Sept. 11, 1962 J. L. PUTZ 3,054,017

ELECTRON DISCHARGE DEVICES

Filed May 6, 1957 2 Sheets-Sheet 1

FIG.1.

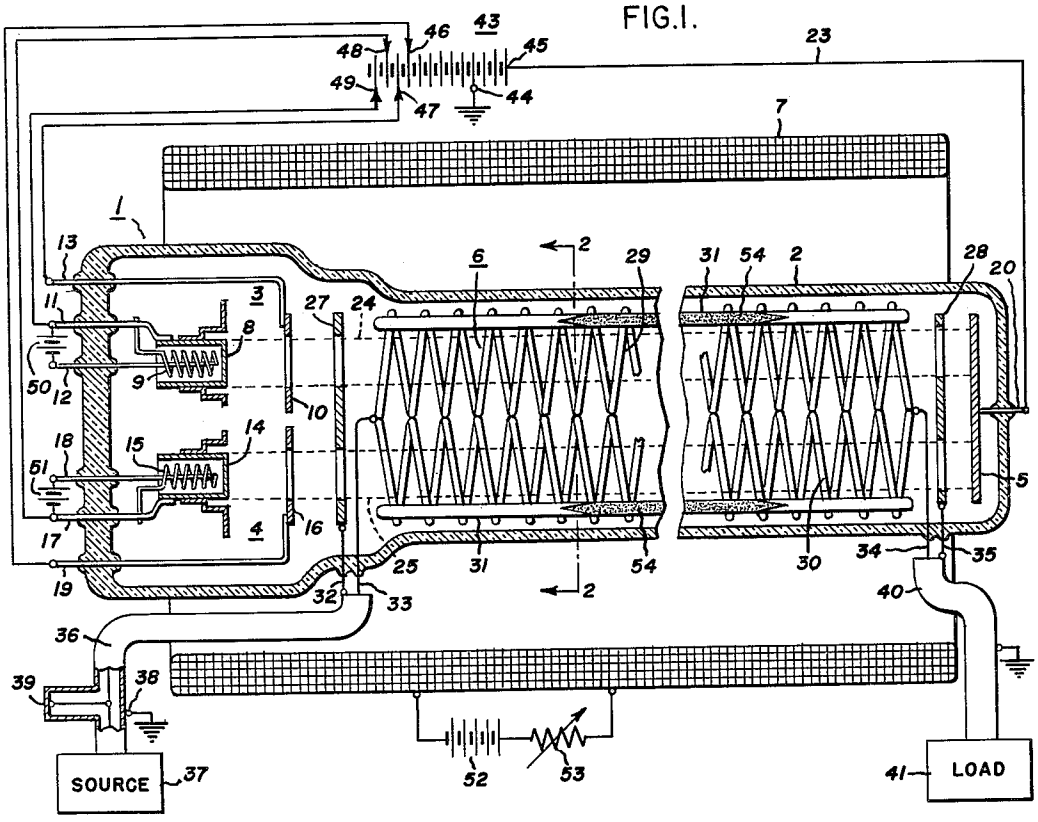


FIG.2.

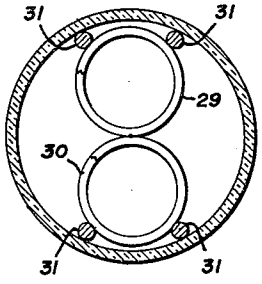


FIG.3.

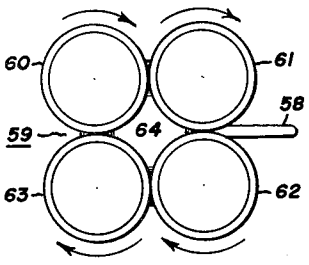
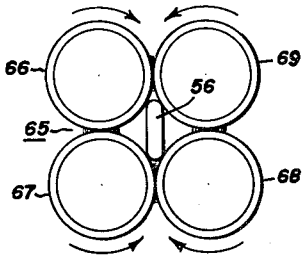


FIG.4.



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Filed May 6, 1957 2 Sheets-Sheet 2

FIG.5.

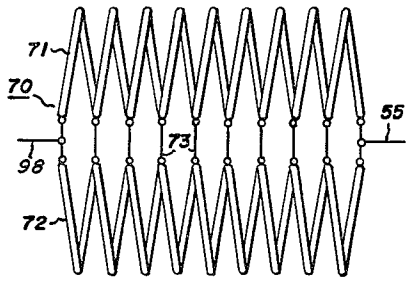


FIG.6.

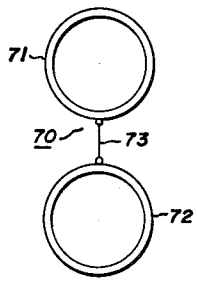


FIG.7.

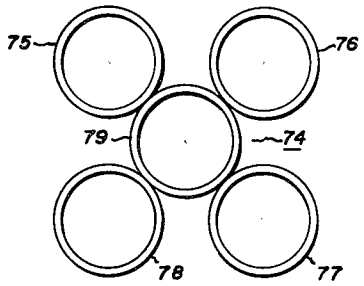


FIG.8.

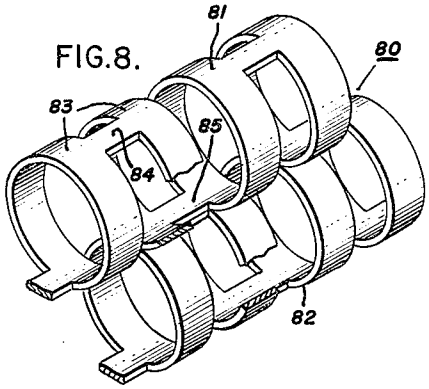


FIG.9.

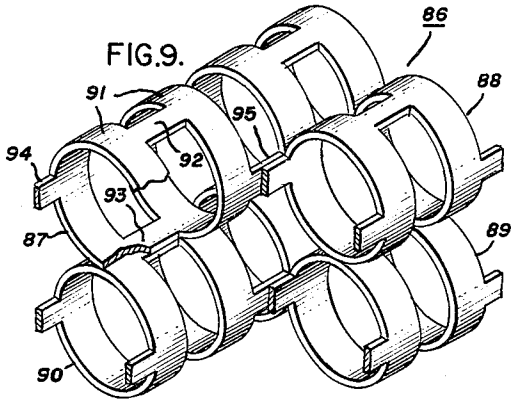


FIG.10.

