Sept. 10, 1957 | A. V. HAEFF | 2,806,177

SIGNAL DELAY TUBE

Filed May 5, 1953 | 4 Sheets-Sheet 1

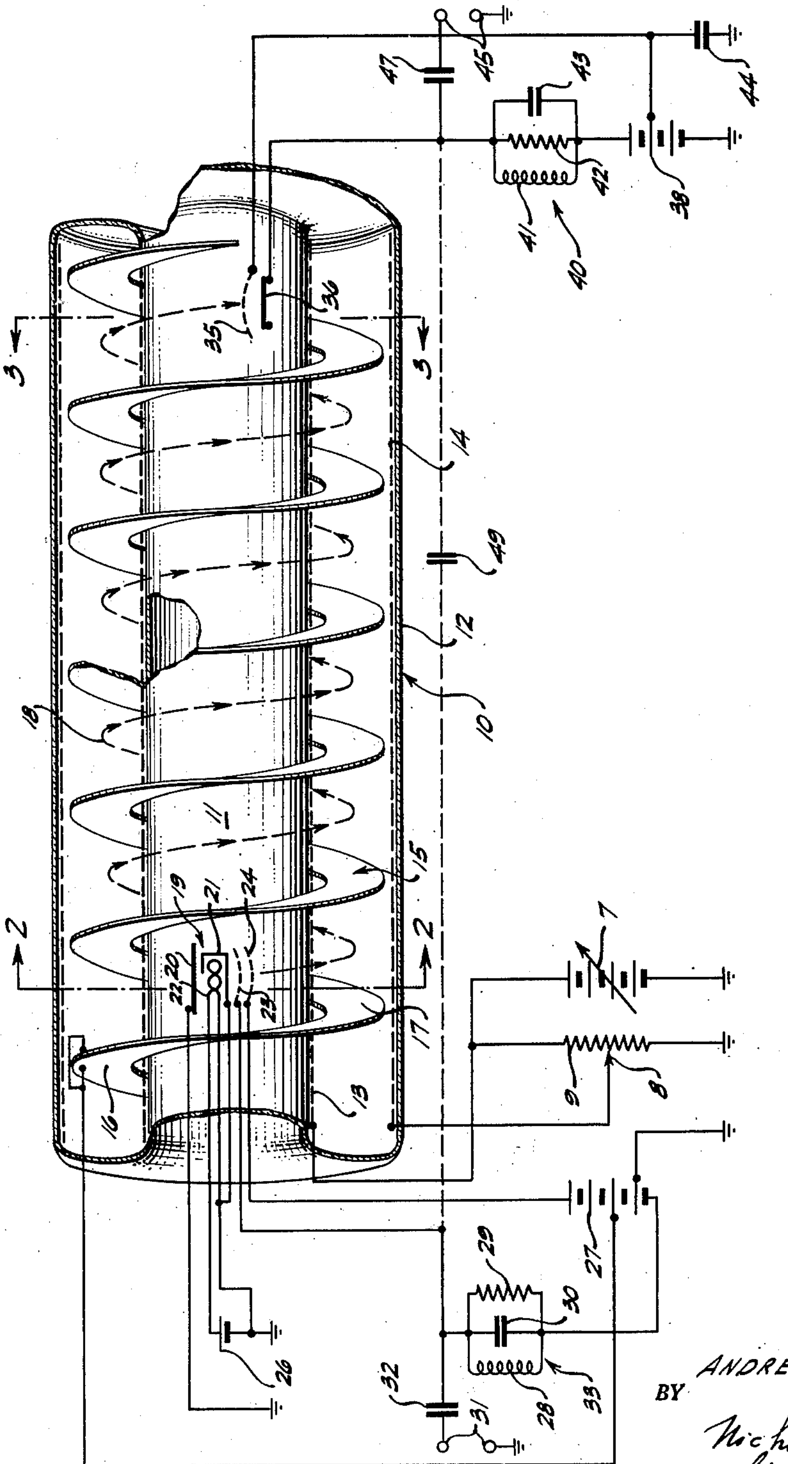

FIG. 1.

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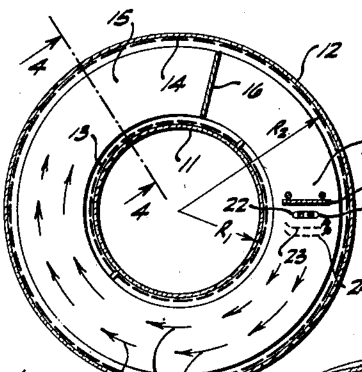


FIG. 2.

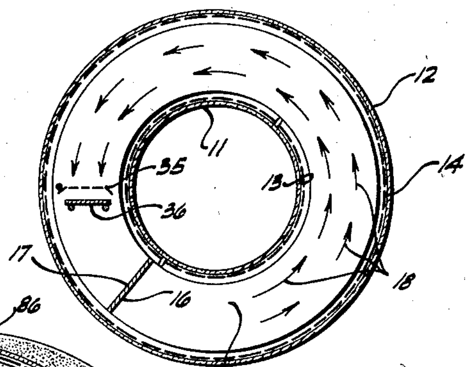


FIG. 3.

