sectional view taken along line 9—9 of FIG. 8;

FIG. 10 is a sectional view similar to FIG. 9 illustrating another embodiment of the present invention; and

FIG. 11 is a sectional view similar to FIG. 9 illustrating still another embodiment of the present invention.

Referring with more particularity to the drawings, in FIG. 1 there is illustrated a traveling-wave tube **10** having a slow-wave structure **11** constructed according to the principles of the present invention. The slow-wave structure **11** is mounted in a tubular metallic envelope **12**, which may be of molybdenum, for example, and which may be evacuated to a desired pressure. The slow-wave structure **11** will be described in more detail later on; however, for the present it suffices to state that the slow-wave structure serves to propagate electromagnetic wave energy along and about an electron beam traveling along the longitudinal axis of the envelope **12**.

For generating the electron beam a conventional electron gun **14** is disposed in an enlarged portion of the envelope **12** at one end thereof. The electron gun **14** may include an electron-emitting cathode **16**, a filamentary heater **18**, a focusing electrode **20** and an accelerating anode **22**. A voltage source **24** is tapped at appropriate potentials, as shown, to provide operating voltages for the electrodes **16**, **20** and **22**.

Disposed at the opposite end of the envelope **12** is a collector electrode **24** for intercepting the electrons and dissipating their kinetic energy. A source of potential **26** is connected to the collector **24** to apply a positive bias to the collector **24** to prevent secondarily emitted electrons from the slow-wave structure **11** from returning to the interaction region, thereby reducing noise and other interference.

Input electromagnetic wave energy to be amplified is applied to one end of the slow-wave structure **11** by means of a coaxial input waveguide **28** having an inner conductor **30** which is connected to the slow-wave structure **11**. The conductor **30** may be provided with a step transition **31** in its cross-section and may be tapered in a desired manner, as shown at **32**, to provide an impedance transformation. A ceramic window **34** may be provided in the waveguide **28** to support a pressure differential and thereby enable the desired evacuated pressure to be maintained within the envelope **12**, while allowing electromagnetic wave energy to enter the envelope **12** through the waveguide **28**. Similarly, a coaxial output waveguide **28'** is provided at the opposite end of the slow-wave structure **11** for propagating amplified electromagnetic wave energy from the slow-wave structure **11** to external circuitry (not shown). The output waveguide **28'** is provided with an inner conductor **30'** which is connected to the slow-wave structure **11** and which defines a step **31'** and tapered portion **32'**, with a ceramic window **34'** also being disposed in the waveguide **28'**. It is pointed out that although the input waveguide **28** is shown as disposed at the electron gun end of the traveling-wave tube **10**, it would be located at the collector end in the event a backward wave amplifier is desired.

For focusing the emitted electrons and constraining them to flow along an axial path toward the collector **24** there may be provided a periodic permanent magnet focusing arrangement. The focusing assembly includes a plurality of annular disk-shaped permanent magnets **40** respectively interposed between a plurality of annular pole pieces **42** of ferromagnetic material. Each pole piece **42** extends radially inwardly of the magnets **40** and defines a ferrule **44** at its inner extremity. The ferrules **44** protrude outwardly from the planes of the pole pieces **42** along directions parallel to the longitudinal axis of the traveling-wave tube **10**, with the inner lateral surfaces of the ferrules **44** abutting against the enevelope **12**. It is pointed out that although a periodic permanent magnet focusing arrangement is shown, other focusing schemes, for example non-periodic permanent magnet focusing, solenoid focusing, or electrostatic focusing, may be employed instead.

Referring now to FIGS. 2–4, as well as to FIG. 1, the slow-wave structure **11** for the traveling-wave tube **10** will be described in more detail. The slow-wave structure **11** includes a multifilar helix, illustrated as a bifilar helix consisting of a first helical conductor **50** and a second helical conductor **52**. The helices **50** and **52**, which may be of a metal such as molybdenum or copper, are co-directionally wound, are equally spaced from each other, and are disposed about a common axis coincident with the electron beam path. The helices **50** and **52** are of the same size, and have the same helical diameter D (the diameter of a circle defined by the projection of points along the inner extremities of the helical conductor in a plane perpendicular to the electron beam axis) and the same pitch P (the axial distance in which the helical conductor makes one complete revolution about its axis).

