Oct. 29, 1957 C. K. BIRDSALL 2,811,641

MICROWAVE TUBE

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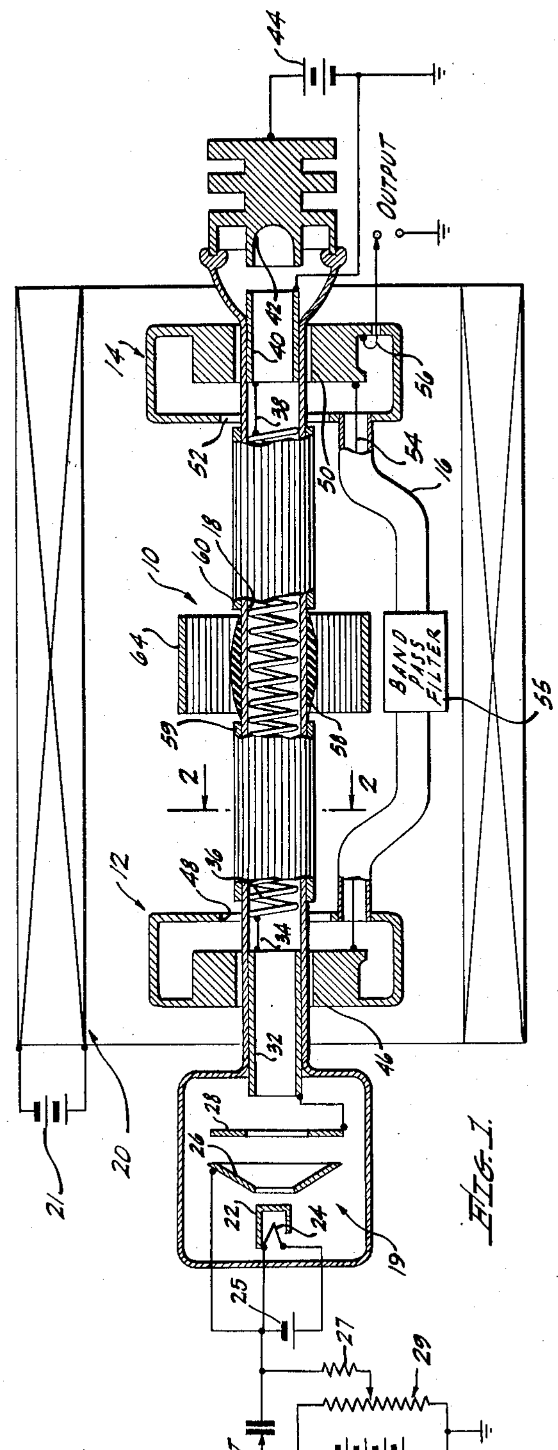

FIG. 1.

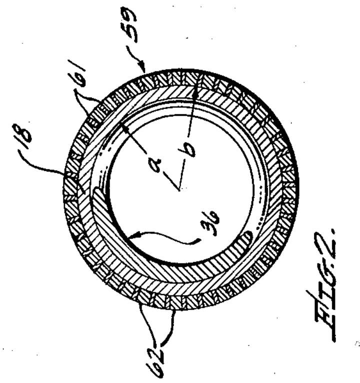

FIG. 2.

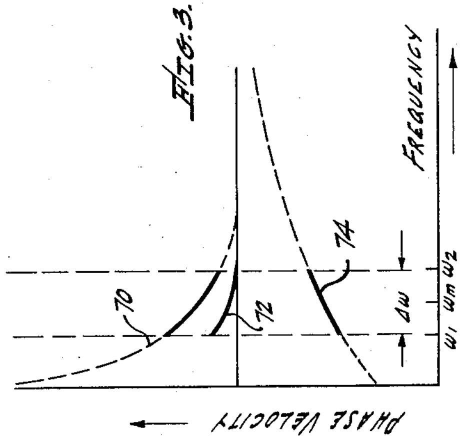

FIG. 3.

INVENTOR.
CHARLES K. BIRDSALL,
BY
Henry Heyman
ATTORNEY.

United States Patent Office

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MICROWAVE TUBE

Charles K. Birdsall, Venice, Calif., assignor to Hughes Aircraft Company, Culver City, Calif., a corporation of Delaware

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4 Claims. (Cl. 250—36)

The invention relates to wave-type tubes and more particularly to a device for decreasing the normal dispersion of the helical slow-wave structure of a traveling-wave tube whereby the electronic tuning range of wave-type oscillators may be increased or the bandwidth of a traveling-wave amplifier tube widened.