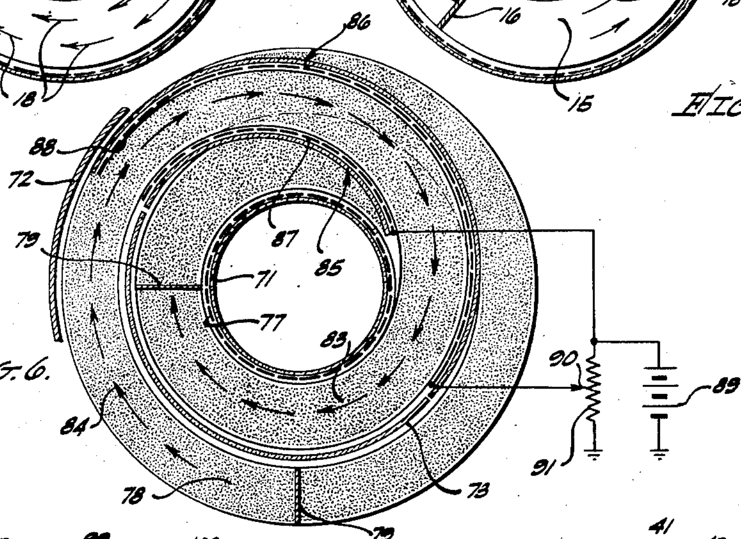
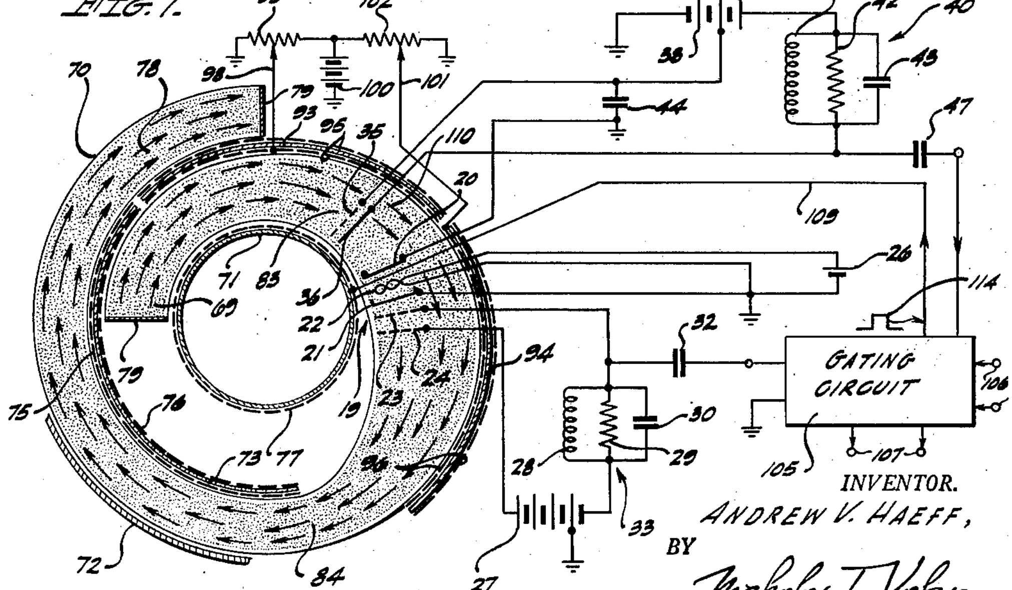


FIG. 6.

FIG. 7.



