Oct. 4, 1960 R. KOMPFNER ET AL 2,955,223

TRAVELING WAVE TUBE

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FIG. 1

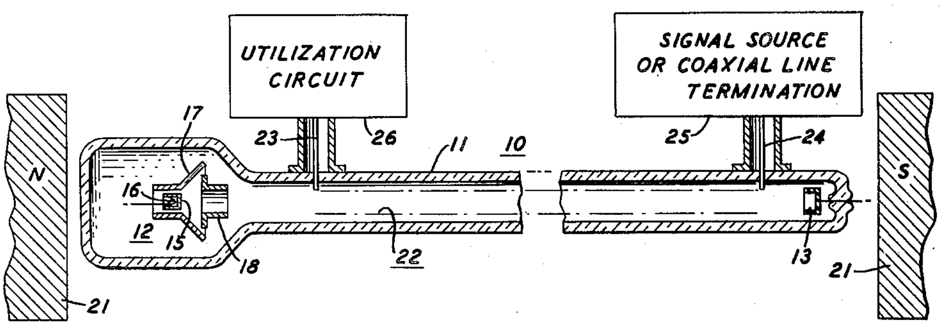


FIG. 2A

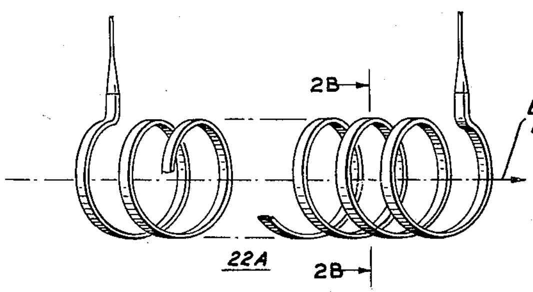


FIG. 2B

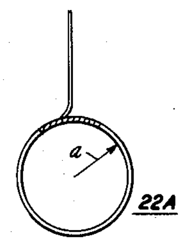


FIG. 3A

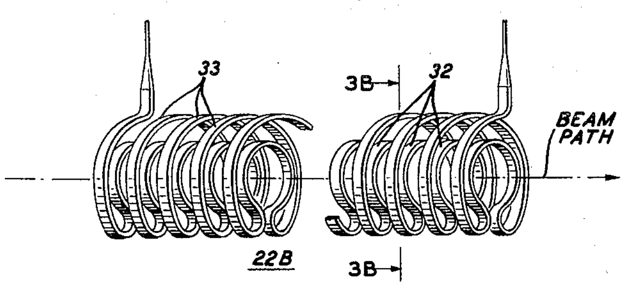
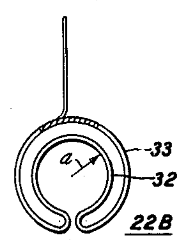