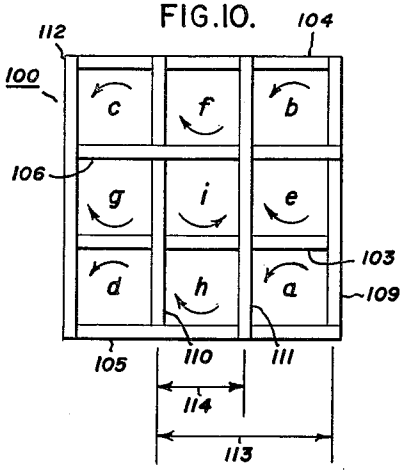
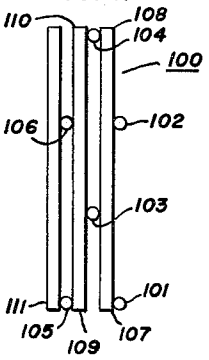


FIG.11.



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3,054,017

ELECTRON DISCHARGE DEVICES

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Filed May 6, 1957, Ser. No. 657,367
15 Claims. (Cl. 315—3.6)

This invention relates generally to electron discharge devices, and more particularly to improvements in electron discharge devices of the kind involving interaction of an electron beam with an electromagnetic wave propagated on a waveguide structure disposed adjacent to the path of the electron beam.

Such devices are generally referred to in the art as traveling-wave tubes. One type of traveling-wave tube comprises a waveguiding conductor of generally helical configuraion several wavelengths long measured along the axis thereof at the frequency of operation of the tube. The helical conductor is proportioned and arranged to produce an electric field directed along the axis of helical conductor and moving at a velocity substantially less than the velocity of the wave along the conductor itself and within the range of practically obtainable electron beam velocities when an electromagnetic wave is applied to one end of the conductive structure. Such waveguiding structures which have the effect of producing a component of electric field of an electromagnetic wave which moves at a lower velocity than the wave itself on the structure are commonly referred to as slow-wave structures. A variety of conductive structures have such properties and are suitable for use in traveling-wave devices.

Associated with the helical conductor is a means for producing an electron beam oriented on the axis of the helical conductor. When the tube is energized to produce an electron beam therein and an electromagnetic wave is applied to the beam entrance end of the helical conductor, the wave travels along the helical conductor producing an axially-directed component of electric field traveling at a velocity less than the velocity of the wave along the helical conductor. The average velocity of the electron beam is arranged with respect to the velocity of the axially-directed component of electric field of the applied wave to effect a conversion of energy associated with the electron beam into electromagnetic wave energy. Accordingly, as the applied electromagnetic wave moves along the helical conductor, it is augmented in amplitude. The wave augmented in amplitude is removed at the beam exit end of the helical conductor.

Traveling-wave devices of the kind described above are useful as amplifiers, oscillators and the like at radio frequencies and are capable of delivering appreciable amounts of power at these frequencies. However, a need exists in the art for obtaining higher power outputs from such traveling-wave tubes. As the power output of a traveling-wave tube depends on the conversion of beam power into radio frequency power, to obtain higher power outputs from traveling-wave tubes of the kind having a single slow-wave structure it is necessary to increase either the current of the electron beam, the voltage applied between the ends of the electron beam, or increase both, that is, it is necessary to suply more power to the electron beam which can then be converted into radio frequency power.

One of the principal problems encountered in obtaining higher power outputs from traveling-wave tubes of the kind described above has been that of supplying more power to the electron beam. This is particularly true at high frequencies, i.e. above about 2000 megacycles. The densities and cross-sectional areas obtainable in beam currents are limited by present-day technology. Practical cathodes and electron beam convergence arrangements limit the current densities obtainable. With electron

beams of limited cross-sectional areas, problems of focusing the electron beam are made increasingly difficult as the current density is increased. Increases in beam cross-sectional areas, while allowing larger beam currents, necessitate alterations in the slow-wave structure of such tubes, such as increasing its diameter, which deleteriously affects such things as the interaction impedance and variation of gain with frequency for the tube. Accordingly, it is seen that the art has reached definite limitations with regard to increasing beam current in devices employing single slow-wave structures. Although higher voltages may be utilized to obtain higher beam powers, problems of insulation, of availability of higher voltage, and of hazards to operating personnel are encountered. Accordingly, it is apparent that a traveling-wave tube utilizing a single slow-wave structure has in certain respects reached definite limitations with regard to power output capabilities.

It has been proposed to operate a plurality of slow-wave structures in parallel, each with its respective electron beam and thus obtain the advantages of a single waveguiding structure with regard to such matters as beam current and voltage, yet obtain the greater power output desired. However, in view of the fact that the length of a slow-wave structure as measured along the axis of the structure is many times, for example, twenty to fifty times, the slowed-down wavelength of an applied electromagnetic wave, a slight variation in the dimensions, particularly length, of one slow-wave structure from that of another has the effect of producing an appreciable difference in the phase of the output obtainable from one of said structures with respect to the output of the other of said structures. Hence, when such outputs of different phase are combined, a resultant output less than the sum of the individual outputs is obtained. Additionally, juxtaposition of two slow-wave structures electrically connected only at the input and output thereof permits modes of propagation of electromagnetic waves on the structures other than the desired mode, particularly when the structures are not appreciably separated or shielded from one another.

It is, accordingly, an object of the present invention to provide electron beam-eletromagnetic wave interaction type tubes capable of developing high power output.

It is another object of the present invention to provide means for advantageously operating a plurailty of slow-wave structures in parallel in electron beam-electromagnetic wave interaction devices.

It is another object of the present invention to provide improved slow-wave structures useful in traveling-wave tubes.

Helical conductors are commonly used in tubes of the kind described above. One of the problems generally encountered in constructing helical conductors for use at high frequencies and for high power outputs is that of providing helical conductors with sufficiently small helix diameters yet mechanically strong and electrically effective.

It is, accordingly, another object of the present invention to provide simple, yet mechanically rugged and electrically effective, slow-wave structures of helical configuration for traveling-wave tubes for high frequency operation.

It is another object of the present invention to provide slow-wave structures for electron beam-electromagnetic wave interaction type tubes which are relatively simple in construction yet highly effective and efficient in operation.