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SIGNAL DELAY TUBE

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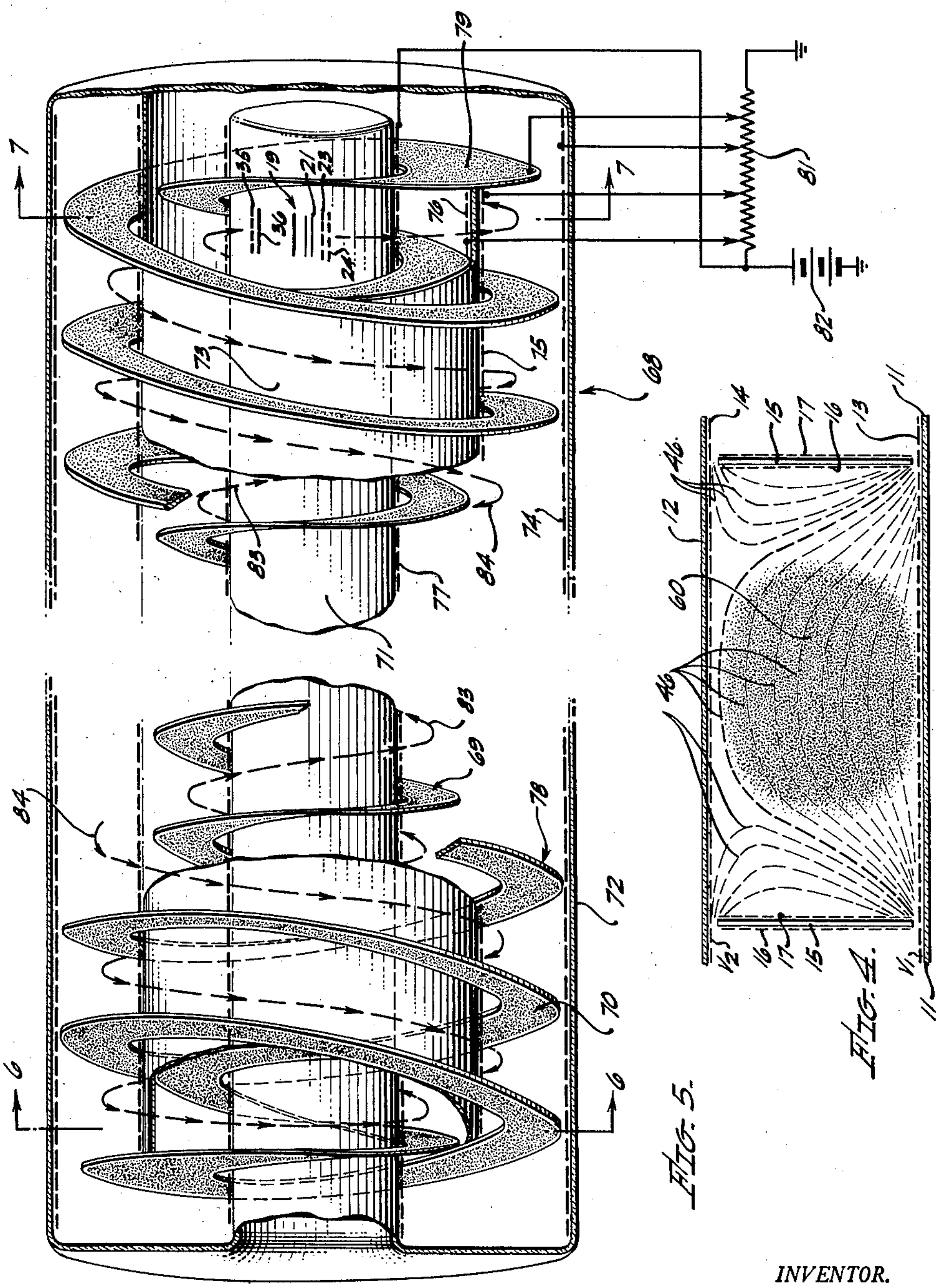

FIG. 5.

FIG. 4.

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SIGNAL DELAY TUBE

Filed May 5, 1953 4 Sheets-Sheet 4

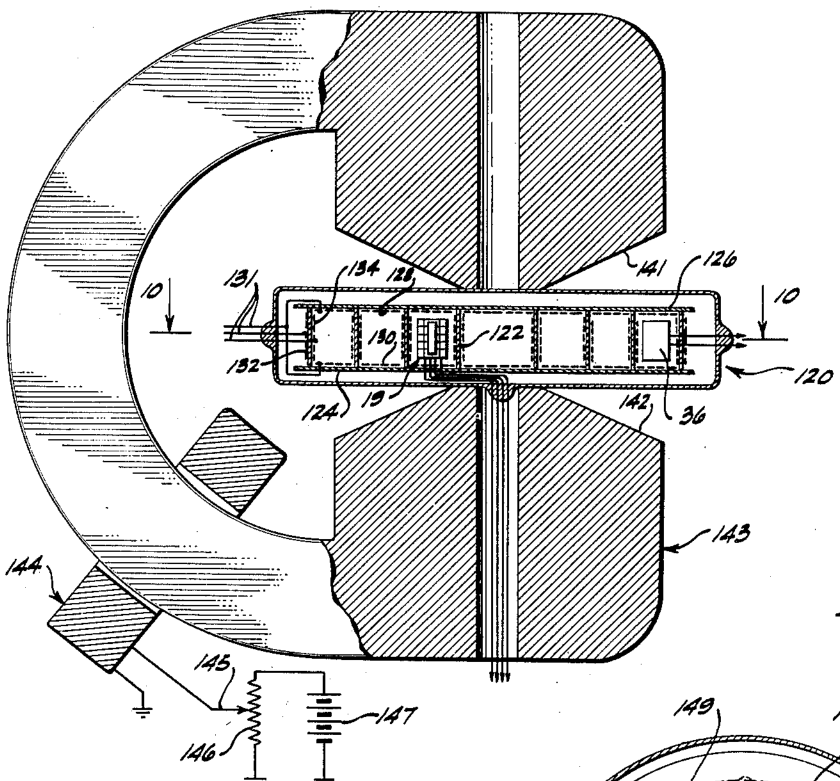


FIG. 8.