FIG. 3B



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TRAVELING WAVE TUBE

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FIG. 4A

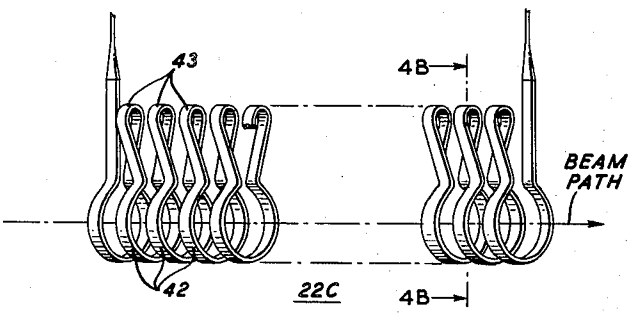


FIG. 4B

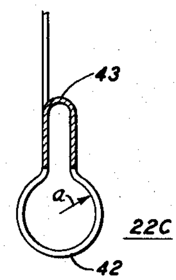


FIG. 5A

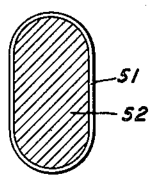


FIG. 5B

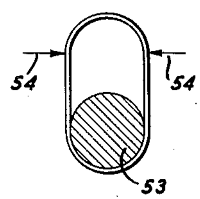


FIG. 5C

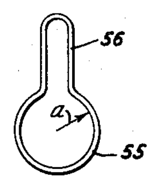


FIG. 6A

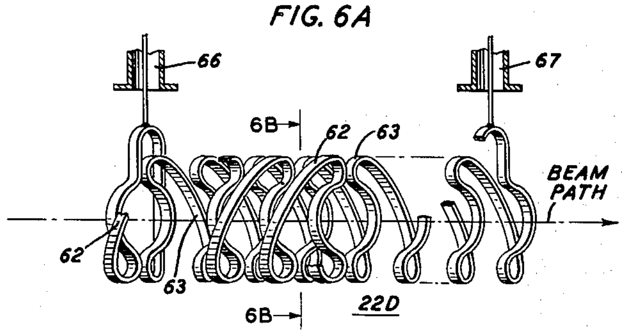
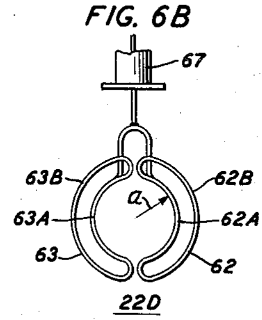


FIG. 6B



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TRAVELING WAVE TUBE

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15 Claims. (Cl. 315—3.5)

This invention relates to a traveling wave tube and, more particularly, to a traveling wave tube of the spatial harmonic type.

The present application is a continuation-in-part of an earlier application Serial No. 572,322, now abandoned, filed March 19, 1956.

In a traveling wave tube, an electromagnetic wave is propagated along a specially designed wave transmission line and an electron beam is projected along a path in coupling proximity with the transmission line for amplifying the propagating wave. As the beam passes in coupling proximity to the propagating wave, there results a bunching of the beam electrons and a net deceleration of these electrons. This deceleration represents a loss in kinetic energy of the beam and a consequent gain in electromagnetic energy of the field of the propagating wave. Thus the wave becomes amplified.

In order to achieve this energy transfer to the field of the propagating wave, it is necessary that the speed of the electron beam be approximately synchronous either with the fundamental of the propagating wave or with a spatial harmonic component thereof. The present invention is concerned with the latter case where the speed of the beam is synchronous with a spatial harmonic component of the propagating wave and hence beam interaction is had with such component. Since this type of interaction finds more use in traveling wave tubes of the so-called backward wave type than in forward wave type, the present invention will be discussed with particular reference to the tubes of the former type, although it is to be understood that we do not intend to limit our invention to backward wave type tubes.

In backward wave operation, a wave propagating in one direction along the transmisison line interacts with a beam projected in the opposite direction, the interaction occurring between the beam and a negative spatial harmonic component of the wave, as explained in an article entitled "A Spatial Harmonic Traveling-Wave Amplifier for Six Millimeter Wavelength," by S. Millman, appearing in the Proceedings of the I.R.E., vol. 39, page 1035, September 1951. Backward wave operation is useful at high frequencies in both amplifiers and oscillators, particularly the latter.

In one form of backward wave tube, the transmission line comprises a conductor wound to form a helix and the electron beam is projected along the axis of the helix. The conductor is advantageously a flat tape-like member. Such a transmission line is particularly desirable because of its structural simplicity and broad band characteristics. Disadvantageously, however, no one has priorly succeeded in simultaneously achieving efficient operation and maximum gain with such a transmission line when using it in conjunction with a solid electron beam. The reason for this will be explained hereinafter but, briefly speaking, it is because when the helix is dimensioned for maximum interaction impedance, and consequently maximum gain, the spatial harmonic fields of a wave propagating therealong are confined close to the helix and substantially no spatial harmonic fields exist near the helix axis. Thus a solid beam projected along the helix axis will, for the most part, be in a low spatial harmonic field region. Only the periphery of the beam will be close enough to the helix for efficient interaction and hence the center of the beam is wasted.

In the past, one technique proposed for minimizing the inefficiency occasioned by the waste of centrally located electrons of the beam involved the use of a hollow or annular beam. This eliminated the electrons which failed to achieve interaction with the spatial harmonic fields proximate the helix, with a consequent saving in power. However, the use of an annular beam is often undesirable since the amount of current containable in such a beam is obviously substantially less than in a solid beam and, further, difficulties arise in generating and focusing such a beam.

Accordingly, an object of the present invention is to achieve high gain and high efficiency in a traveling wave tube of the spatial harmonic type which utilizes a solid electron beam in connection with a helix-like transmission line.