The helices **50** and **52** are electrically connected together at spaced points along their lengths by a series of electrically conductive crosspiece elements, or webs, **54** (with a prime or a double prime designation being added to indicate the orientation of the webs as will be explained below). The crosspieces **54** may take the form of metal plates, for example of molybdenum or copper. Either the crosspieces **54** or the helices **50** and **52**, or both, may be gold-plated to facilitate attachment of the crosspieces **54** to the helices **50** and **52**, for example by brazing or spot-welding. The webs **54** are disposed in planes perpendicular to the axis of the slow-wave structure **11** and in their central regions define aligned circular apertures **56** of a diameter *d* to provide a passage for the axially traveling electron stream. Each web **54** defines first and second portions **54***a* and **54***b*, respectively, which extend radially outwardly from opposite sides of its aperture **56** to the bifilar helix. Thus, each web **54** is of greater extent in a direction through its extended portions **54***a* and **54***b* than in an orthogonal direction in the plane in which it is mounted, with its greater, or longitudinal, dimension being essentially equal to the helix diameter D and its smaller, or transverse, dimension being slightly greater than the diameter *d* of its aperture **56**.

A key feature of the present invention, and one which enables many of its significant advantages to be achieved, lies in the orientation of the crosspieces **54** which interconnect the helices **50** and **52**. Specifically, the crosspieces **54** are staggered along the length of the slowwave structure in accordance with a predetermined relation, i.e., the longitudinal dimension of each crosspiece is angularly displaced by a predetermined amount with respect to the longitudinal dimension of the next successive crosspiece along the axis of the slow-wave structure. Preferably, the staggering relationship is such that successive crosspieces **54** are disposed in quadrature along the axis of the helices, i.e., the longitudinal dimension of each crosspiece **54** is rotated by 90° with respect to that of the preceding and following crosspieces. Thus, there is provided a first series of crosspieces **54'** longitudinally aligned in a first direction perpendicular to the electron beam axis and a second series of crosspieces **54''** longitudinally aligned in another direction perpendicular to both the first direction and the electron beam axis, with individual crosspieces in each series being alternately disposed with despect to individual crosspieces in the other series along the length of the slow-wave structure.

The spacing S between individual crosspieces of the slow-wave structure of the present invention may be determined in accordance with the relation:

$$S=nP/4 \qquad (1)$$

where P is the helix pitch as defined above and *n* is an odd integer. In the embodiment of FIGS. 1–4, *n* is equal to one, and therefore, the web spacing is ¼ of the pitch of the helical conductors, with the webs interconnecting the helices every 90° along their lengths.

In prior art helix slow-wave circuits, the pitch of the helix is designed so that the phase velocity *v* of the wave traveling along the helix is approximately synchronous with the electron beam, in practice being slightly less than

the average beam velocity v_0. This is accomplished by making the ratio of helix pitch P to the actual helix length L for one complete revolution approximateliy equal to the ratio of the desired phase velocity v to the velocity of light c.

In the slow-wave circuit of the present invention, however, the helical conductors are not designed to be synchronous with the electron beam; but rather a ratio of a modified waveguiding length L′ to web spacing S is employed in the design. The modified length L′ is measured from the center of the beam aperture **56** in a web **54′** outwardly to one of the helical conductors **50** or **52**, then along the helix **50** or **52** to the next web **54″**, and inwardly along the web **54″** to the center of its beam aperture **56**. The result is that the pitch of the helices of the slow-wave circuit of the present invention is greater than that of a slow-wave circuit designed so that the phase velocity of the wave traveling along the helix is synchronous with the electron beam.

The slow-wave structure **11** may be mounted within the tubular envelope **12** on a plurality of longitudinally extending support rods **60** of insulating material which may be, for example of sapphire or beryllia. Although four support rods equally circumferentially spaced about the helices **50** and **52** at points opposite their points of attachment to the webs **54** are used in the embodiment illustrated in FIG. 1, other numbers and orientations of helix support rods may alternately be employed.

The inner conductor **30** of the coaxial input waveguide **28** is connected to the web **54″** nearest the electron gun **14** at **62**, for example by brazing or spot-welding; while the inner conductor **30′** of the coaxial output waveguide **28′** is similarly fastened at **62′** to the web **54″** nearest the collector **24**. It is pointed out that the points of attachment **62** and **62′** of the conductors **30** and **30′** need not be located circumferentially along the edge of the web **54″** midway between the points of attachment to the helices **50** and **52**, as shown, but may be circumferentially disposed at an angle of around 45° with respect to point of attachment of the web **54″** to the helix which bends away more rapidly from the web edge in question.