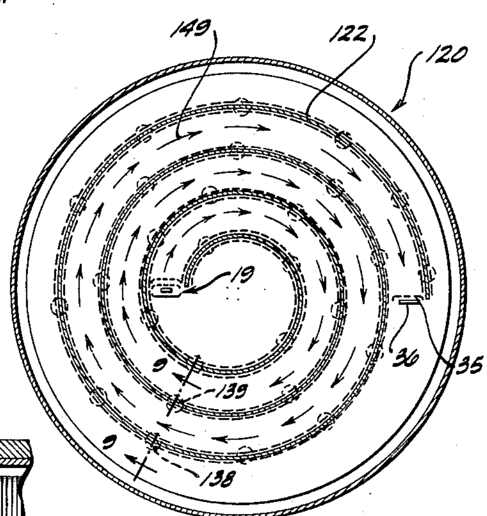
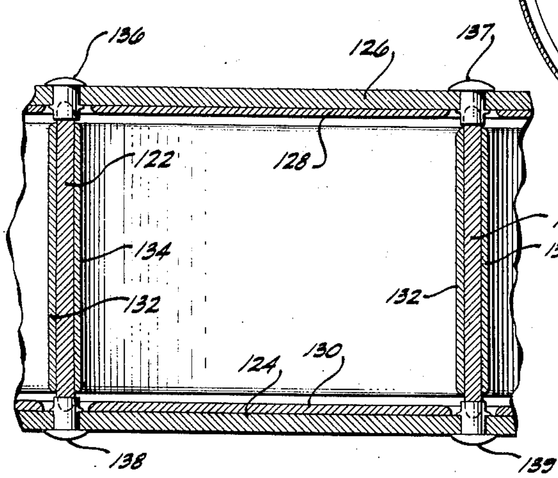


FIG. 10.

FIG. 9.



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United States Patent Office

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Patented Sept. 10, 1957

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SIGNAL DELAY TUBE

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Application May 5, 1953, Serial No. 353,119

2 Claims. (Cl. 315—39.3)

This invention relates to signal delay devices and more particularly to electron tubes wherein signal information is propagated by an electron stream which is directed along a helical path at a relatively low velocity so that an output signal may be obtained with a substantial time delay with respect to an input signal.

There exists a need for devices which delay a signal by a substantial period of time to compare, for example, two or more signals not concurrent in time. As is commonly known, a transmission line may be made to function as a delay line. Space limitations, however, usually require the use of lumped parameters to represent or simulate the distributed parameters of the transmission line, thus restricting the frequency response and time delay of the device. It is also well known that most prior art signal delay devices have considerable signal attenuation and distortion. In addition, most conventional signal delay devices have a restricted frequency bandpass and a fixed time delay period which may change with temperature or signal frequency. All of these disadvantages of prior art signal delay devices have been minimized or overcome by the electron delay tubes of the present invention.

Electron tubes in accordance with the present invention comprise an electron gun for producing an electron stream, and a control element for modulating the density of the electron stream with the signal to be delayed. The electron stream is made to traverse a long "delay" path, this path being a helix in some embodiments and an expanding spiral in another, for producing a compact tube. The electron stream is electrostatically and dynamically focused over its entire distance of travel. Finally, the tube includes output means having a screen grid and a plate or collector to intercept the electron stream and convert the signal information carried by the stream into an output signal delayed in time with respect to the input signal.

The disclosed delay tubes are capable of counteracting signal attenuation by directing the electron stream propagating the signal contiguous to a member having a resistive surface for the entire length of the delay path. A detailed explanation of amplifying a "space-charge wave" or density modulations propagated by an electron stream is described in Patent No. 2,740,917, "Electron Stream Amplifier Tube," issued April 3, 1956, to Andrew V. Haeff and assigned to the same assignee as in the present case. This amplification of a space-charge wave will be described in more detail hereinafter.

In the one embodiment of electron delay tube wherein the electron stream is directed along a helical path, the electron stream is initially caused to follow a circular path by dynamically balancing the forces acting on the electrons of the stream. In order to transform this circular path of the electron stream into the desired helical path, the electron stream is directed between the walls of an edge-wound helix. In an alternate embodiment of electron delay tube, the electron stream is

directed along an expanding spiral path by the use of magnetic and electric fields.

As explained previously, there are located at the end of the delay path of the electron stream, a screen grid and a plate or collector positioned so as to intercept the stream electrons for the purpose of converting the space charge condensations or density modulations of the stream into an output signal that is delayed in time with respect to the input signal. It is to be noted that the signal delay obtained by the tubes of the present invention may be varied by merely changing the velocity of the stream electrons traveling along the spiral delay path.