To these ends, a feature of the present invention is an arrangement of one or more conductive tapes wound in a helix-like manner, each of which is designed to provide both high interaction impedance between spatial harmonic field components and the beam and the establishment of finite spatial harmonic fields over the entire beam cross section.

In certain illustrative embodiments of the present invention for use as a backward wave amplifier or oscillator, a solid electron beam of substantially circular cross section is projected along an extended path and a helix-like member forming a wave propagating circuit is positioned along a substantial portion of that path. For securing maximum gain for a backward traveling wave, the distance between corresponding points on successive turns of the helix-like member measured around the periphery of the helix, that is, the length of one complete turn, is adjusted to be approximately one half of a free space wavelength. Additionally, for establishing finite spatial harmonic field components over the entire beam cross section while maintaining maximum gain, each turn of the member has a first portion contiguous to the beam path and a second portion more remote therefrom and the contiguous portion of each turn lies along an arc of a circle whose circumference is approximately equal to $1.5\lambda_g$, where λ_g is the wavelength of a wave propagating along the helix-like member.

In an alternative embodiment for use as an amplifier or oscillator, the helix-like conductive member is replaced by two such members each of which propagates a wave in interacting relation with the beam and which together are likewise dimensioned to secure maximum gain and finite spatial harmonic field components over the entire beam cross section.

The invention will be explained in greater detail in the following description taken in connection with the accompanying drawing, in which:

Fig. 1 is a longitudinal sectional view of a traveling wave tube of the backward wave type whose transmission line is shown in phantom;

Figs. 2A and 2B are perspective and end views, respectively, of a transmission line which comprises a single conductive tape wound to form a helix as used in tubes known in the prior art;

Figs. 3A and 3B are perspective and end views, respectively, of a transmission line comprising a single conductive tape wound in a helix-like fashion and embodying the principles of the present invention;

Figs. 4A and 4B are perspective and end views, respectively, of a transmission line in accordance with another embodiment of this invention which comprises a single conductive tape wound in a helix-like fashion;

Figs. 5A to 5C show the steps of a technique for fabricating the structure of Figs. 4A and 4B; and

Figs. 6A and 6B are perspective and end views, respectively, of a transmission line comprising two conductive tapes wound in a helix-like fashion, in accordance with still another illustrative embodiment of this invention.

Referring now more particularly to the drawing, Fig. 1 shows a traveling wave tube **10** comprising an evacuated envelope **11**, typically of glass or nonmagnetic metal such as copper, enclosing an electron gun **12** for forming a solid electron beam and projecting the beam along an extended path toward collector **13**. The electron gun as shown schematically includes a cathode **15**, heater **16**, beam forming electrode **17**, and accelerating anode **18**. In practice, these elements are maintained in place by suitable supporting members, and there are provided lead-in conductors from suitable voltage sources for maintaining the various elements at appropriate potentials. In particular, the cathode is maintained at a potential slightly positive with respect to the beam forming electrode and appreciably negative with respect to the accelerating anode so that the beam will be projected toward the collector which is also biased positively with respect to the cathode. Additionally, permanent magnets **21** are provided for establishing a magnetic field whose flux lines extend along the length of the beam path for focusing the beam. These magnets may be replaced by a solenoid or other suitable apparatus for focusing the beam along its length.

A transmission line **22**, depicted in Fig. 1 as a pair of dot-dash lines, is positioned to surround the beam along a major portion of its path and is preferably arranged coaxially with the beam axis. The line is maintained at a suitable positive D.C. potential with respect to the cathode. Such potential fixes the velocity of the electrons in their flow past the line. Coaxial connectors **23** and **24** are provided at the upstream and downstream ends, respectively, of the transmission line for transferring wave energy between the line and various external circuits.

For operation as an amplifier of the backward wave type, wave energy is supplied from signal source **25** and passes by way of coaxial line **24** to transmission line **22**. The wave energy thus supplied is amplified in passing from right to left along the transmission line in a direction opposite to that of electron flow, in accordance with the principles of backward wave operation wherein interaction occurs between the electron beam and a negative spatial harmonic of the wave, and finally passes by way of coaxial line **23** to utilization circuit **26**.