In a further embodiment of the present invention, illustrated in FIGS. 5–7, the value of n in Equation 1 is, made equal to three so that the web spacing S becomes ¾ of the helix pitch P. Thus, in this embodiment helical conductors **70** and **72** are interconnected at spaced points 270° apart along their lengths by alternately disposed webs **74′** and **74″** having their longitudinal dimensions rotated by 90° with respect to one another along the axis of the helices. The webs **74′** and **74″** define aligned circular apertures **76** of a diameter d to accommodate the electron beam.

In the operation of a traveling-wave tube employing a slow-wave structure according to the present invention, electromagnetic wave energy to be amplified is fed to the input end of the slow-wave structure **11** via coaxial input line **28**. This wave energy then propagates along the slow-wave structure **11** toward the collector electrode **24**, and in so doing interacts with electrons in the axially traveling electron beam which traverses the apertures **56**. Energy is transferred from the electrons to the traveling electromagnetic waves, thereby amplifying the traveling waves. The amplified electromagnetic wave energy is removed from the traveling-wave tube via coaxial output line **28′**.

In order to gain a better understanding and appreciation for the vastly improved results afforded by the slow-wave structure of the present invention, a brief and simplified discussion of the theory underlying the present invention will be presented. A bifilar helix will support the propagation of electromagnetic wave energy in both a symmetric mode (having fields propagating in phase with each other along the two helices) and an asymmetric mode (having fields propagating 180° out of phase from each other along the two helices). The fundamental space harmonic of the symmetric mode is the one normally used for forward-wave amplification, while the asymmetric mode is capable of producing backward-wave oscillations. Thus, in a forward-wave amplifier it is desired to maximize interaction with the fundamental component of the symmetric mode, while minimizing interaction with the asymmetric mode in order to reduce oscillations and other spurious outputs. As is the case with the crossbars of the strapped bifilar helix, the helix-connecting webs **54** of the slow-wave circuit of the present invention tend to provide a short circuit between opposite points on the helices **50** and **52**. However, on account of their configuration, the webs **54** of the slow-wave circuit of the present invention have a much lower inductance than do the narrow bars of the strapped bifilar helix, thereby providing a path of lower impedance between the helices which more closely approaches an ideal short circuit. Since in the symmetric mode the same "voltage" exists on both helices at a given cross-section, while for the asymmetric mode opposite "voltages" are present, the short circuits will strongly perturb the asymmetric mode while having little effect on the propagation of the asymmetric mode. Thus, the slow-wave circuit of the present invention inherently functions to suppress the asymmetric mode and the undesirable backward-wave oscillations which could otherwise result from its propagation.

In a conventional helix slow-wave circuit when the helix is designed to propagate waves of greater phase velocities, interaction in the fundamental forward space harmonic decreases while interaction in the backward space harmonic increases. However, on account of its mode-selective properties, this effect is minimized with the slow-wave circuit of the present invention so that the helices may be designed to propagate waves with greater phase velocities. This makes possible interaction with faster traveling (higher voltage) electron beams, resulting in higher power operation than is possible with conventional helix circuits.

In addition, with prior art helical slow-wave structures including the strapped bifilar helix, the fundamental forward space harmonic of the wave propagating along the helix consists of both TE portions (transverse-electric waves in which there is no component of electric field along the direction of propagation) and TM portions (transverse-magnetic waves in which there is no component of magnetic field along the direction of propagation) in approximately equal amounts. Since the axial magnetic fields do not interact with the electron beam, only the TM waves (with their axial electric field components) are useful for interacting with the beam. Thus, a substantial part of the fundamental component of the circuit wave energy is wasted in these prior art slow-wave circuits. However, the slow-wave circuit of the present invention strongly favors the propagation of fundamental TM waves over fundamental TE waves, and hence almost all of the fundamental space harmonic energy propagating along the slow-wave circuit of the present invention is useful for interaction with the electron beam. Thus, there is provided greater interaction for a given amount of input wave energy, greater efficiency, and a higher interaction impedance than with prior art helical slow-wave structures.

Moreover, since the fundamental space harmonic propagated by the slow-wave structure of the present invention contains a greater portion of TM energy than do fundamental space harmonics of prior art helical slow-wave circuits, the other space harmonics propagated by the slow-wave circuit of the present invention contain a smaller portion of TM energy than do those of prior art helices. Therefore, there is less interaction with these other space harmonics with the slow-wave circuit of the present invention than with the prior art circuits, thereby further reducing spurious mode interaction.