In addition to the above, the disclosed signal delay devices have a wide frequency bandpass characteristic and furthermore, may be designed to delay signals which may have a frequency within the range of from 100 to 3000 megacycles without introducing attentuation. It is to be noted that the range of frequencies from 100 to 3000 megacycles is generally included in the very high frequency and ultra high frequency ranges.

It is therefore an object of this invention to provide a device having a broad frequency bandpass characteristic for delaying microwave signals without causing signal attenuation.

A further object of this invention is to provide a stream type electron tube having a short length and small volume for delaying microwave signals.

Another object of this invention is to provide a stream type electron tube for delaying microwave signals, the tube having a desired amount of gain which may be selected to suit any particular application.

Still another object of this invention is to provide a stream type electron tube capable of delaying a microwave signal by an adjustable period of time.

The novel feature which is 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 drawings in which an embodiment of the invention is illustrated by way of example. It is to be expressly understood, however, that the drawings are for the purpose of illustration and description only, and are not intended as a definition of the limits of the invention.

Fig. 1 is a sectional view of a preferred embodiment of the invention together with associated circuitry;

Figs. 2 and 3 are sectional schematic views taken along lines **2—2** and **3—3** of Fig. 1, respectively;

Fig. 4 is a sectional schematic view taken along line **4—4** of Fig. 2 and illustrating the electron stream and equipotential lines;

Fig. 5 is a schematic sectional view of an alternative embodiment of the invention having a continuous delay path and associated energizing circuits;

Figs. 6 and 7 are sectional schematic views taken along lines **6—6** and **7—7** of Fig. 5, respectively, and associated circuits;

Fig. 8 is a schematic elevational view partly in section of a modified embodiment of the invention incorporating a spiral delay path; and

Figs. 9 and 10 are sectional schematic views taken along lines **9—9** and **10—10** of Figs. 10 and 8, respectively.

Referring to Fig. 1, there is shown one embodiment of an electron delay tube which comprises an envelope **10**, preferably of glass, for providing an evacuated chamber of annular shape formed by two concentric glass cylinders, namely, an inner cylinder **11** and an outer cylinder **12**, the two cylinders being joined together and sealed at their ends as shown in the drawing. Resistive coatings **13** and **14**, such as, for example, tin-oxide, are deposited on the outer surface of the inner cylinder **11**, and on the inner surface of the outer cylinder **12**, respectively.

Resistive coatings **13**, **14** provide means for maintaining a static charge over the outer and inner surfaces of inner cylinder **11** and outer cylinder **12**, respectively. The tube of the invention requires that different potentials be applied to resistive coatings **13**, **14** so as to produce a radial potential gradient between the cylinders **11**, **12** throughout the length of the tube. In accordance with the present invention, an adjustable positive potential with respect to ground is applied to resistive coating **13** by means of a connection to a potential source **7** and an adjustable smaller positive potential is applied to resistive coating **14** by means of a connection to an adjustable contact arm **8** of a potentiometer **9** which is, in turn, connected across potential source **7**. These potentials may, for example, be of the order of +10.4 and +9.6 volts positive with respect to ground, respectively.

An edge-wound helix **15**, made of a flat ribbon, is inserted between the cylinders **11** and **12**. This edge-wound helix extends over the complete length of the tube in the axial direction and is spaced from and extends radially between cylinders **11**, **12**. Helix **15** is preferably fabricated from insulating material such as, for example, sheet mica, although conductive materials can be used if desired. In case an insulating material is used, the flat surfaces of the edge-wound helix **15** are painted or otherwise coated with a suitable conductive material such as an aqueous solution of graphite to provide resistive coatings **16** and **17**. Resistive coatings **16**, **17** of the edge-wound helix **15** are in electrical contact with each other, but care should be taken so that they do not electrically contact resistive coatings **13** and **14** on the concentric cylinders **11**, **12** so that coatings **13**, **14** can be maintained at different potentials. Thus, a helical path indicated by dotted arrows **18** is formed between the resistive coatings **13**, **14**, **16** and **17** within the evacuated annular space provided by envelope **10**. The resistance of resistive coatings **13**, **14**, **16**, **17** depends on the desired amplification or attenuation of the signal to be delayed along spiral path **18**, a representative resistance value for the resistive coatings being 10,000 ohms per square centimeter.

In case edge-wound helix **15** is made of conductive material, it should be mounted so as to be insulated from resistive coatings **13**, **14** of cylinders **11**, **12**. A suitable positive potential is applied to resistive coatings **16**, **17** so as to provide a desired electric field configuration along helical path **18** as illustrated in Fig. 4. This potential may be of the order of +8 volts with respect to ground and is applied by a connection of both coatings **16**, **17** to an appropriate terminal or tap of a potential source **27**.