For operation as an oscillator of the backward wave type, the signal source **25** is replaced by a coaxial line termination for making the downstream end of the line substantially reflectionless and the electron beam intensity is increased to a value sufficient to initiate oscillations. In this case, wave manifestations existing as noise on the electron beam initiate a wave along transmission line **22**. Additional interaction between the beam and a negative spatial harmonic component of the initiated wave causes such wave to be amplified. The wave thus amplified is transferred by way of coaxial line **23** to utilization circuit **26**. The oscillator in effect constitutes a closed loop formed by the electron beam which serves as a wave path to propagate wave energy from left to right along the tube and transmission line **22** which serves to propagate wave energy from right to left along the tube.

Transmission line **22** in the past has sometimes taken the form of a conductive tape wound to form a simple helix, as shown in Figs. 2A and 2B. With such a transmission line as the interaction circuit of a backward wave device, it is found that efficient operation cannot be achieved with a solid electron beam. The reason for this, viewed from a physical standpoint, is that when the helix is dimensioned for maximum gain the field of the spatial harmonic components of a wave propagating therealong is closely confined to the helix; substantially none of this field exists near the helix axis. Thus with the helix so dimensioned only the periphery of a solid beam projected along the helix axis would pass through the high field region proximate the helix. Moreover, it is not practicable, even if possible, to utilize a beam whose radius is as great as the inside radius of the helix. The outer electrons of such a beam would tend to strike the helix, causing damage thereto and creating an intolerable amount of noise on the beam with a consequent distortion of the amplified wave. A practical limit on the radius of the beam is found to be $0.8a$ where a is the effective inner radius of the surrounding interaction circuit, in this case the radius of the helix **22A**. Thus it can be appreciated that even the outer electrons of such a beam are somewhat removed from the helix.

With a beam having a radius of $0.8a$ or less, a finite spatial harmonic field can be achieved at the axis of the beam by dimensioning the helix so that γa equals 1.5, where γ is the propagation constant of the helix given approximately by the expression

$$\gamma = \frac{2\pi}{\lambda_0 v/c}$$

where

λ_0 is the wavelength in free space,
v is the velocity of propagation along the helix, and
c is the velocity of the propagation in free space.

The requirement that γa equal 1.5 is a condition previously known in the art to provide a finite spatial harmonic field at the helix axis. See Fig. 3.6 on page 29 of "Traveling Wave Tubes" by J. R. Pierce, Van Nostrand Company (1950). The requirement that γa equal 1.5 is equivalent to a requirement that the circumference of the surrounding helix **22A** equal $1.5\lambda_g$, where λ_g is the wavelength of a wave propagating along the helix. Disadvantageously, in the simple helix **22A** it is not possible to satisfy this condition while at the same time maintaining the distance between corresponding points on successive turns of the helix measured around the periphery of the helix equal to $.5\lambda$, where λ is a free space wavelength of the signal wave to be amplified, this latter condition being desirable for maximum interaction impedance for the negative spatial harmonic components of the signal wave, and hence for maximum gain.

However, both of these conditions may be satisfied, and hence maximum gain may be achieved and a finite spatial harmonic field established over the entire beam cross section in the helix-like transmission circuits in accordance with our invention.

The first of these helix-like transmission circuits **22B**, shown in Figs. 3A and 3B, comprises a succession of turns of a conductive tape each of which has an inner portion **32** which is positioned contiguous to the beam path along the axis of the helix and an outer portion **33** more remote from the beam path. The inner portions **32** effectively define the inner radius of circuit **22B** since the beam is to be projected along the hollow within these portions. Thus maximum efficiency is obtained by dimensioning these portions to lie along an arc, advantageously subtending an angle greater than 300, of a circle whose circumference is approximately $1.5\lambda_g$ or, stated in another way, by dimensioning a, the inner radius of the cicuit, to be approximately

$$\frac{1.5}{\gamma}$$

The inner portions **32** effectively form a succession of ring-like conductive members, each of which is not a complete ring but includes an interruption, and these members are interconnected by the outer portions **33** to form a continuous wave guiding structure. Additionally, each of the inner potions 32 of the turns of the helix-like member is made substantially pitchless whereby the electric field of a wave passing along the circuit 22B is advantageously substantially symmetric about the axis of a solid beam. Further, by suitably choosing the pitch angle, the radius, and the length of the outer portions 33 which are not in interacting relation with the electron beam, the distance between corresponding points on portions 32 of successive turns measured around the periphery of the helix, that is, the length of one complete turn, can readily be made to equal a half free space wavelength without disturbing the prescribed condition for maximum efficiency. Thus both the condition for achieving a finite field over the entire beam cross section and the condition for maximum gain may be simultaneously satisfied. Both of the conditions can simultaneously be satisfied in the structure 22B since, unlike helix 22A, the inner radius a of the circuit and the distance between corresponding points on successive helix-like turns may be adjusted independently. Contrariwise in the prior art helix 22A, these parameters are directly related, so choosing one fixes the other.