In further embodiments of the present invention additional means are provided in order to afford an even

greater reduction in spurious mode interaction. Thus, in the embodiment illustrated in FIGS. 8 and 9, a web **84** used to interconnect the two helical conductors may be constructed with first and second metal members **84***a* and **84***b*, respectively, which extend radially outwardly from opposite sides of its aperture **86** to the respective helical conductors, and with a pair of lossy elements **88** and **89** disposed on opposite sides of the aperture **86** between the metal members **84***a* and **84***b*. The lossy elements **88** and **89** each extend outwardly from the aperture **86** in a radial direction orthogonal to the radial direction in which the members **84***a* and **84***b* extend, with the radial extent of the lossy elements **88** and **89** being less than that of the metal members **84***a* and **84***b*. The elements **88** and **89** may be composed of a material such as kanthal, aquadag or a lossy ceramic such as a mixture of forsterite and silicon carbide.

In the symmetric mode there will be a minimum current flow through the lossy elements **88** and **89** of the connecting webs **84**, while in the asymmetric mode substantially greater current will flow through the connecting webs **84**. On account of the lossy elements **88** and **89**, greater power dissipation will occur for the asymmetric mode than for the symmetric mode. Thus, mode-selective loss is introduced into the webs **84** which attenuates the asymmetric mode while having essentially no effect on the symmetric mode.

In an alternate mode-selective loss arrangement illustrated in FIG. 10, a helix-connecting web **94** is constructed in a single piece, as are the webs **54** and **74**, and the loss is provided by coatings **98** on both broad surfaces of the web **94** in regions extending radially outwardly from opposite sides of its aperture **96** along the transverse, or smaller, dimension of the web **94** in the plane in which it is mounted. The coatings **98** may be of a material such as kanthal and may have a thickness of approximately one skin depth.

In the mode-selective loss arrangement shown in FIG. 11, lossy material **108** is disposed in indentations **107** in the helix-connecting web **104**. Each broad surface of the web **104** defines a pair of such indentations **107** which extend radially outwardly from opposite sides of its aperture **106** along a direction orthogonal to the longitudinal, or greater, dimension of the web **104** in the plane in which it is mounted. The loss **108** may be applied, for example, by flame-spraying the entire broad surfaces of the web **104** with kanthal, and subsequently grinding the web **104** to remove the lossy coatings in all regions other than in the indentations **107**.

A further advantage of the slow-wave circuit of the present invention over prior art helical slow-wave circuits such as the strapped bifilar helix lies in the fact that an additional design parameter is afforded; namely, the diameter *d* of the beam apertures **56** may be varied in addition to the diameter D of the helices **50** and **52**. For example, the beam hole diameter *d* may be increased without changing the helix diameter D, thus affording operation with beams of a larger diameter. Not only does a greater beam diameter allow higher power operation to be achieved, but it also enables the use of beams with lower space charge densities so that lower magnetic focusing fields may be employed, such as those readily achievable with periodic permanent magnet focusing.

A further characteristic of the slow-wave structure of the present invention, and one which readily lends itself to high power operation, is its excellent thermal capabilities, resulting from two considerations. First, on account of their relatively large cross-sections, the webs **54** provide a good thermal path away from the interaction region. Second, the field intensity outside of the helices **50** and **52** is such that the slow-wave structure housing **12** may be located closer to the helices **50** and **52** than in prior art helical circuits without introducing appreciable loading. This enables smaller support rods **60** to be employed than for the prior art circuits, thereby affording a lower thermal resistance.

The angularly staggered relationship between the successive crosspieces **54'** and **54''** reduces the opposing area of their broad surfaces. This reduces the capacitance between crosspieces, thereby lowering the stored energy per unit volume along the slow-wave structure. Since the interaction impedance is inversely proportional to stored energy, an increase in interaction impedance results.

As has been mentioned above, for the slow-wave structure of the present invention current paths are provided outwardly along a web from the beam hole to the helices, along the helices to the next web, and inwardly along that web to the beam hole. Thus, the helices and webs function together as the slow-waveguiding circuit, and the circuit may be visualized as a "folded helix" since the webs cause the current paths to be "folded in" toward the beam at spaced points along the helices.