In carrying out the present invention in one illustrative form thereof as applied to electron discharge devices of the type wherein each of a plurality of electron beams interacts with respective ones of a plurality of moving electromagnetic waves, each of said waves being asso-

ciated with a respective waveguiding structure of the slow-wave type to effect a conversion of beam energy into electromagnetic energy, I have arranged each one of said slow-wave structures to be conductively connected to at least one other of said slow-wave structures at points spaced along said structures. The points of connection of the conductors are arranged to be at substantially electrically equivalent intervals from the input ends of said conductors. The intervals between successive points of connection are arranged to be sufficiently small to maintain the axial components of the traveling electromagnetic waves associated with said conductors in phase during their propagation from the input end of the conductors to the output ends thereof. With such arrangement, the power output capabilities of single slow-wave structures are extended without encountering the aforementioned disadvantages associated with paralleling a plurality of slow-wave structures, and in addition, other advantages over a simple slow-wave structure are obtained.

The features of my invention which I believe to be novel are set forth with particularity in the appended claims. My invention itself, however, both as to its organization and method of operation, together with further objects and advantages thereof, may best be understood by reference to the following description taken in connection with the accompanying drawing, in which:

FIGURE 1 shows a cross-sectional view of a traveling-wave tube embodying the present invention and shows the tube connected in an operative circuit;

FIGURE 2 shows an enlarged cross-sectional view of the tube of FIGURE 1 taken along section 2—2 of FIGURE 1;

FIGURES 3 and 4 show end views of slow-wave structures embodying the present invention and consisting of four helical conductors;

FIGURES 5 and 6 show side and end views, respectively, of a slow-wave structure embodying the present invention and consisting of two helical conductors spaced apart;

FIGURE 7 shows an end view of a composite slow-wave structure embodying the present invention and consisting of five helical conductors;

FIGURE 8 shows an isometric view partly broken away of a composite slow-wave structure embodying the present invention and consisting of a pair of slotted contra-wound helix structures;

FIGURE 9 shows an isometric view partly broken away of a composite slow-wave structure consisting of four bi-filar, slotted contra-wound, helix conductors;

FIGURES 10 and 11 show plan and side views, respectively, of a composite slow-wave structure utilizing a plurality of linear conductors.

Referring now to FIGURE 1 of the drawing, there is shown in accordance with the present invention a traveling-wave tube 1 functioning as an amplifier. Traveling-wave tube 1 comprises an evacuated elongated dielectric envelope 2 mounted at one end of which are a pair of electron guns or sources 3 and 4 for producing beams of electrons in the evacuated space of the envelope, and mounted at the opposite end of which is a collector structure 5 for intercepting the electrons ejected from the electron gun. A wave transmission circuit or waveguiding structure 6, commonly referred to as a slow-wave structure, for developing from electromagnetic waves applied thereto a component of electric field moving along a dimension thereof at a velocity substantially less than the free space velocity of the electromagnetic waves, is centrally mounted between the electron gun structure and the collector structure in energy interchanging relationship with the electron beams. An elongated coil 7 of generally cylindrical configuration for developing a unidirectional magnetic field directed along the axis of the envelope for focusing the electron beams is located substantially concentric with respect to the envelope 2 and substantially surrounds the envelope 2 along its length.

The electron gun structure 3 comprises a cathode 8, a heater 9 therefor mounted in insulating relationship therewith, and an accelerating or beam-forming electrode 10 spaced and insulated from the cathode 8. Accelerating electrode 10 has an aperture therein in axial registration with cathode 8. External connections are made to the cathode 8 by means of conductor 11, to the heater 9 by means of conductors 11 and 12, and to the accelerating electrode 10 by means of conductor 13. The electron gun structure 4 comprises a cathode 14 and a heater 15 therefor mounted in insulating relationship therewith, and an accelerating or beam-forming electrode 16 spaced and insulated from the cathode 14. Accelerating electrode 16 has an aperture therein in axial registration with cathode 14. External connections are made to the cathode by means of conductor 17, to the heater 15 by means of conductors 17 and 18, and to the accelerating electrode 16 by means of conductor 19.

The collector structure 5 comprises a conductive plate mounted on conductor 20 by means of which suitable external connections may be made to the plate. When the electron gun structures and the collector 5 are suitably energized as will be more fully explained below, beams 24 and 25 are formed and extend into the elongated region of the envelope from the gun structure to the collector 5.

Electrode 27 having apertures in registration with beams 24 and 25 is provided adjacent gun structures 3 and 4 and serves both to shape the electron beams and to terminate or "match" the radio frequency field on the waveguiding structure 6 to an external circuit. Electrode 28 having apertures in registration with electron beams 24 and 25 is provided adjacent to collector 5 and functions principally to match the output of the waveguiding structure 6 to an external circuit.

Waveguiding structure 6 comprises a pair of conductors 29 and 30 of helical configuration, each having the same helix diameter, pitch and axial length. The considerations entering into the design and construction of the individual helical conductors are very similar to the considerations used for traveling-wave tubes employing a single helical conductor.

Each of the helical conductors has a helix diameter relatively small compared to the wave length of an applied electromagnetic wave or electrical signal in free space. For a single helix slow-wave structure, the diameter for maximum gain per unit axial length of structure and maximum efficiency is arranged so that the ratio of the helix diameter to free space wave length of the applied wave is about 0.4 times the ratio of velocity of an electromagnetic wave along the axis of the helix to its free space velocity or the velocity of light.

The pitch of each of the helical conductors is arranged to provide a predetermined velocity of propagation for the applied electromagnetic wave through the structure substantially less than the free space velocity of the electromagnetic wave and in the range of conveniently obtainable electron beam velocities, i.e. from about five to fifty percent of the velocity of light, and is additionally arranged to optimize interaction of the electron beam with the axially-directed component of the electric field of the electromagnetic wave.