Another helix-like transmission circuit in accordance with our invention is shown in Figs. 4A and 4B. This circuit 22C is substantially keyhole-shaped in cross section. As the circuit of Figs. 3A and 3B, it comprises a succession of turns of a conductive tape each of which has a first portion 42 positioned contiguous to the beam path and a second portion 43 more remote from the beam path. In this circuit maximum efficiency is achieved by dimensioning the contiguous portion 42 of each helix-like turn to lie along an arc, advantageously subtending an angle greater than 300°, of a circle whose circumference is approximately $1.5\lambda_g$, or alternatively stated, to have dimension a of Fig. 4B approximately equal to

$$\frac{1.5}{\gamma}$$

Additionally, maximum gain is achieved by suitably choosing the pitch angle and length of remote portions 43 to make the distance between corresponding points on contiguous portions 42 measured around the periphery of the helix approximately equal to one half a free space wavelength. This latter condition is readily achieved without disturbing the prescribed condition for maximum efficiency and so, as in the structure of Figs. 3A and 3B, maximum efficiency and maximum gain are realized simultaneously.

For maintaining the field of a propagating wave symmetric about the beam path through circuit 22C, the contiguous portions 42 of each helix-like turn of the circuit are made substantially pitchless as shown in Fig. 4A. In such an arrangement the remote portions are suitably pitched to join these pitchless portions in a manner to achieve the dimensions described for maximum efficiency and gain. However, it is found that the circuit is more readily fabricated if both the contiguous and remote portions of each turn are similarly pitched. Additionally, it appears that the advantage obtained by this ease in fabrication more than compensates for the disadvantage of the slight field asymmetry occasioned by virtue of the pitch of the contiguous portions. The fabricating technique employed is to wind a simple helix on a suitable mandrel to have a cross-sectional shape which is substantially rectangular but has curved edges. Such a helix 51 is shown in Fig. 5A wound on mandrel 52. Various known coil winding machines may be employed for winding the helix. Then a second mandrel 53 is positioned to extend longitudinally within the helix, as shown in Fig. 5B, and pressure is applied at one end of the two long sides of the rectangularly cross-sectional helix as shown by arrows 54. This results in the circuit of Fig. 5C, which is similar to the circuit of Fig. 4B except that its portions 55 which in operation will be contiguous the beam path are pitched similarly to the more remote portions 56. However, both of these circuits, as the circuit of Figs. 3A and 3B, may be viewed as a succession of peripherally interrupted ring-like conductive members, formed by the contiguous portion of each turn or the circular portion of the keyhole, which are interconnected by the more remote portions of each turn to form a continuous wave guiding circuit.

Another alternative embodiment of the present invention is disclosed in Figs. 6A, 6B. In this embodiment, the helix-like circuit 22D comprises two conductive tapes 62 and 63 which are preferably wound in the same pitch, as shown, for maximum coupling therebetween. By providing maximum coupling between the two tapes, it is possible to maximize the difference in phase velocities of the two distinct modes capable of propagation along the circuit and, thus, there is facilitated the achievement of interaction with only a desired one of the two possible modes. Each of the tapes is wound in helix-like fashion and has an inner portion 62A, 63A which is positioned contiguous to the beam path along the axis of the circuit and an outer portion 62B, 63B more remote from the beam path and not in interacting relation with the beam. The two helices are coupled in-phase to suitable external circuitry by coaxial lines 66 and 67 which correspond to lines 23 and 24, respectively, of Fig. 1. To facilitate such in-phase coupling from a single coaxial line, the two helices shown are connected together at each end. When alternative arrangements are used to excite the two helices in-phase, it may be advantageous to keep the two helices separate. As in the embodiment of Fig. 3A, inner portions 62A and 63A of the instant helix-like circuit are dimensioned to lie along an arc, each preferably subtending an angle greater than 150°, of a circle whose circumference is approximately equal to $1.5\lambda_g$. Thus dimension a of Fig. 6B is approximately