Traveling-wave tubes are commonly employed in oscillators, modulators, and amplifiers. Traveling-wave tubes normally are constructed of a helical conductor which is disposed within an evacuated envelope about the path of the electron stream, the helix having an organization such that the electromagnetic wave propagated by the helix has electric field components in the direction of electron flow and a velocity approximately equal to that of the electrons of the stream. The stream then interacts with the wave to increase its amplitude as it is propagated by the helix.

Traveling-wave tubes are conventionally incorporated into external feedback path traveling-wave tube oscillators. The necessary conditions for sustained oscillations in this type of oscillator are that there be an integral number of wavelengths around the feedback loop with a gain greater than unity. A specific number of wavelengths around the feedback loop is generally designated as a mode of oscillation. In order to provide continuous electronic tuning, it is necessary that the oscillations be restricted to one of these modes of oscillation. In accordance with the present invention, the width of this electronic tuning range may be substantially increased by making the wave transmission path anomalously dispersive.

Dispersion, in general, is proportional to the rate of change of phase velocity with frequency. When this rate is negative, dispersion is said to be negative or "normal." When the rate is positive, dispersion is said to be positive or "anomalous." It is known that a traveling-wave tube helix and an oscillator feedback path are usually "normally" dispersive. In the past, it has been impractical, if not impossible, to design a practical anomalously dispersive structure although it has been recognized that, should one be available, it would have considerable utility when employed either as the external feedback path or for the traveling-wave transmission path. Such a structure may be employed to displace or cancel normal dispersion in the wave transmission path of a traveling-wave tube oscillator to substantially increase its electronic tuning range. For a more detailed explanation of the advantages of an anomalously dispersive structure in connection with an electronically tuned traveling-wave tube oscillator, see copending application Serial No. 309,175, filed September 12, 1952, by John R. Whinnery, now abandoned.

In accordance with the present invention, a helix may be made anomalously dispersive by disposing a plurality of conductive strips lengthwise of and spaced around the helix. A simplified explanation regards this addition of structure as equivalent to the addition of shunt capacitance to the wave transmission path, which addition reduces the phase velocities of waves propagated along the path. The structure reduces the phase velocity of the lower frequency waves more than for the higher frequency waves so that the rate of change of phase velocity with frequency may be made positive thereby effecting anomalous dispersion.

The invention also has advantages attendant upon its employment in traveling-wave or otherwave-type tubes in general. For example, a lossy material is often employed along a traveling-wave tube helix for attenuating reflected waves which sometimes produce undesirable self-oscillation. When the lossy material is employed, gain is not only decreased but varies with frequency because of nonuniformity in the phase velocity of the propagated wave produced by interference effects of certain space charge waves which are propagated by the electron stream. Compensation may be made for this nonuniformity in phase velocity, however, by using the present invention. Further, the present invention may be employed in conjunction with a helical slow-wave structure to provide a wave transmission path having zero dispersion for use either in a ultra-broadband traveling-wave tube or as a delay device that is entirely independent of frequency.

It is therefore an object of the invention to provide apparatus for use in conjunction with a helical slow-wave structure to decrease the phase velocity of a propagated wave and to make its dispersion more positive.

It is another object of the invention to provide a wave-type oscillator having a substantially increased electronic tuning range.

Still another object of this invention is to provide an ultra-broadband traveling-wave type tube.

It is a further object of the invention to provide means for delaying microwaves of all frequencies by substantially equal periods of time.

It is a still further object of the invention to provide means for compensating for the nonuniformity in the phase velocities of microwaves propagated along a conductive helix through an attenuator region.

The novel features which are believed to be characteristic of the invention, both as to its organization and method of operation, together with further objects and advantages thereof, will be better understood from the following description considered in connection with the accompanying drawing in which an embodiment of the invention is illustrated by way of example. It is to be expressly understood, however, that the drawing is for the purpose of illustration and description only, and is not intended as a definition of the limits of the invention.

Fig. 1 is a sectional view of one embodiment of the present invention employed in a traveling-wave tube connected to function as an electronically tuned oscillator.

Fig. 2 is the section 2—2' of Fig. 1.

Fig. 3 shows typical phase velocity characteristics involved in the employment of the invention which are explanatory of its operation.