Each of the helical conductors is made of such a length as to produce the desired gain in the tube. When the length of a helical conductor is made very long, the increment of length over an optimum length becomes increasingly less effective in the conversion of beam energy into electromagnetic energy. Of course, if the length of the helical conductor is made too small, insufficient amplification is obtained. Additionally, with very long helical conductors, practical difficulties arise with respect to maintaining an electron beam in association therewith in proper focus. The axial length of helical conductors commonly used in traveling-wave tubes is usually many

wavelengths long, in the range from about twenty to fifty wavelengths long. The helical conductors are arranged so that their axes form the opposite sides of a rectangle, the other sides of each of which are equal to the diameter of the helix formed by each of said conductors. With such an arrangement, the helical conductors are in conductive contact along the entire length thereof at points one turn apart as measured along the helical conductors. Conductive engagement of the conductors may be assured by soldering or brazing the conductors at the points of contact. The helical conductors **29** and **30** are mounted in the envelope so that helical conductor **29** is concentric with respect to beam **24** and helical conductor **30** is concentric with respect to beam **25**. Suitable elongated insulating members **31** may be used to hold or wedge the helical conductors in the envelope **2** in proper alignment with the electron beams as more clearly shown in FIGURE 2. The ends of the helical conductors **29** and **30** are spaced from the input matching electrode **27** and output matching electrode **28**, but sufficiently closely spaced thereto so that waves may be applied between the beam entrance end of the helix and the input matching electrode **27** and may be removed between the beam exit end of the helical conductors and output matching electrode **28**. External conductive connections are made to the input matching electrode, the input end of the helical conductors, the output end of the helical conductors and the output maching electrode by means of conductors **32**, **33**, **34** and **35**, respectively.

The input electrodes **32** and **33** are connected to the outer and inner conductor of a transmission line **36**, respectively, to the other end of which is connected a source **37** of high frequency waves to be amplified. Outer conductor of transmission line **36** is grounded at **38**. In order to maintain the helical conductors **29** and **30** at a D.-C. ground potential, a high frequency choke **39** is provided in the transmission line **36**. This choke takes the form of a quarter-wave length transmission line having one end short-circuited and having the other end connected in shunt across the transmission line **36**. Of course, other kinds of chokes having the desired frequency versus impedance characteristics may be used. Output conductors **34** and **35** are connected to the inner and outer conductor, respectively, of a transmission line **40**, to the other end of which is connected a utilization device or load **41**.

Power supply **43** provides unidirectionally operating potentials to various electrodes of the device. Power supply **43** includes a grounded point **44**, a point **45** positive with respect to the ground and points **46**, **47**, **48** and **49** of variable potential arranged in order of increasingly negative potential with respect to the ground point. Cathode **8**, cathode **14**, accelerating electrode **10**, and accelerating electrode **16** are connected respectively to points **49**, **48**, **47** and **46**, respectively, over conductors **11**, **17**, **13** and **19**, respectively. Collector electrode **5** is connected over conductor **23** to point **45**.

Source of power **50**, having one terminal connected to conductor **11** and the other terminal thereof connected to conductor **12**, supplies power for the heater **8**. Source **51**, having one terminal connected to conductor **17** and the other terminal connected to conductor **18**, supplies power to heater **15**. Source **52**, having one terminal thereof connected to one terminal of the focus coil **7** and having the other terminal thereof connected to the other terminal of the coil through a variable focusing resistance **53**, provides current to the coil for focusing the electron beams.

In the operation of the device of FIGURE 1 as a forward traveling-wave amplifier, a high frequency signal from the source **37** is applied between the beam entrance end of the helical conductors **29** and **30** and electrode **27** to initiate a wave on each of the helical conductors. As previously mentioned, each of the helical conductors is arranged such that the application of signals thereto produces a wave having a component of electric field which is directed along the axis of the helical conductor and which travels at a velocity substantially less than the free space velocity of the electromagnetic wave. This velocity of the electromagnetic wave along the axis of the helical slow-wave structure is commonly referred to as the phase velocity of the wave on the structure. The average velocity of each of the beams is adjusted to be slightly greater, i.e. about ten to fifteen percent, than the velocity of the aforementioned axially-directed component of electric field. Under these conditions, the electromagnetic wave on each of the helical conductors interacts with a respective electron beam and a net interchange of energy from the beam to the electromagnetic wave is effected. Thus, as each of the waves travels on the respective helical conductor from the entrance to the exit end thereof, it is continuously augmented in amplitude. Waves of augmented amplitudes appear at the exit ends of the helical conductors and are applied over conductors **34** and **35** and transmission line **40** to the utilization circuit or load **41**.

With the composite structure shown and described in FIGURE 1 in which the conductors are conductively connected at points spaced at electrically equivalent intervals along the conductors, differences in phase of the outputs of the helical conductors are substantially eliminated. It is understood that an interval or distance along a slow-wave structure is electrically equivalent to another interval or distance along another slow-wave structure if waves applied in the same phase at the beginning of each interval arrive in the same phase at the end of each interval. Similarly, electrically corresponding parts when used in connection with waveguiding structures refer to parts that are at substantially the same radio frequency potential. Accordingly, substantially higher power outputs are obtainable than by use of a pair of paralleled single slow-wave structures not so interconnected. Additionally, spurious modes of operation of the composite parallel structure are avoided. Preferably the helical conductors are conductively connected at points spaced a turn apart. As the intervals of coupling are increased, less satisfactory operation results. Also it has been found that with conductive coupling once every turn, a few poor connections randomly distributed on the structure are not detrimental to the operation of the tube.

FIGURE 2 shows a sectional view of the tube of FIGURE 1 and in particular shows the positioning of the insulating rods **31**.

The helical conductors of the device of FIGURES 1 and 2 are wound in the same sense, that is, as shown they are both right-hand helices. Of course, they both may be left-hand helices or one may be a right-hand helix and the other a left-hand helix. A right-hand helical conductor is a conductor the direction of advance of which in an axial direction as one proceeds along the conductor is the same as the direction of advance of the thread of a right-hand screw. A left-hand helical conductor is a conductor the direction of advance of which in an axial direction as one proceeds along the conductor is the same as the direction of advance of the thread of a left-hand screw.

The exact nature of the fields associated with the structures and their modes of propagation are complex. However, it is generally recognized in traveling-wave tubes that traveling-wave structures will support a number of traveling waves including a forward traveling wave and a reflected traveling wave. When traveling-wave tube devices are suitably energized, both the forward traveling wave and the reflected traveling wave may appear on the structure. The velocity of the electron beam in devices used as a forward traveling-wave amplifier is adjusted to be slightly greater than the axially-directed velocity of the applied wave and to effect an interchange of energy between the beam and the electromagnetic wave. In order to minimize the effect of the reflected traveling waves on

the operation of the device, attenuators are placed along the helical conductors to attenuate the reflected traveling waves. The attenuator may take the form of conductive strips **54** distributed along the length of insulators **31**, for example. Aquadag, an aqueous suspension of graphite commonly used in the electron tube art because of its good heat absorption properties, is suitable for this purpose.