As has also been mentioned above, the slow-wave circuit of the present invention enables lower magnetic fields to be employed to focus the electrons in the beam, and thus, traveling wave tubes incorporating such a slow-wave structure are ideally suited for periodic permanent magnet focusing. It is further pointed out that the magnetic field strength required for focusing is sufficiently low so that the webs **54** need not be of a ferromagnetic material but may be of any metal. Thus, the period of the magnetic focusing circuit comprising the magnets **40** and pole pieces **42** need not bear any particular relationship to the slow-wave circuit period, i.e., the distance between the webs **54**. On the other hand, if high magnetic focusing field strengths are desired, ferromagnetic material would be used for the webs **54**, in which case the period of the magnetic focusing structure must be equal to or an integral multiple of the period of the slow-wave structure.

The slow-wave circuit of the present invention may also be visualized as a helical meander line in which (instead of interconnecting a plurality of aligned apertured cross-pieces by a pair of conductors which are twisted in a single plane as in a conventional meander line) the conductors are made helical, with the cylinder defined by the helices completely enclosing the crosspieces, and with the crosspices being angularly staggered along the lengths of the helices. Not only does the slow-wave structure of the present invention provide substantially less spurious mode interaction than do conventional meander lines, but in addition, its meander length is greater than that of a conventional meander line. Thus, for the same crosspiece spacing, the phase velocity of waves propagating along the slow-wave circuit of the present invention is lower than that of waves traveling along a conventional meander line, making possible interaction with beams of a lower voltage (slower average velocity v_o). In this connection it may be further observed that for equal crosspiece spacings S, the modified length L' of the wave propagating structure of the slow-wave circuit of FIGS. 5–7 is substantially greater than that of the circuit of FIGS. 2–4. Thus, the embodiment of FIGS. 5–7 is able to operate with beams of lower voltage and is less dispersive (i.e., the frequency-phase characteristic has a smaller second derivative) than the circuit of FIGS. 2–4.

Thus, it will be apparent that on account of its ability to handle large diameter electron beams and its excellent thermal capabilities, the slow-wave structure of the present invention can operate at power levels approaching those of such high power circuits as the cloverleaf, ring-bar and folded waveguide circuits. At the same time, the slow-wave circuit of the present invention provides a high interaction impedance and wide bandwidth comparable to that achievable with helix circuits, while surpassing prior art helix circuits in ability to suppress spurious modes. In addition, the circuit of the present invention is able to operate with low magnetic focusing

fields and a wider range of beam voltages than prior art slow-wave structures.

It will be appreciated that while the embodiments of slow-wave structures illustrated herein have employed bifilar helices, the principles of the present invention are also applicable to multifilar helices employing more than two individual helical conductors. In the general case of an N-filar helix, where N is an integer not less than two, each helix-connecting crosspiece may define N portions equally spaced circumferentially about its electron beam aperture. Each portion would extend radially outwardly from the aperture to the N-filar helix and would be electrically connected to a different one of the N individual helical conductors. In addition, each radially extending portion in each crosspiece would be angularly displaced with respect to each radially extending portion in the next successive crosspiece along the slow-wave structure axis, for example by displacing each radially extending portion of a crosspiece by an angle of $180°/N$ with respect to one of the radially extending portions of the next crosspiece.

It will also be apparent that when bifilar helices are used the angle of displacement of successive crosspieces need not be 90° or 270°, but rather other staggering angles, for example 45°, 60°, 120°, 225°, etc., may be employed.

Thus, although the present invention has been shown and described with reference to particular embodiments, nevertheless, various changes and modifications obvious to one skilled in the art are deemed to be within the spirit, scope and contemplation of the invention as set forth in the appended claims.

What is claimed is:

1. A slow-wave structure for a traveling-wave tube comprising: a multifilar helix including a plurality of equally spaced individual helical conductors having the same helical diameter and pitch disposed about a common axis, a plurality of electrically conductive elements spaced along said multifilar helix in planes perpendicular to said axis, each of said elements defining an aperture encompassing said axis and aligned with the respective apertures in the other ones of said elements, each of said elements having a plurality of portions equal in number to the number of individual helical conductors extending radially from its aperture to the multifilar helix, with each of said portions being electrically connected to a different one of said helical conductors, and each said radially extending portion in each of said elements being angularly displaced by an angle other than 180° with respect to each said radially extending portion in the next successive one of said elements along said axis.

2. A slow-wave structure for a traveling-wave tube comprising: an N-filar helix where N is an integer not less than two, said N-filar helix including N equally spaced individual helical conductors having the same helical diameter and pitch disposed about a common axis, a plurality of electrically conductive webs equally spaced along said N-filar helix in planes perpendicular to said axis, each of said webs defining an essentially circular aperture encompassing said axis, the apertures in successive webs being aligned with one another, each of said webs defining N portions equally spaced circumferentially about said aperture and extending radially from said aperture to said N-filar helix, with each of said portions being electrically connected to a different one of said helical conductors, and each said radially extending portion of each of said webs being angularly displaced by an angle of $180°/N$ with respect to one of said radially extending portions of the next successive web along said axis.