$$\frac{1.5}{\gamma}$$

Additionally, as in the embodiment of Fig. 3A, such inner portions effectively form a succession of peripherally interrupted ring-like conductive members which are interconnected by outer portions 62B, 63B to form a continuous wave guiding circuit. The inner portions are pitchless for achieving a substantially symmetric field pattern about the axis of the beam path through the circuit. Further, the pitch angle, radius, and length of outer portions 62, 63 are chosen to obtain a distance between corresponding points on the inner portion of successive helix-like turns measured around the periphery of the helix, that is, the length of one complete turn, equal to one half a free space wavelength.

It is to be understood that the specific embodiments described are merely illustrative of the general principles of the present invention. Various other arrangements may be devised by one skilled in the art without departing from the spirit and scope of the invention. In particular, each of the embodiments has been described for use in a tube of the backward wave type. However, it is to be understood that the principles of the invention are applicable also to a forward wave tube, where interaction is of the spatial harmonic type. Such a tube can be obtained merely by interchanging the input and output terminals of the tube described. A showing of such a tube has been omitted since it will readily appear to one skilled in the art and it is not deemed to be as important an application of spatial harmonic operation as the backward wave tube.

What is claimed is:

1. A spatial harmonic traveling wave tube comprising means for forming a solid electron beam and for projecting said beam along an extended path, an electromagnetic wave propagating circuit comprising a helix-like member having a succession of turns, the length of each complete turn of which is approximately one half a

free space wavelength, and means for establishing a finite spatial harmonic field along and substantially encompassing the region about the axis of said electron beam, said means comprising a first wave propagation portion of said helix-like member contiguous to the beam path and a second portion more remote therefrom, said first portion defining an arc of a circle subtending an angle greater than 180 degrees and whose circumference is approximately equal to $1.5\lambda_g$, where λ_g is the wavelength of the wave propagating along the helix-like member.

2. A spatial harmonic traveling wave tube comprising means for forming an electron beam and for projecting said beam along an extended path, an electromagnetic wave propagating circuit comprising a conductive tape wound to form a helix-like structure having a distance around each turn thereof of approximately one half a free space wavelength, and means for establishing a finite spatial harmonic field along and substantially encompassing the region about the axis of said electron beam, said means comprising a first wave propagation portion of said helix-like structure contiguous to the beam path and a second portion remote therefrom, said first portion defining an arc of a circle subtending an angle greater than 180 degrees and whose circumference is approximately equal to $1.5\lambda_g$, where λ_g is the wavelength of the wave propagating along the helix-like structure.

3. A device which utilizes the interaction between an electron beam and a negative spatial harmonic component of an electromagnetic wave comprising means for forming an electron beam and for projecting said beam along an extended path, and an electromagnetic wave propagating circuit comprising a conductive tape wound to form a helix-like structure having a distance around each turn thereof of approximately one half a free space wavelength, each complete turn having a first substantially pitchless wave propagation portion contiguous to the beam path and a second portion remote therefrom, and pitched with respect to the axis of said structure, and said first portion lying along the arc of a circle whose circumference is approximately $1.5\lambda_g$, where λ_g is the wavelength of a wave propagating along the helix-like structure.

4. A device which utilizes the interaction between an electron beam and a negative spatial harmonic component of an electromagnetic wave comprising means for forming an electron beam and for projecting said beam along an extended path, and an electromagnetic wave propagating circuit comprising a conductive tape wound to form a helix-like structure having a distance around each turn thereof of approximately one half a free space wavelength, each complete turn having a first wave propagation portion contiguous to the beam path and a second portion remote therefrom, the contiguous and remote portions being similarly pitched with respect to the axis of the structure, and said first portion lying along the arc of a circle whose circumference is approximately $1.5\lambda_g$, where λ_g is the wavelength of a wave propagating along the helix-like structure.

5. In a device which utilizes the interaction between an electron beam and an electromagnetic wave, means for forming and projecting an electron beam along an extended path, and a transmission line for propagating an electromagnetic wave in coupling relation with said beam over a distance of several wavelengths at the mid-band operating frequency including a helix-like structure which comprises a series of substantially pitchless ring-like conductive wave propagation portions spaced apart in a linear array, each of which has at least one interruption point along its periphery, and a plurality of conductive portions each being pitched with respect to the axis of the helix-like structure and connected between the free ends of adjacent ring-like portions to form a single conductive wave propagation path along a continuous structure.