Additionally, "backward waves" may appear on the structure. In present usage, the term "backward wave" has been applied to any space-harmonic component of a propagated wave which has phase and group velocities in opposite directions. The most important of such space-harmonic components as far as traveling-wave tubes are concerned is the so-called −1 component, since the tube will tend to oscillate at a frequency for which the phase velocity of this −1 component is nearly equal to the velocity of the beam. The frequency of oscillation is considerably higher (two to three times) the normal operating frequency of the tube but, nevertheless, it interferes with normal operation. The presence of the attenuator does not appreciably affect this backward-wave interaction, except to determine the length of the tube over which the interaction can take place. Many things affect the beam current level at which this type of oscillation starts, and some traveling-wave tubes are not troubled by it. The introduction of an effective velocity spread in the various beams (by operating them at different velocities) reduces the tendency of a tube to backward-wave oscillate, since the oscillation frequency is normally very much a function of beam velocity, and a number of velocities would "confuse" the operation with regard to the backward waves. At the same time, such a velocity spread, if moderate, does not have too much of an effect on the normal forward-wave interaction.

Unequal velocities and also unequal currents in the beams can be used to increase the bandwidth of the tube or permit simultaneous operation in two separate frequency ranges.

FIGURES 3, 4, 5, 6 and 7 show various composite helical conductive structures which may be associated with beam-producing structures to form traveling-wave devices of the kind shown in FIGURE 1.

Referring particularly now to FIGURE 3, there is shown a composite slow-wave structure **59** consisting of four helical conductors **60**, **61**, **62** and **63**, each having the same diameter, pitch and axial length. The conductors are arranged so that their axes form the parallel sides of a rectangular parallelepiped, the other sides of which are equal to the diameter of the helical condutcor. Each of the helical conductors of FIGURE 3 are wound in the same sense, that is, they are right-handed as indicated by arrows adjacent each of the helical conductors. But, of course, they all may be left-hand helices, if desired. With such an arrangement, each helical conductor contacts two other adjacent helical conductors along their lengths at points that are spaced a turn apart. The resultant composite structure **59** may be associated with beam-producing structures forming a single or a plurality of beams axially directed through one or more of the helical conductors and function as a traveling-wave tube in the manner described in connection with FIGURE 1. Input connection may be made to the structure **59** by means of conductor **58** corresponding to conductor **33** of FIGURE 1 connected to a point of contact between helices **61** and **62** at the entrance end thereof. Similar provisions may be made at the output end of the helical conductors.

A particularly useful mode of operation of the slow-wave structure FIGURE 3 is in conjunction with beam-producing means forming a single beam axially directed through axial opening **64** of the composite helical structure. The structure of FIGURE 3 has the advantage that though the electrically effective dimensions of the composite structure are small and hence suitable for operation at very high frequencies, the structure is formed, not from elements which are delicate and difficult to produce, but from elements which are large and mechanically strong. Also, the large conductive mass associated with the composite structure considerably improves heat dissipation qualities of the high-frequency structure. Additionally, when four or more helices are employed, the composite array may be mounted in a cylindrical dielectric envelope with only minor dielectric loading effects since only a relatively small part of the circuit, hence only a small part of the total electric field, is near the dielectric material of the envelope. Accordingly, it is seen that the structure of FIGURE 3 provides an efficient slow-wave structure for use at high frequencies, having excellent heat dissipation qualities.

FIGURE 4 shows a composite slow-wave structure **65** consisting of helical conductors **66**, **67**, **68** and **69**, identical in all respects to the structure **59** of FIGURE 3 except that helical conductors **66** and **68** are in the form of right-hand helices and conductors **67** and **69** are in the form of left-hand helices. The composite structure **65** of FIGURE 4 may be used in association with beam-producing means in the manner explained in connection with FIGURES 1, 2 and 3. Conductor **56** connected between the junction of conductors **66**, **67** and conductors **68**, **69** and energizable at a mid-point **57** thereof provides a means for applying energization thereof. Similar means may be provided at the output end of the composite structure. A particular advantage of the structure of FIGURE 4 is that better performance is obtained over a wider frequency range.

In FIGURES 5 and 6 there are shown side and end views, respectively, of another composite structure **70** comprising helical conductors **71** and **72** suitable for use in traveling-wave tubes. The composite structure is similar to the slow-wave structure of the embodiment of FIGURE 1, except that the axes of the helical conductors **71** and **72** are separated by a distance greater than the helix diameter of the conductors. The conductors are joined at adjacent points along their lengths by straps **73**. Conductors **98** and **55** connected to one of the straps **73** at the entrance and exit end of the composite structure provide means for coupling energy into and out of the composite structure. Successive points of connection on a conductor are arranged to be a turn apart and preferably the straps should not be more than a small fraction of a wavelength long at the frequency of operation of the structure. If desired, small conductive rings having a diameter small in comparison to a wavelength at the frequency of operation may be used in place of the straps. This structure is advantageously used where the beams formed by a cathode gun structure are separated by radial distances greater than the diameter of the helical conductors.

In FIGURE 7 is shown a further composite structure **74**, suitable for use in traveling-wave tubes consisting of five helical conductors **75**, **76**, **77**, **78** and **79**, each having the same diameter, pitch and length, in which the axes of four of the conductors form the parallel sides of a rectangular parallelepiped, and in which the axis of the fifth helical conductor extends through the center of the parallelepiped parallel to the other axes and separated therefrom by the helix diameter of a helical conductor. Such an arrangement produces a structure in which the center helical conductor contacts each of the other helical conductors. The fifth or center helical conductor may also be replaced by a series of discrete rings. Waves to be amplified may be applied to the structure and removed therefrom by input and output conductors similar to those shown and described in connection with FIGURES 3, 4 and 5, or by waveguide coupling means which convey electromagnetic wave energy to and from appropriate portions of the composite structure in a manner well known in the art.

FIGURES 8, 9, 10 and 11 show various composite helix-derived structures which may be associated with beam-producing structures to form traveling-wave devices of the kind shown in FIGURE 1. Helix-derived structures

are those structures wherein there is provided a conductive path or plurality of conductive paths on a structure which extends about and along an axis of the structure. Electromagnetic waves or signals may be coupled to and from the structures of FIGURES 8, 9, 10 and 11 by conductive or waveguiding means described in connection with FIGURES 2, 3, 4, 5, 6 and 7.