3. A slow-wave structure for a traveling-wave tube comprising: a bifilar helix including first and second equally spaced individual helical conductors having the same helical diameter and pitch disposed about a common axis, a plurality of electrically conductive elements mounted along said bifilar helix in planes perpendicular to said axis, each of said elements defining an aperture encompassing said axis and aligned with respective apertures in the other ones of said elements, each of said elements further defining first and second portions extending radially from opposite sides of its aperture to said bifilar helix, with said first and second portions respectively being electrically connected to said first and second helical conductors, and said first portion of each of said elements being angularly displaced with respect to both said first and said second portions of the next successive one of said elements along said axis.

4. A slow-wave structure for a traveling-wave tube comprising: a bifilar helix including first and second equally spaced individual helical conductors having the same helical diameter and pitch disposed about a common axis, a plurality of electrically conductive crosspieces equally spaced along said bifilar helix in planes perpendicular to said axis, each of said crosspieces being electrically connected to both said first and said second helical conductors, each of said crosspieces defining an aperture encompassing said axis, the apertures in successive crosspieces being aligned with one another, each of said crosspieces having a dimension essentially equal to said helical diameter along at least one direction in the plane in which it is mounted, and said one direction in each crosspiece plane being angularly displaced by an angle other than 180° with respect to the said one direction in the plane of the next successive crosspiece along said axis.

5. A slow-wave structure for a traveling-wave tube comprising: a bifilar helix including a pair of equally spaced individual helical conductors having the same helical diameter and pitch disposed about a common axis, a plurality of equally spaced electrically conductive plates mounted along said bifilar helix in planes perpendicular to said axis, each of said plates being electrically connected to both of said pair of helical conductors, each of said plates defining an aperture encompassing said axis, the apertures in successive plates being aligned with one another, each of said plates having a dimension essentially equal to said helical diameter along a first direction in the plane in which it is mounted and having a smaller dimension along a second direction in said plane orthogonal to said first direction, said first direction in each of said planes being aligned with said second direction in the plane of the next successive plate along said axis.

6. A slow-wave structure for a traveling-wave tube comprising: a bifilar helix including a pair of equally spaced individual helical conductors having the same helical diameter and pitch disposed about a common axis, a first and a second series of identical electrically conductive elements mounted along said axis in planes perpendicular thereto, each of said elements being electrically connected to both of said pair of helical conductors, each of said elements defining an aperture encompassing said axis and aligned with the respective apertures in the other ones of said elements, each of said elements having a greater extent in one direction in the plane in which it is mounted than in a transverse direction in said plane, the greater extent direction for each of the elements in each series being aligned with the greater extent direction for each of the other elements in its series and with the transverse direction for each of the elements in the other series, and individual ones of the elements of said first and second series being alternately disposed along said axis.

7. A slow-wave structure for a traveling-wave tube comprising: a bifilar helix including first and second equally spaced individual helical conductors having the same helical diameter and pitch disposed about a common axis, a plurality of conductive webs electrically interconnecting said first and said second helical conductors at spaced points therealong, said webs being equally spaced along said bifilar helix in planes perpendicular to said axis and having a greater extent in one direction in the plane in which it is mounted than in an orthogonal direction in said plane, each of said webs defining an aperture encompassing said axis and aligned with the respective apertures in

the other ones of said webs, and successive ones of said webs being disposed in quadrature along said bifilar helix.

8. A slow-wave structure for a traveling-wave tube comprising: a bifilar helix including first and second equally spaced individual helical conductors having the same helical diameter and pitch disposed about a common axis, a plurality of electrically conductive elements spaced along said bifilar helix in planes perpendicular to said axis, each of said elements being electrically connected to both said first and said second helical conductors, each of said elements defining an aperture encompassing said axis and aligned with the respective apertures in the other ones of said elements, and the spacing between said elements being equal to $nP/4$ where n is an odd integer and P is the pitch of said helical conductors.

9. A slow-wave structure according to claim 8 wherein n is equal to one.

10. A slow-wave structure according to claim 8 wherein n is equal to three.

11. A slow-wave structure according to claim 7 wherein said webs are provided with loss means for increasing the electrical resistance to the flow of current through said webs between said first and said second helical conductors.