Referring now to the drawing, there is shown in Fig. 1 and embodiment of the disclosed microwave oscillator which comprises a traveling-wave tube **10** including input and output matching cavities **12** and **14**, respectively, with a feedback circuit such as, for example, a coaxial cable **16** completing the connection between cavities **12** and **14** for providing the necessary feedback loop required to produce oscillations. An envelope **18**, which provides the evacuated chamber of traveling-wave tube **10**, consists of a long cylindrical structure which has an enlarged portion at the left extremity, as viewed in the drawing. Within this enlarged portion there is located an electron gun **19** for producing a stream flow of electrons which is directed along a predetermined path that lies on the longitudinal axis of elongated envelope **18**.

A solenoid **20** is axially positioned symmetrically about the complete length of envelope **18**. An appropriate direct current is maintained in solenoid **20** by means of a connection across a potential source, such as a battery **21**, so as to produce a magnetic field which may be of the order of 600 to 1000 gauss running axially along the entire length of the tube. The purpose of this magnetic field is to keep the electron stream focused or constrained while traversing the path along the longitudinal axis of envelope **18**.

Electron gun **19** comprises a cathode **22** with a heating element **24**, a focusing electrode **26**, and an accelerating anode **28**. Heater **24** is connected across a source of potential, such as battery **25**, the negative terminal of which may be connected to cathode **22**. Cathode **22** is, in turn, maintained at an adjustable potential of the order of from 500 to 2000 volts negative with respect to ground by means of a connection through a resistor **27** to the adjustable tap of a potentiometer **29** which is in turn connected across a battery **30**, the positive terminal of which is connected to ground. A capacitor **31** is coupled directly to cathode **22** to provide a means of varying the velocity of the electron stream along the predetermined path in accordance with a signal. Focusing electrode **26**, sometimes called a Pierce electrode, is designed to have a frustro-conical shape with a surface of revolution at 67½ mechanical degrees from its axis of symmetry and is maintained at a potential of zero volts with respect to cathode **22** in order to simulate the space charge effect of an infinitely large stream so as to focus the electrons emitted from cathode **22** into a solid cylindrical electron stream. Focusing electrode **26** is accordingly connected directly to cathode **22** to accomplish this result. Anode **28** is maintained at a potential sufficiently positive with respect to the potential of cathode **22** to accelerate the electrons to a desired velocity by means of a connection therefrom to ground.

Disposed concentrically about the electron stream path in the direction of electron flow within envelope **18** are a matching ferrule **32** connected over a lead **34** to helix **36**, which is in turn connected over a lead **38** to a matching ferrule **40**. Helix **36**, and ferrules **32**, **40** are maintained at the same potential as anode **28** by means of a suitable connection thereto. A collector electrode **42** is disposed at the right extremity of envelope **18**, as viewed in the drawing, to intercept and collect the stream electrons. Collector **42** is maintained at a potential of the order of 200 volts positive with respect to the potential of ferrule **40** so as to minimize the number of secondary electrons. This voltage is impressed on collector **42** by a connection to the positive terminal of a battery **44**, the negative terminal of which is connected to ground.

Helix **36**, which serves as a slow-wave circuit for traveling-wave tube **10**, preferably has an inner diameter substantially equal to the inner diameter of ferrules **32** and **40** so that the stream electrons can be made to pass as closely to helix **36** as possible without being intercepted by the latter. A material such as tungsten is suitable for making helix **36**, the principal requirement being that it retain its form, especially with respect to its pitch and diameter.

As previously mentioned, helix **36** is connected to ferrules **32** and **40** by leads **34** and **38**, respectively. Leads **34** and **38** are located parallel to the electric fields excited within matching cavities **12** and **14**. Matching cavity **12** has the configuration of a rectangular toroid with a concentric collar **46** disposed about matching ferrule **32** and a slot opening coextensive with and adjacent to lead **34**. An opening **48** in the end plate of cavity **12** facing the left end of helix **36** allows the full length of lead **34** to be energized and, in addition, decreases the tendency of the electric field produced by the potential on the cavity to disturb the flow of the stream electrons. Cavity **14** is similarly shaped, having a corresponding concentric collar **50** arranged about matching ferrule **40** and an opening **52** facing the right end of helix **36**.