Referring specifically to FIGURE 8, there is shown a composite slow-wave structure **80** suitable for use in traveling-wave tubes comprising individual helix derived members **81** and **82** of circular cross section. Each of the members comprises a plurality of annular conductors **83**, each axially aligned and displaced from an annular conductor. Each of the annular conductors is joined to adjacent annular conductors by a pair of conductive straps **84, 85**, one conductive strap joining one annular conductor with an adjacent annular conductor on one side thereof, and the other conductive strap diametrically opposite the one conductive strap and joining the annular conductor with the adjacent annular conductor on the other side thereof. The members **81** and **82** are arranged in tangential relationship with their axes aligned in parallel and with the adjacent conductive straps of one member in conductive contact with the adjacent conductive straps of the other member. The diameter of the annular conductors are chosen with respect to the frequency of operation to obtain the desired operation and the members may be many wavelengths long as explained in connection with FIGURE 1. In each of the members **81** and **82** of FIGURE 8, a pair of contra-wound helical paths may be traced. Accordingly, it is referred to as a contra-wound helix-derived structure.

Referring now to FIGURE 9, there is shown another composite slow-wave structure **86** made up of four complex helix-derived members **87, 88, 89** and **90**. The four members are identical to one another in all respects. Each of the members is comprised of a plurality of annular conductors **91**, each lying on the same axis and each being displaced by a predetermined distance from adjacent annular conductors on each side thereof. Each annular conductor is connected to an adjacent annular conductor on one side thereof by a pair of conductive straps **92** and **93** diametrically opposite one another and is connected to an adjacent annular member on the other side thereof by a pair of conductive straps **94** and **95** diametrically opposite one another and generally displaced in a plane perpendicular to the plane of the first-mentioned straps. The members **87, 88, 89** and **90** are arranged in contactive relationship with their axes forming the parallel sides of a parallelepiped, the other sides of which are equal to the diameter of the annular conductors **91**. The members are further arranged so that the composite structure of the annular conductors are aligned in planes perpendicular to the axes of the individual members. The members are still further arranged so that the conductive straps of a pair of vertically disposed members, one with respect to the other, are in conductive contact and so that the conductive straps of a pair of horizontally disposed members, one with respect to the other, are in conductive contact. In each of the members **87, 88, 89** and **90** two pairs of contra-wound helical paths may be traced. Accordingly, it is referred to as a bi-filar contra-wound helix-derived structure.

FIGURE 10 shows a plan view and FIGURE 11 shows a side view of a portion of a composite helix-derived structure **100** which is rugged and is economical to construct. The composite structure comprises two groups of rod-like linear conductors, one group comprising elements **101–106**, the other group comprising elements **107–112**. The conductors in each group are parallel to one another and the conductors of one group are in space quadrature relationship to the conductors of the other group. The conductors of each of the groups are arranged into a plurality of sets. In the one group conductors **101** and **102** comprise one set, conductors **103** and **104** comprise a second set, and conductors **105** and **106** comprise a third set. In the other group conductors **107** and **108** comprise a first set, conductors **109** and **110** comprise a second set, and conductors **111** and **112** comprise a third set. The conductors in each set lie in a plane and successive conductors in a set are laterally displaced from one another by a predetermined distance **113**. The conductors of each set of one group are conductively stacked or interleaved between the conductors of successive sets of conductors of the other group. Conductors **101** and **102** of an odd-numbered set of the one group are first laid down. Conductors **107** and **108** of the odd-numbered set of the other group are then laid down. Next, conductors **103** and **104** of the even set of the one group are laid over conductors **107** and **108**. Finally, conductors **109** and **110** of the next even set of conductors of the other group are laid over conductors **103** and **104** to complete a repeating pattern of the composite structure which may include many sets of conductors. The conductors of the odd-positioned sets of each group lie in a respective set of planes perpendicular to the planes of said sets. The conductors of the even-positioned sets of each group also lie in a respective set of planes perpendicular to the planes of said sets. The number of planes in a set of planes is equal to the number of conductors in a set of conductors. Adjacent planes of the even and odd position sets of planes of one group of conductors are spaced apart by a predetermined distance **114** equal to one-half the first-mentioned predetermined distance.

With such a construction as described above, a plurality of generally helical conductive configurations made up of rectilinearly oriented elements, instead of the usual curvilinear elements, joined together along their length are formed. In the drawing, a turn and a half for each of nine such conductive configurations are formed, designated *a* through *i*. Configurations *a, b, c, d* and *i* are left-hand helical configurations as viewed looking into the plane of the figure and as indicated by arrows adjacent each of the configurations. Configurations *e, f, g* and *h* are right-hand helical configurations as indicated by arrows adjacent each of the configurations. Helices *a, b, c* and *d* each have two sides in common with other helices of the combination. Helices *e, f, g* and *h* have three sides in common with the other helices. The helix *i* not only has four sides in common with other helices *e, f, g* and *h*, but also has a point in common with each of the helices *a, b, c* and *d*. With such a structure a single or plurality of beams may be utilized. Of course, the number of helix-derived configurations formed can be increased, if desired, by simply increasing the number of linear conductors in each set. Such a composite structure may be used in conjunction with beam-producing means forming a single or a plurality of beams coupling with one or a plurality of helical conductors in the manner described in connection with FIGURE 3.

While I have shown and described particular embodiments of my invention, it will be obvious to those skilled in the art that various changes and modifications may be made without departing from my invention in its broader aspects and I, therefore, aim in the appended claims to cover all such changes and modifications as fall within the true spirit and scope of my invention.

What I claim as new and desire to secure by Letters Patent of the United States is:

1. An electron discharge device of the type wherein an electron beam interacts with a traveling wave, comprising a plurality of individual waveguiding members of circular cross section each adapted to develop a velocity of travel for an applied electromagnetic wave along an axis thereof substantially less than the free-space velocity of said wave, each of said waveguiding members being several wavelengths long at the frequency of said applied electromagnetic wave and having an input and an output, a plurality of electrically corresponding parts of said waveguiding member being joined to one another along the lengths thereof at intervals less than a wave-length apart, and means for producing an electron flow in an axial di-

rection in the path of travel of said applied wave in energy interchanging relationship with said traveling wave in each of said waveguiding members.