12. A slow-wave structure for a traveling-wave tube comprising: a bifilar helix including first and second equally spaced individual helical conductors having the same helical diameter and pitch disposed about a common axis, a plurality of electrically conductive means mounted along said bifilar helix in planes perpendicular to said axis, each of said conductive means defining an aperture encompassing said axis and aligned with respective apertures in the other ones of said conductive means, each of said conductive means defining first and second portions of essentially no electrical resistance extending radially outwardly from opposite sides of its aperture to said bifilar helix and being respectively connected to said first and second helical conductors, each of said conductive means further defining third and fourth portions of relatively high electrical resistance disposed between said first and second portions and each extending radially outwardly from opposite sides of said aperture in a radial direction essentially orthogonal to the radial directions in which said first and second portions extend, the radial extent of said third and fourth portions being less than that of said first and second portions, and the radial extent direction of said first portion of each of said conductive means being aligned with the radial extent direction of said third portion of the next successive conductive means along said axis.

13. A slow-wave structure according to claim 12 wherein said first and said second portions of said conductive means are of metal and said third and fourth portions are of lossy ceramic material.

14. A slow-wave structure for a traveling-wave tube comprising: a bifilar helix including first and second equally spaced individual helical conductors having the same helical diameter and pitch disposed about a common axis, a plurality of equally spaced electrically conductive plates mounted along said bifilar helix in planes perpendicular to said axis, each of said plates being electrically connected to both said first and said second helical conductors, each of said plates defining an aperture encompassing said axis, the apertures in successive plates being aligned with one another, each of said plates having a dimension essentially equal to said helical diameter along a first direction in the plane in which it is mounted and having a smaller dimension along a second direction in said plane orthogonal to said first direction, said first direction in each of said planes being aligned with said second direction in the plane of the next successive plate along said axis, and a coating of lossy material having a thickness of approximately one skin depth on both broad surfaces of said plates in regions extending radially outwardly from opposite sides of said aperture along a direction essentially orthogonal to said first direction.

15. A slow-wave structure for a traveling-wave tube comprising: a bifilar helix including first and second equally spaced individual helical conductors having the same helical diameter and pitch disposed about a common axis, a plurality of equally spaced electrically conductive plates mounted along said bifilar helix in planes perpendicular to said axis, each of said plates being electrically connected to both said first and said second helical conductors, each of said plates defining an aperture encompassing said axis, the apertures in successive plates being aligned with one another, each of said plates having a dimension essentially equal to said helical diameter along a first direction in the plane in which it is mounted and having a smaller dimension along a second direction in said plane orthoganal to said first direction, said first direction in each of said planes being aligned with said second direction in the plane of the next successive plate along said axis, each said plate defining first and second indentations in each broad surface of said plate, with said first and second indentations extending radially outwardly from opposite sides of the aperture in said plate along a direction essentially orthogonal to said first direction, and lossy material disposed in each of said indentations.

16. A traveling-wave tube comprising in combination: electron gun means for launching a stream of electrons in a predetermined direction; collector means spaced from said electron gun means for intercepting electrons of said stream; focusing means for constraining said stream of electrons to flow along a predetermined path toward said collector means; and a slow-wave structure disposed between said electron gun means and said collector means; said slow-wave structure comprising a multifilar helix including a plurality of equally spaced individual helical conductors having the same helical diameter and pitch disposed about a common axis coincident with said electron stream path, a plurality of electrically conductive elements spaced along said multifilar helix in planes perpendicular to said axis, each of said elements defining an aperture encompassing said axis and aligned with the respective apertures in the other ones of said elements, each of said elements having a plurality of portions equal in number to the number of individual helical conductors extending radially from its aperture to the multifilar helix, with each of said portions being electrically connected to a different one of said helical conductors, and each said radially extending portion in each of said elements being angularly displaced by an angle other than 180° with respect to each said radially extending portion in the next successive one of said elements along said axis.