An electron gun **19**, for launching an electron stream, is located at the beginning or left hand portion of helical path **18** and comprises a shield **20**, a cathode **21** with a heater **22**, a control grid **23** and a screen grid **24**. A side view of the electron gun **19** showing its position with respect to concentric cylinders **11**, **12** is illustrated in Fig. 2. Returning to Fig. 1, heater **22** of electron gun **19** is connected across a potential source **26**, the negative terminal of which is connected to cathode **21**, which in turn is connected to ground. A bias of, for example, −2 volts is maintained on control grid **23** by the negative terminal of potential source **27**, which is applied through the parallel combination of an inductor **28**, a resistor **29** and a capacitor **30** which constitutes a broadly resonant input circuit **33**. An intermediate tap of potential source **27** is connected to ground as shown. The input signal to be delayed is applied to input terminals **31** and through a coupling capacitor **32** to the input circuit **33** and to the control grid **23**.

An appropriate potential is applied to screen grid **24** of electron gun **19** so as to accelerate the electrons emitted from cathode **21** and project them along helical path **18**. This potential may be of the order of +10 volts with respect to ground and is applied to screen grid **24** by means of a connection to the positive terminal of potential source **27**. The magnitude of the potential applied to screen grid **24** depends on the desired radius of the helical path **18** and on the potentials applied to resistive coatings **13**, **14**.

Located at the opposite or right hand extremity of helical path **18** are a screen grid **35** and a plate **36**, in a plane perpendicular to the longitudinal axis of the tube, as illustrated in Fig. 3, which also shows a cut portion of the edge-wound helix **15**. Returning again to Fig. 1, a positive potential of the order of 12 volts with respect to ground is applied to plate **36** by a connection to the positive terminal of a potential source **38**, having its negative terminal grounded through a parallel resonant output circuit **40** consisting of an inductor **41**, a resistor **42** and a capacitor **43**. The frequency response characteristic of the tuned output circuit **40** may be generally similar to that of the input circuit **33**. Screen grid **35** is maintained at a suitable positive potential with respect to ground by a connection to an appropriate tap of potential source **38**, this tap being bypassed to ground by a capacitor **44**. The potential applied to screen grid **35** may be of the order of −4 volts with respect to the potential applied to plate **36** for preventing the secondary electrons emitted by the plate **36** from interfering with the flow of the electron stream. The output signal is available at output terminals **45**, one of which is connected to plate **36** through a capacitor **47**, the other one being grounded.

When the delay tube of the present invention is energized, electron gun **19** projects a continuous stream of electrons along helical path **18**. A cross section of the electric field along helical path **18** is shown in Fig. 4. In order to cause the electrons of the stream to follow helical path **18**, the average potential throughout the path with respect to cathode **21** of electron gun **19** must correspond to the desired accelerating potential for the stream electrons. In addition, the difference in potential between resistive coatings **13** and **14** must produce a radial potential gradient such that the outward centrifugal force acting on the stream electrons is counterbalanced by an inward electrostatic force. The potential applied to resistive coatings **16**, **17** on edge-wound helix **15** should be sufficiently negative with respect to the average potential of the center region of path **18** so that the radial potential gradient remains substantially constant across the width of the path and the component of the potential gradient normal to surfaces **16** and **17** exert forces on the stream electrons so as to keep them in the center region of the path. The stream electrons will then follow helical path **18** because they will be repelled by the potential maintained on resistive coatings **16**, **17** since it is negative with respect to the equivalent energy level represented by the potential of the center region of helical path **18** combined with the kinetic energy of the stream electrons normal to resistive coatings **16**, **17** of the edge-wound helix **15**.

In order for the electrostatic forces acting on the stream electrons to balance the centrifugal forces, it is necessary to satisfy the approximate equation:

$$\frac{V_1-V_2}{V_1+V_2}=2\left(\frac{R_2-R_1}{R_2+R_1}\right) \qquad (1)$$

wherein

V_1 is the potential applied to resistive coating **13** with respect to that of cathode **21** of electron gun **19**

V_2 is the potential applied to resistive coating **14** with respect to that of cathode **21** of electron gun **19**

R_1 is the outside diameter of inner cylinder **11**, and

R_2 is the inside diameter of outer cylinder **12**

As indicated, Equation 1 is an approximation insofar as it does not take the axial velocity component of the stream electrons into consideration.

The delay tube of the present invention is operated by applying a signal to be delayed through input terminals **31** and capacitor **32** across input circuit **33** to control grid

23 of electron gun 19, thereby to modulate the density of the electrons emanating from cathode 21 in accordance with the signal. The modulation of the electron stream exists in the form of space charge condensations or current modulations of the stream. These space charge condensations are propagated by the electron stream in the form of a space charge wave along the helical path 18 followed by the stream.