2. An electron discharge device of the type wherein an electron beam interacts with a traveling wave comprising an electron source, a collector electrode spaced apart from said source for defining therebetween a path of electron flow, a wave transmission circuit positioned along the path of electron flow for propagating an electromagnetic wave in energy coupling relation with electron flow in said path including a plurality of individual electromagnetic wave propagation members of circular cross section, each of said members comprising a continuous conductive member constructed to produce from an applied electromagnetic wave a component of electric field in the direction of electron flow having a velocity substantially lower than the free-space velocity of said wave, each of said members having a length in the direction of flow several wavelengths long at the frequency of said wave and positioned so that electrons from said electron source traverse the length thereof, each of said members being conductively joined to at least one other member at a plurality of points spaced at electrically equivalent intervals less than a wavelength apart along the length thereof, and means for coupling electromagnetic wave energy to said wave transmission circuit at one point thereof and for removing electromagnetic wave energy from said circuit at another point thereof.

3. An electron discharge device of the type wherein an electron beam interacts with a traveling wave comprising a plurality of sources of electrons, a collector electrode means spaced apart from said sources for defining therebetween a plurality of distinct paths of electron flow, a wave transmission circuit positioned along said paths of electron flow for propagating a traveling wave in energy coupling relation with electron flow in said paths including a plurality of individual electromagnetic wave propagation members of circular cross section, each of said members comprising a continuous conductive member constructed to produce from an applied electromagnetic wave a component of electric field in the direction of electron flow having a velocity along the axis of said member substantially lower than the free-space velocity of said applied wave, each of said members having a length in the direction of electron flow several wavelengths long at the frequency of said wave, each of said members being conductively joined to at least one other member at points spaced at electrically equivalent intervals less than a wavelength apart along the length thereof, and means for coupling electromagnetic wave energy to said wave transmission circuit at one point thereof and for removing electromagnetic wave energy from said circuit at another point thereof.

4. An electron discharge device which utilizes the interaction between an electromagnetic wave and an electron beam to augment the amplitude of said wave comprising an electron source, a collector electrode spaced apart from said source for defining therebetween a path of electron flow, a wave transmission circuit positioned along the path of electron flow for propagating an electromagnetic wave in energy coupling relation with electron flow in said path including a plurality of individual electromagnetic wave-propagation members of circular cross section, each of said members producing from an applied electromagnetic wave a component of electric field in the direction of electron flow having a velocity substantially lower than the free-space velocity of said wave, each of said members having a length in the direction of electron flow several wavelengths long at the frequency of said wave, each of said members being conductively joined to at least one other member at points spaced at electrically equivalent intervals less than a wave-length apart along the length thereof, means for applying an electromagnetic wave to said wave transmission circuit at one point thereof, means for establishing an electron flow between said electron source within each of said members and said collector electrode of an average velocity to augment the amplitude of said applied wave, and means for removing electromagnetic wave energy augmented in amplitude from said circuit at another point thereof.

5. An electron discharge device which utilizes the interaction between an electromagnetic wave and an electron beam to augment the amplitude of said wave, comprising a plurality of sources of electrons, a collector electrode means spaced apart from said source for defining therebetween a plurality of distinct paths of electron flow, a wave transmission circuit positioned along said paths of electron flow for propagating a traveling wave in energy coupling relation with electron flow in said paths including a plurality of individual electromagnetic wave-propagation members of circular cross section, each of said members comprising a continuous conductive member constructed to produce from an applied electromagnetic wave a component of electric field in the direction of electron flow having a velocity substantially lower than the free-space velocity of said applied wave, each of said members having a length in the direction of electron flow several wavelengths long at the frequency of said wave, each of said members being conductively joined to at least one other member at points spaced at electrically equivalent intervals less than a wave-length apart along the length thereof, means for applying an electromagnetic wave to said wave transmission circuit at one point thereof, means for establishing an electron flow between said electron sources and said collector electrode of an average velocity to augment the amplitude of said applied wave, and means for removing electromagnetic wave energy augmented in amplitude from said circuit at another point thereof.

6. An electron discharge device which utilizes the interaction between an electromagnetic wave and an electron beam to augment the amplitude of said wave, comprising a pair of electron sources, a collector electrode means spaced apart from said sources for defining therewith a pair of distinct paths of electron flow, a wave transmission circuit positioned along said paths of electron flow for propagating a traveling wave in energy coupling relation with electron flow in said paths including a pair of individual electromagnetic wave-propagation members of circular cross section, each of said members comprising a continuous conductive member constructed to produce from an applied electromagnetic wave a component of electric field in the direction of electron flow having a velocity substantially lower than the free-space velocity of said applied wave, each of said members having a length in the direction of electron flow several wavelengths long at the frequency of said wave, one of said members being conductively joined to the other of said members at points spaced at electrically equivalent intervals less than a wave-length apart along the lengths thereof, and means for coupling electromagnetic wave energy to said wave transmission circuit at one point thereof and for removing electromagnetic wave energy from said circuit at another point thereof.

7. An electron discharge device which utilizes the interaction between an electron beam and an electromagnetic wave traveling in the direction of flow of electrons of said beam to augment the amplitude of said wave, comprising a pair of electron sources, a collector electrode means spaced apart from said source for defining therewith a pair of distinct paths of electron flow, a wave transmission circuit positioned along said paths of electron flow for propagating a traveling wave in energy coupling relation with electron flow in said paths including a pair of individual electromagnetic wave-propagation members of circular cross section, each of said members constructed of a continuous conductive member having a configuration to produce from an applied electromagnetic wave a component of electric field in the direction of electron flow having a phase velocity substantially lower than the free-space velocity of said applied wave,

each of said members having a length in the direction of electron flow several wavelengths long at the frequency of said wave, one of said members being conductively joined to the other of said members at points spaced at electrically equivalent intervals less than a wave-length apart along the lengths thereof, means for applying an electromagnetic wave to said wave transmission circuit at one point thereof, means for establishing an electron flow in each of said paths between said electron sources and said collector electrode, means of adjusting the electron velocity to augment the amplitude of said applied wave, the average velocity of electron flow in one of said paths being different from the average velocity of electron flow of the other of said paths to suppress amplification of backward waves without appreciably affecting forward traveling waves, and means for removing electromagnetic wave energy augmented in amplitude from said circuit at another point thereof.

8. An electron discharge device which utilizes the interaction between an electromagnetic wave and an electron beam to augment the amplitude of said wave, comprising a plurality of sources of electrons, a collector electrode means spaced apart from said source for defining therebetween a plurality of distinct paths of electron flow, a wave transmission circuit positioned along said paths of electron flow for propagating a traveling wave in energy coupling relation with electron flow in said paths including a plurality of individual electromagnetic wave-propagation members of circular cross section, each of said members having a length in the direction of electron flow several wavelengths long at the frequency of said wave, each of said members constructed of a continuous conductive member having configuration to produce from an applied electromagnetic wave an electric field component having a velocity substantially lower than the free-space velocity of said electromagnetic wave and being aligned with a respective one of said paths to permit interaction with electron flow therewith, each of said members being conductively joined to at least one other member at points spaced at electrically equivalent intervals less than a wave-length apart along the length thereof, and means for coupling electromagnetic wave energy to said wave transmission circuit at one point thereof and for removing electromagnetic wave energy from said circuit at another point thereof.