The coaxial cable **16** couples input cavity **12** to output cavity **14** through a band pass filter **55** to provide an external feedback path for the oscillator. The center conductor **54** of coaxial cable **16** extends through the apertures in the end plates of cavities **12** and **14** to connect to collars **46** and **50**, respectively, while the outer conductor of cable **16** is bonded to the periphery of the apertures. Band pass filter **55** restricts the frequency of the energy feedback to input cavity **12** so as to limit oscillation to a band of frequencies coextensive with a desired mode of oscillation. Also, the electrical length of the connection between output cavity **14** and input cavity **12** should be as short as possible for maximum range through which the oscillator of the present invention can be electronically tuned. An output for the oscillator is provided by a loop **56** which extends through an aperture in cavity **14** to couple to the electric field therein. Cavities **12** and **14** are fabricated with an inner surface composed of a highly conductive material and are broadly resonant so as not to control the frequency of oscillation. The configuration shown for cavities **12** and **14** in the drawing may provide, for example, suitable matching from helix **36** to coaxial cable **16** over a 2:1 range of frequencies extending from 2000 to 4000 megacycles.

Due to the fact that traveling-wave amplifiers are broadband amplifiers, it is difficult to obtain a proper impedance matching for all frequencies at the output. A resistive coating **58**, which may be of carbon black, is applied on the outside of envelope **18** about the center turns of helix **36** for the purpose of attenuating waves which may be reflected from the output end of tube **10** because of an impedance mismatch. Resistive coating **58**, which may be applied to any structure in the vicinity of its present position, is thus employed to decrease the tendency of the tube to break into oscillation by means of internal feedback. Forward waves traveling along with the stream electrons are not appreciably attenuated since they are propagated partially by the stream. It is to be noted that there are numerous methods of attenuating an electromagnetic wave and that the method described is merely for the purpose of illustration.

Coating **58** serves an extremely useful purpose; however, there are certain inherent disadvantages in its employment. In the first place, its use decreases the phase velocity of a wave being propagated through it. This causes the gain of the tube to vary unfavorably with frequency because of the interference effects of space charge waves which are propagated by the electron stream which produce narrower operating frequency bands and appreciably decrease the gain of the tube. These reduced gain and bandwidth effects may be minimized by decreasing the phase velocity of a wave within the unattenuated regions of the wave transmission path to a velocity equal to that of the wave within the attenuated region. In accordance with the present invention, equalization of the phase velocities is accomplished by the employment of two cylinders **59**, **60** disposed lengthwise of and spaced about the unattenuated regions of helix **36** and a third cylinder **64** disposed concentrically about the remaining portion of helix **36** wherein the electromagnetic wave is attenuated. Cylinders **59**, **60** and **64** each comprise a plurality of conductive strips **61** which are spaced uniformly about the helix **36** with a suitable dielectric binder **62** interposed between the conductive strips **61**. The diameter of cylinder **64** is larger than the diameters of cylinders **59**, **60** so as to compensate for the effect of resistive coating **58** on the phase velocity.

With respect to cylinders **59**, **60**, it is not necessary for strips **61** to be outside envelope **18**, nor is it necessary for them or equivalent structure to be at any critical position; however, if the diameter of helix **36** is not kept small for high frequency operation, a self-oscillation of a wave called a backward wave ordinarily renders the tube useless for other purposes. From this standpoint, it is more practicable to employ strips 61 on the outside of envelope 18. Strips 61 should be composed of a highly conductive material such as, for example, copper or silver. Alternatively, strips 61 may be replaced by a continuous conductive multifilar helix having a substantially smaller number of turns per unit length than that of helix 36. Equivalent impedance may also be produced by a mesh of insulated, plaited conductors constituted of two multifilar helices of reverse pitch and of the same relative dimensions.

Strips 61 should usually be spaced apart by a distance substantially shorter than the diameter of cylinders 59, 60. Likewise, their maximum cross-sectional dimension should also be as small as possible consistent with the dimensions of the helix 36 and envelope 18. A cross section of cylinder 59 at section 2—2' is shown in Fig. 2. In this figure, the symbol "a" is employed to denote the outside radius of helix 36 and "b" is used as the inside radius of the cylinder 59 constituted of strips 61 and dielectric 62. The ratio of "b" to "a" determines the effectiveness of the strips 61 with respect to the extent that the phase velocity is decreased. More particularly, for employment in the traveling-wave tube oscillator of the present inventor, the ratio