In order to prevent undue attenuation of the space charge wave propagated by the electron stream, or, if desired, to produce amplification of the wave, the electron stream is caused to flow contiguous to the conductive coatings 13, 14, 16, 17. The space charge condensations of the electron stream representative of the signal, produce corresponding electric field variations which, in turn, induce currents in the adjacent resistive coatings 13, 14, 16, 17, thereby producing, in turn, electric fields which interact with the stream electrons. Hence, the modulations of the stream are attenuated or amplified as desired. In order to provide signal amplification, the resistive coatings 13, 14, 16, 17 which are contiguous to the electron stream, are made to have a predetermined conductivity in order that the phase of the reaction fields produced by the currents induced in these coatings is such as to produce increased space charge condensations or "bunching" of the stream electrons with the concomitant growth of the amplitude of the space charge wave as it is propagated by the electron stream. The conductivity of the resistive coatings 13, 14, 16, 17 may also be chosen so as to provide attenuation of the space charge wave, if desired.

Consequently, appreciable amplification of the space charge wave is attainable only when conductive coatings 13, 14, 16, 17 have such surface resistivity or conductivity, σ, which will produce proper phase relationship between the electrons of the stream and the electric fields induced along the coatings. By surface resistivity is meant the actual resistance to an electrical wave per unit area of surface. In the case of a conductive coating such as tin-oxide on glass, the direct-current resistance per unit area approximates the value of surface resistance offered to a wave since the thickness of the coating in this case is less than the usual skin depth encountered at the frequencies used. In the case of a thick material, the surface resistivity is approximately equal to the direct-current resistance per unit area of a sheet of the material having a thickness equal to the skin depth. The choice of the surface resistivity required for optimum amplification per unit length of the surface depends on the signal frequency, the separation between the electron stream and the conductive surface, the electron velocity, and the dielectric constant of the material forming the surface contiguous to the electron stream. In normal practice, typical values of surface resistivity that provide amplification of the space charge wave will be found to range from 500 to 10,000 ohms per square centimeter. Optimum amplification of the space charge wave is obtained for an angular frequency, ω, when the material contiguous to the electron stream satisfies the following relation:

$$\frac{\sigma}{\omega\epsilon_0\epsilon_1}=\sqrt{3} \tag{2}$$

wherein

σ is the conductivity of the material
ϵ_1 is the real part of the relative dielectric constant of the material
ϵ_0 is the absolute dielectric constant of free space, and
ω is angular frequency of the signal

When the foregoing conditions are satisfied, the maximum gain, G, in decibels per centimeter, can be estimated from the following formula:

$$G=8.7\sqrt{\frac{J_0}{3\epsilon_1 V_0^{3/2}}} \tag{3}$$

where,

J_0 is the current density of the electron stream in amperes/square centimeters; and
V_0 is the potential in kilovolts through which the stream electrons are accelerated

It is to be noted that the Equation 3 applies for optimum amplification which may not necessarily be desired in a particular embodiment of the electron delay tube of the invention.

The stream electrons propagating the space charge wave progress around the helical path 18 until they are intercepted by the screen grid 35 and plate 36. The density of the electron stream has been modulated, and hence when the electrons of the stream are intercepted by plate 36, they will be converted to a delayed output signal developed across the output circuit 40. The delayed output signal is available at output terminals 45.

To explain more adequately how the electron stream is caused to follow helical path 18, reference is again made to Fig. 4. Loci of equipotential points, as measured with respect to the potential of the source of electrons, cathode 21, are indicated by dashed lines 46. Proceeding from resistive coating 13 on the inner cylinder 11 (shown at the bottom of Fig. 4) of envelope 10 to resistive coating 14 on the outer cylinder 12 (shown at the top of Fig. 4) of envelope 10, the equipotential lines 46 may have values which decrease, for example, from 10.4 volts to 9.6 volts with respect to the potential of the source of the stream electrons. The potential at which both the resistive coatings 16, 17 of edge-wound helix 15 are maintained, produces electrostatic fields which may be represented by equipotential lines indicating a negative potential with respect to the equipotential lines indicative of the electrostatic fields produced by the potentials on resistive coatings 13, 14, an approximate configuration being illustrated in Fig. 4.

The electrostatic forces on an electron in the plane of Fig. 4 are, of course, normal to the equipotential lines and are proportional to the potential gradient. The electrostatic forces produced must have a radial component sufficient to counterbalance the centrifugal forces on the stream electrons which exist in the center dotted region 60 of Fig. 4 and, in addition, must have components forcing the stream electrons towards the center region 60 of the path 18 to counteract the natural tendency of bunched electrons to expand. The electrostatic forces increase as resistive coatings 16 or 17 on the edgewound helix 15 are approached because of the denser concentration of the equipotential lines 46. Thus, the potential applied to resistive coatings 16, 17 may be adjusted so that the radial forces acting on the electrons and counterbalancing the centrifugal forces remain essentially unchanged while the added components of force tend to keep the stream electrons within the center region 60 of the path 18.