17. A traveling-wave tube comprising in combination: electron gun means for launching a stream of electrons in a predetermined direction, collector means spaced from said electron gun means for intercepting electrons of said stream, focusing means for constraining said stream of electrons to flow along a predetermined axis toward said collector means, a tubular electrically conductive envelope coaxially disposed within said focusing means and about said electron stream axis between said electron gun means and said collector means, a plurality of insulating support rods mounted within said envelope and disposed parallel to said electron stream axis, a multifilar helix mounted on said insulating support rods, said multifilar helix including a plurality of equally spaced individual helical conductors having the same helical diameter and pitch coaxially disposed about said electron stream axis, a plurality of electrically conductive elements equally spaced along said multifilar helix in planes perpendicular to said axis, each of said elements defining an essentially circular aperture encompassing said axis and aligned with the respective apertures in the other ones of said elements, each of said elements having a plurality of portions equal in number to the number of individual helical conductors extending radially from its aperture to the multifilar helix, with each of said portions being electrically connected to a different one of said helical conductors, and each said

radially extending portion in each of said elements being angularly displaced by an angle other than 180° with respect to each said radially extending portion in the next successive one of said elements along said axis.

18. A traveling-wave tube comprising in combination: electron gun means for launching a stream of electrons in a predetermined direction; collector means spaced from said electron gun means for intercepting electrons of said stream; focusing means for constraining said stream of electrons to flow along a predetermined path toward said collector means; a slow-wave structure disposed between said electron gun means and said collector means; said slow-wave structure comprising a multifilar helix including a plurality of equally spaced individual helical conductors having the same helical diameter and pitch disposed about a common axis coincident with said electron stream path, a plurality of electrically conductive elements spaced along said multifilar helix in planes perpendicular to said axis, each of said elements defining an aperture encompassing said axis and aligned with the respective apertures in the other ones of said elements, each of said elements having a plurality of portions equal in number to the number of individual helical conductors extending radially from its aperture to the multifilar helix, with each of said portions being electrically connected to a different one of said helical conductors, and each said radially extending portion in each of said elements being angularly displaced by an angle other than 180° with respect to each said radially extending portion in the next successive one of said elements along said axis; coaxial input means for propagating input electromagnetic wave energy to the end of said slow-wave structure nearest said electron gun means, the inner conductor of said input means being electrically connected to one of said elements at the electron gun end of said slow-wave structure at a point spaced from said helical conductors; and coaxial output means for propagating amplified electro-magnetic wave energy away from the end of said slow-wave structure nearest said collector means, the inner conductor of said output means being electrically connected to one of said elements at the collector end of said slow-wave structure at a point spaced from said helical conductors.

19. A slow-wave structure for a traveling-wave tube comprising: a multifilar helix including a plurality of equally spaced individual helical conductors having the same helical diameter and pitch disposed about a common axis, a plurality of electrically conductive elements spaced along said multifilar helix in planes perpendicular to said axis, each of said elements defining an aperture encompassing said axis and aligned with the respective apertures in the other ones of said elements, each of said elements being electrically connected to each of said helical conductors at at least a point, and each of said points for each of said elements being angularly displaced by an angle other than 180° with respect to each of said points for the next successive one of said elements along said axis.

20. A slow-wave structure for a traveling-wave tube comprising: an N-filar helix where N is an integer not less than two, said N-filar helix including N equally spaced individual helical conductors having the same helical diameter and pitch disposed about a common axis, a plurality of electrically conductive webs equally spaced along said N-filar helix in planes perpendicular to said axis, each of said webs defining an essentially circular aperture encompassing said axis, the apertures in successive webs being aligned with one another, each of said webs being electrically connected to each of said helical conductors at at least a point, and each of said points for each of said webs being angularly displaced by an angle of $180°/N$ with respect to one of said points for the next successive web along said axis.

21. A slow-wave structure for a traveling-wave tube comprising: a bifilar helix including first and second equally spaced individual helical conductors having the same helical diameter and pitch disposed about a common axis, a plurality of electrically conductive elements mounted along said bifilar helix in planes perpendicular to said axis, each of said elements defining an aperture encompassing said axis and aligned with respective apertures in the other ones of said elements, each of said elements being electrically connected to said first helical conductor at at least a first point and to said second helical conductor at at least a second point, each of said first and said second points for each of said elements being angularly displaced by an angle other than 180° with respect to each of said first and said second points for the next successive one of said elements along said axis.

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UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Patent No. 3,268,761 August 23, 1966

Michael M. Mann

It is hereby certified that error appears in the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

Column 4, line 60, for "despect" read -- respect --; column 5, line 3, for "approximateliy" read -- approximately --; column 6, lines 22 and 23, for "asymmetric" read -- symmetric --.

Signed and sealed this 1st day of August 1967.

(SEAL)
Attest:

EDWARD M. FLETCHER, JR.
Attesting Officer

EDWARD J. BRENNER
Commissioner of Patents