9. An electron discharge device which utilizes the interaction between an electromagnetic wave and an electron beam to augment amplitude of said wave comprising a structure including a plurality of individual electromagnetic wave-propagating substantially continuous conductors, each of said conductors extending about and along an axis thereof to provide a member of circular cross section whereby an electromagnetic wave applied thereto has a component of electric field along said axis having a velocity along said axis less than the velocity of said wave along said conductor, each of said conductors having an axial length of several wavelengths at the frequency of said applied wave, one of said conductors being connected to at least one other of said conductors at points spaced along the conductors, said points for each of said conductors being at substantially electrically equivalent intervals from the ends of said conductors, said intervals being sufficiently small to maintain the axial component of the wave associated with each of said conductors in phase during propagation of the wave from one end of each of the conductors to the other end thereof, and means for producing a flow of electrons along an axis of each one of said conductors in energy interchanging relationship with the applied electromagnetic wave.

10. An electron discharge device of the kind depending for operation on the interaction of an electron beam with a traveling electromagnetic wave comprising a plurality of individual electromagnetic wave-propagating conductors, each of said conductors having an input and an output, each of said conductors including an individual continuous conductive member extending about and along the axis thereof to provide a member of circular cross section whereby the velocity of an electromagnetic wave on said conductor in the direction of said axis is less than the velocity of said wave along said conductor, and means for producing a plurality of electron beams, each of said beams being axially directed with respect to a respective conductor and in energy exchanging relationship therewith, each of said conductors having a length of several wavelengths long at the frequency of said wave, each one of said conductors and another of said conductors conductively connected at points spaced along said conductors, said points for each of said conductors being at substantially electrically equivalent intervals from the input end of said conductors, said intervals being sufficiently small to maintain the axial component of the wave associated with each of said conductors in phase during the propagation of the wave from the input end of said conductors to the output ends thereof.

11. A slow-wave structure for use in connection with devices for propagating electromagnetic waves comprising a plurality of individual identical helix-derived conductive members of circular cross section for guiding said electromagnetic wave, a means to introduce and extract electromagnetic waves from each of said members, each of said members comprising a continuous conductor having an input and an output, each of said individual members being capable of propagating an electromagnetic wave and proportioned to produce a component of electric field having a phase velocity substantially lower than the free-space velocity of an applied electromagnetic wave, each of said members having an axial length of many wavelengths at the frequency of said waves, each one of said members conductively connected to at least one other of said conductors at points spaced along said members, said points for each of said members being at substantially electrically equivalent intervals from the input end of said members, said intervals being sufficiently small to maintain the axial component of waves associated with each of said members in phase during the propagation thereof from the input end of said members to the output ends thereof.

12. A slow-wave structure for use in connection with devices for translating electromagnetic waves comprising a pair of identical helix-derived conductive members of circular cross section for guiding said electromagnetic wave, each of said members having an input and an output, each of said members being composed of a continuous conductor and proportioned to produce a component of electric field having a phase velocity substantially lower than the free-space velocity of an applied electromagnetic wave, said members being of equal axial lengths many wavelengths long at the frequency of said wave, each of said members including a plurality of annular conductive elements, the conductive elements of each member being spaced apart on a common axis, one of said conductive elements being conductively joined on one side to an adjacent conductive element by a conducting strap and being joined with an annular element on the other side thereof by another conductive strap diametrically opposite said first strap, the axes of said member being arranged in parallel and said members being in tangential contact at said straps.

13. A slow-wave structure for use in connection with devices for translating electromagnetic waves comprising a pair of identical helix-derived conductive members for guiding said electromagnetic wave, each of said members having an input and an output, each of said members being proportioned to produce a component of electric field having a phase velocity substantially lower than the free-space velocity of an applied electromagnetic wave, said members being of equal axial length many wavelengths long at the frequency of said wave, each of said conductive members including a plurality of annular conductive elements, the conductive elements of each mem-

ber being uniformly spaced apart on a common axis, one of said conductive elements being conductively joined on one side to an adjacent conductive element by a pair of diametrically opposite conductive straps and being joined with an annular element on the other side thereof by another pair of diametrically opposite conductive straps in quadrature space relationship to said one pair of straps, the axes of said members being in parallel and said members being in tangential contact with said straps.

14. A slow-wave structure for use in connection with devices for translating electromagnetic waves comprising a plurality of individual helical conductive members for guiding said electromagnetic wave, a means for introducing and extracting electromagnetic waves from each of said members, each of said members having an input and an output, each of said members being proportioned to produce a component of electric field having a phase velocity substantially lower than the free-space velocity of an applied electromagnetic wave, each of said members having the same helix diameter, pitch and length, the axial length of each of said elements being many wavelengths at the frequency of said wave, the axes of said members being aligned in parallel, each one of said members being conductively connected to at least one other of said members at points spaced along said members a turn apart, the conductive connection from a point of one conductor to a corresponding point on the other member being a small fraction of a wavelength of the applied wave in length.

15. A slow-wave structure for use in connection with devices for translating electromagnetic waves comprising a group of four helical conductive members for guiding said electromagnetic wave, each of said members having an input and an output, each of said members being proportioned to produce a component of electric field having a phase velocity along the axis thereof lower than the free-space velocity of an applied electromagnetic wave, each of said members having the same helix diameter, pitch and length, the axial length of each of said members being many wavelengths at the frequency of said wave, the axes of said members being aligned in parallel and forming the sides of a parallelepiped the other sides of which are equal to said helix diameter, each helical member being in conductive contact with two other helical members once every turn thereof, one pair of diagonally opposite helical conductive members being wound in one sense and the other pair of diagonally opposite helical conductive members being wound in the opposite sense.

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,054,017 September 11, 1962

John L. Putz

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 15, line 26, for "conductor" read -- member --.

Signed and sealed this 8th day of January 1963.

(SEAL)
Attest:

ERNEST W. SWIDER
Attesting Officer

DAVID L. LADD
Commissioner of Patents