$$\frac{b}{a}$$

is less than the quantity

$$\left[2.5-\frac{1}{\epsilon_r+0.18}\right]$$

and as small as practicable in order to produce maximum anomalous dispersion in the wave transmission path. In the aforementioned quantity, ϵ_r is the relative dielectric constant of the intervening medium between helix 36 and the conductive strips 61. With regard to the application of the present invention to an external feedback path electronically tuned traveling-wave tube oscillator shown in Fig. 1, it is desirable to make the wave-transmission path anomalously dispersive so as to increase the frequency range through which the oscillator can be electronically tuned. It can be shown that this frequency range, $\Delta\omega$, is approximately equal to

$$\frac{\omega m}{\eta(1-D)}$$

wherein ωm is the mean angular frequency of oscillation for a mode having η wavelengths about the feedback loop, and D is the dispersion of the wave transmission path. It is readily apparent that if this dispersion is positive i. e. anomalous, the frequency range $\Delta\omega$ is considerably increased over what it would be if it were negative, as is usually the case.

To show more clearly the manner in which the phase velocity is compensated throughout the length of the feedback path, reference is made to Fig. 3. In this figure the frequency range $\Delta\omega$ extending from ω_1, to ω_2 and having a mean frequency ωm represents the electronic tuning range of the oscillator for a mode of oscillation having η wavelengths around the feedback loop. Within the frequency range $\Delta\omega$, a line 70 represents the phase velocity versus frequency characteristic for the unaltered helix 36, a line 72 represents the phase velocity versus frequency characteristic of the helix 36 with only the resistive coating 58, and a line 74 represents the desired phase velocity characteristic of the wave-transmission path of the oscillator. In the present case, the cylinders 59, 60 reduce the phase velocity throughout the unattenuated portions of helix 36 from velocities represented by line 70 to those represented by line 74 while the velocities throughout the region coextensive with resistive coating 58 are reduced

from the velocities represented by line 72 to those represented by the same line 74. This difference in the amount that it is required to reduce the phase velocity in the attenuated region necessitates the cylinder 64 being somewhat larger than the cylinders 59, 60 disposed about the unattenuated regions. In this manner the wave transmission path is maintained uniform throughout the wave transmission path and at the same time, the dispersion of the path is made anomalous.

In the operation of the oscillator, oscillations are restricted to a single mode by band pass filter 55. The frequency of the oscillations are tuned through this mode by varying the velocity of the electron stream along the wave transmission path. The velocity of the electron stream is preferably varied by changing the potential impressed on cathode 22 of electron gun 20. As previously pointed out, the frequency range through which the oscillator may be electronically tuned in this manner is substantially increased by making the wave transmission path anomalously dispersive in accordance with the present invention.

In order to explain more clearly the operation of the present invention, an analogy may be made to a conventional transmission line where the phase velocity of a propagated wave varies inversely as the square root of the product of the series inductance and shunt capacitance per unit length of the line. In this respect, the conductive strips 61 have no substantial effect on the series inductance of the helix 36 in that they are disposed lengthwise therewith, noting that there is no inductive coupling between conductors at right angles to each other. Conductive strips 61 do, however, substantially increase the effective shunt capacitance of the helix 36 to effect a decrease in the phase velocity of a wave propagated by the helix 36 in accordance with the above relation.

As the transit time required for current flow along strips 61 is a finite length of time, their effect with respect to increasing the shunt capacitance of helix 36 increases as the frequency of the propagated wave is decreased. This effect is particularly noticeable where the period of the propagated wave is comparable to this transit time.

It is apparent from the structure shown in Fig. 1 and the foregoing teachings that the apparatus of the present invention may be incorporated with any traveling-wave tube having an attenuating region along a portion of the wave transmission path to reduce the phase velocity along the remaining portion of the path to make the phase velocity uniform for the entire length of the path. In this case, the ratio of the diameter of the cylinder constituting conductive strips 61 and dielectric material 62 to the diameter of the helix 36 would be a function of the characteristics of the resistive coating (i. e. the extent to which the electric fields external to the helix are attenuated) and the dielectric constant of the material interposed between the helix 36 and the cylinder. In this respect, the proper ratio is a matter of design to be determined by the particular characteristics of the tube.