6. The combination of elements set forth in claim 5 wherein the radius of the ring-like conductive portions is approximately equal to

$$\frac{1.5}{\gamma}$$

and such ring-like portions are more proximate to the electron beam than the intermediate portions.

7. The combination of elements set forth in claim 5 wherein the distance between corresponding points on adjacent ring-like conductors measured around the periphery of the helix is approximately one half a free space wavelength at the mid-band operating frequency.

8. In a device which utilizes the interaction between an electron beam and an electromagnetic wave, means for forming and projecting an electron beam along an extended path, and a transmission line for propagating an electromagnetic wave in coupling relation with said beam over a distance of several wavelengths at the mid-band operating frequency including a helix-like structure which comprises a series of pitchless ring-like conductive portions spaced apart in linear array, each of which has only one interruption point along its periphery, and a plurality of conductive portions each being pitched with respect to the axis of the helix-like structure and being connected between the interruption points on adjacent ring-like portions to form a single conductive wave propagation path along a continuous structure.

9. The combination of elements set forth in claim 8 wherein the radium of the ring-like conductive portions is approximately

$$\frac{1.5}{\gamma}$$

and the distance between corresponding points on successive ring-like portions measured around the periphery of the helix is one half a free space wavelength at the mid-band operating frequency.

10. In a device which utilizes the interaction between an electromagnetic wave and an electron beam for amplifying the wave, means for forming an electron beam and for projecting said beam along an extended path, and a transmission line for propagating an electromagnetic wave therealong in coupling relation to said beam comprising a conductor wound in a helix-like fashion to form an iterative pattern, each section of which includes in intermediate conductive wave propagation portion surrounding the beam path at a zero pitch angle therewith bounded by two conductive portions extending at a predetermined pitch angle for interconnecting the zero-pitch portions, said zero-pitch portions being in the form of a conductive ring which is interrupted over a portion of its periphery and having its free ends thus formed connected to the pitched portions for forming a single conductive wave propagation path.

11. In a device which utilizes the interaction between an electron beam and the spatial harmonic component of an electromagnetic wave, means for forming an electron beam and for projecting said beam along an extended path, and a spatial harmonic propagating circuit in coupling proximity with said beam comprising a conductive member wound in helix-like fashion but differing from a simple helix in that its cross section is keyhole-shaped rather than circular, the length of each complete turn of said helix-like circuit being approximately one half a free space wavelength, each complete turn comprising a first wave propagation portion which is circularly shaped and is positioned to surround the beam path and extend contiguous to said path and a second portion more remote from the beam path, said circular portion being in a major arc of a circle whose circumference is approximately equal to $1.5\lambda_g$ where λ_g is the wavelength of a wave propagating along said helix-like circuit.

12. The combination of elements set forth in claim 11 wherein the circular portion lies along an arc of at least 300 degrees of a circle whose circumference is ap-

proximately equal to $1.5\lambda_g$ where λ_g is the wavelength of the wave propagating along the helix-like circuit.

13. The combination of elements set forth in claim 11 wherein the circular portion of the helix-like circuit is pitchless and the more remote portion is pitched at an angle with respect to the beam path.

14. The combination of elements set forth in claim 11 wherein the circular contiguous portion of the helix-like circuit and the more remote portion thereof are similarly pitched with respect to the beam path.

15. In a device which utilizes the interaction between an electron beam and an electromagnetic wave, means for forming and projecting an electron beam along an extended path, and a transmission line for propagating an electromagnetic wave in coupling relation with said beam over a distance of several wavelengths at the mid-band operating frequency including a helix-like structure which comprises a series of pitchless ring-like conductive wave propagation portions spaced apart in a linear array, each of which has two interruption points along its periphery which is defined by the arc of a circle having a radius of approximately

$$\frac{1.5}{\gamma}$$

and a plurality of conductive portions each being pitched with respect to the axis of the helix-like structure and being connected between adjacent ring-like portions to form a continuous structure with the distance between corresponding points on successive ring-like portions to form a continuous structure with the distance between corresponding points on successive ring-like portions measured around the periphery of the helix equaling one half a free space wavelength at the mid-band operating frequency.

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