In addition to the above, the present invention may also be employed to provide a delay line for delaying a wide range of frequencies by a constant period of time. A delay line of this type could be incorporated into a traveling-wave tube to provide an ultra wide-band traveling-wave microwave amplifier tube. This ultra wide-band amplifier is obviously realized because waves of the entire band of frequencies are all propagated at the same velocity in synchronism with the electron stream velocity so as to effect substantially uniform gain at any frequency within the band.

This constant time delay structure is provided by employing a cylinder 59 constituting a plurality of conductive strips 61 disposed uniformly about the helix 36 lengthwise along the entire length of the delay path in the same manner as shown in Figs. 1 and 2. In this case, however, the ratio

$$\frac{b}{a}$$

of the radii of Fig. 2 is made approximately equal to the quantity

$$\left[2.5-\frac{1}{\epsilon_r+0.18}\right]$$

wherein ϵ_r is the relative dielectric constant of the intervening medium between the helix **36** and the conductive strips **61**.

What is claimed as new is:

1. In a traveling-wave tube having a conductive helix for propagating electromagnetic waves along a path whereby the higher frequency components of said waves are propagated along said path at velocities less than the lower frequency components, and having electron beam means for projecting a beam of electrons in interacting relation with the helix, means comprising a plurality of longitudinal conductors disposed lengthwise of and spaced uniformly about said helix to cause the lower frequency components of said waves to be propagated along said path at velocities less than the higher frequency components, and a medium having a predetermined relative dielectric constant, ϵ_r, different from that of a vacuum, interposed between said helix and said plurality of longitudinal conductors, the ratio of the inside diameter of the cylinder formed by said plurality of longitudinal conductors to the outside diameter of said helix being less than the quantity

$$\left(2.5-\frac{1}{\epsilon_r+0.18}\right)$$

2. A broadband traveling-wave amplifier tube including a conductive helix for propagating an electromagnetic signal wave over a wave transmission path, electron beam means for projecting a beam of electrons in interacting relation with said helix, a plurality of longitudinal conductors disposed lengthwise of and spaced uniformly about said helix, and a medium having a predetermined relative dielectric constant, ϵ_r, interposed between said helix and said plurality of longitudinal conductors, the ratio of the inside diameter of the cylinder formed by said longitudinal conductors to the outside diameter of said helix being substantially equal to

$$\left[2.5-\frac{1}{\epsilon_r+0.18}\right]$$

whereby all the frequency components of said signal wave are propagated along said path at substantially the same velocity.

3. A traveling-wave tube delay line comprising electron beam producing means for providing an electron stream, a conductive helix disposed about said stream in energy exchange relation therewith for propagating an electromagnetic signal wave over a wave transmission path, a plurality of longitudinal conductors disposed lengthwise of and spaced uniformly about said helix and spaced from each other by a distance which is very small relative to the diameter of said helix, and a medium of predetermined dielectric constant, ϵ_r, interposed between said helix and said plurality of longitudinal conductors, the ratio of the inside diameter of the cylinder formed by said longitudinal conductors to the outside diameter of said helix being substantially equal to

$$\left[2.5-\frac{1}{\epsilon_r+0.18}\right]$$

whereby all the frequency components of said signal wave are propagated along said path at substantially the same velocity.

4. A microwave oscillator comprising a conductive helix having an input circuit and an output circuit at opposite extremities thereof, a plurality of longitudinal conductors disposed lengthwise of and spaced uniformly about said helix, a medium having a predetermined dielectric constant, ϵ_r, interposed between said helix and said plurality of longitudinal conductors, the ratio of the inside diameter of the cylinder formed by said longitudinal conductors to the outside diameter of said helix being less than

$$\left[2.5-\frac{1}{\epsilon_r+0.18}\right]$$

to effect an anomalous dispersion, D, in said helix, means for producing an electron stream, and means for directing said electron stream contiguously along the length of said helix; a filter having an angular frequency passband coextensive with a predetermined tuning range, $\Delta\omega$, having a mean frequency, ωm; and means including said filter coupled from said output circuit to said input circuit to provide a feedback loop to restrict the operation of said oscillator to a single mode of oscillation coextensive with said predetermined tuning range whereby an integral number, η, wavelengths exist about said feedback loop whence said tuning range, $\Delta\omega$, is approximately equal to

$$\frac{\omega m}{\eta(1-D)}$$

whereby the velocity of said electron stream along the length of said helix may be varied to electronically tune said oscillator to a desired frequency within an unusually large tuning range.

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