The stream electrons flow essentially normal to the cross section of the helical path 18 and occupy, for the most part, a region indicated by the dotted area 60 as shown in Fig. 4. The stream electrons have essentially a zero transverse velocity, that is, they have nearly zero kinetic energy in a direction normal to the walls formed by edge-wound helix 15. Since the stream electrons are flowing in a region having a negligible velocity component with which they might overcome the decrease in potential in order to proceed towards the walls formed by edge-wound helix 15, the electrons will necessarily continue to flow in the more positive center region 60 of the path 18. As mentioned previously, resistive coating 13 is maintained at a potential that is sufficiently positive with respect to that of resistive coating 14 so as to overcome the centrifugal force acting on the stream electrons.

In the embodiment of the present invention described in connection with Figs. 1 to 4, the path of the electron stream can be made as long as desired, limited only by the size of the tube and the mean free path of the electrons. For example, a helical path 18 having an average diameter of 10 centimeters, a pitch of two turns per centimeter, a total length of 30 centimeters, and an electron velocity of 10 volts will produce a delay time of the order of 10 microseconds. As mentioned previously, the delay time may be varied, within limits, by merely varying the velocity of the stream electrons by means of potential source 7 (shown adjustable in Fig. 1) and adjustable contact arm 8 of potentiometer 9.

If desirable, a considerable increase in the delay time may be obtained by the use of a feedback arrangement for circulating the signal from the input circuit 33 through the delay tube to the output circuit 40 and back again through the feedback arrangement to the input circuit 33 as many times as desired. In this manner, very long delay times may be obtained, limited only by the noise generated in the tube and the selectivity of the input and output circuits 33, 40. The output signal may be fed back by the use of conventional circuitry such as, for example, a capacitor 49 connecting the output circuit 40 with the input circuit 33 as shown in dotted lines in Fig. 1. The disadvantage of using this type of feedback is that the frequency response is progressively narrowed each time the signal is circulated because of the relative attenuation caused by the tuned input and output circuits 33, 40 of the outer portions of the frequency band of the signal with respect to the center signal frequency.

In order to circumvent the relatively narrow frequency response obtainable with such an external feedback loop, another embodiment of the disclosed invention illustrated in Figs. 5, 6 and 7 uses electronic feedback. In this modification of the invention, feedback is accomplished by modulating a portion of the electron stream immediately after it is launched from an electron gun by means of interaction with a bypassed portion of the same electron stream after it has propagated a signal over a delay path as shown particularly in Fig. 7. In a practical application of an electronic feedback type of electron delay tube, the time duration of the signal to be delayed, obviously cannot be longer than the time delay obtained by a single traversal of the electrons along the delay path of the tube, since an electron stream cannot, without complications, propagate more than one distinct signal at a time within one predetermined frequency range. An electron delay tube of this type may, for example, be "gated" on to receive the signal to be delayed, and then after the electron stream has propagated the signal around the delay path a desired integral number of times, the output circuit could be gated so as to allow the delayed signal to appear at a pair of output terminals. Since the electron stream would continue to propagate the signal around the delay path, it is necessary that the tube be cleared before a new signal to be delayed is applied.

Referring now to Fig. 5, there is illustrated an electron delay tube of the electronic feedback type. An evacuated envelope 68 formed by an inner cylinder 71 and a concentric outer cylinder 72, closed at their right hand ends and joined at their left hand ends, provides an annular evacuated chamber for the electron stream. An intermediate concentric cylinder 73 is positioned midway between inner cylinder 71 and outer cylinder 72. A resistive coating 74 is deposited on the inner surface of outer cylinder 72, resistive coatings 75 and 76 are deposited on the outer and inner surfaces of concentric cylinder 73, respectively, and a resistive coating 77 is deposited on the outer surface of inner cylinder 71. As explained before, these resistive coatings may be of tin-oxide or other suitable resistive material.

A continuous edge-wound helix 78 is positioned between the three concentric cylinders 71, 72, 73 as illustrated in Fig. 5, and has a function similar to that of helix 15 of Fig. 1. Edge-wound helix 78 comprises an inner and an outer concentric edge-wound helix 69 and 70, respectively, connected together at both of their ends by transition turns, each consisting of a fraction of a turn, so as to form a single continuous member. Inner edge-wound helix 69 forms a right-hand screw thread and outer edge-wound helix 70 forms a left-hand screw thread. Hence, when the inner and outer edge-wound helices 69 and 70 are disposed concentric to each other and connected together at both of their ends by the transition turns, the intervening space between the flat surfaces forms a continuous chamber for the delay path. As before, edge-wound helix 78 may be made of an insulating material such as, for example, mica, having a resistive coating 79 deposited on both of its flat surfaces as shown in Fig. 5. As in Fig 1, a potential is applied to resistive coating 79 by means of a connection or lead to a potential divider 81 connected across a potential source 82, having its negative terminal grounded as shown. Potential divider 81 also provides suitable potentials for conductive coatings 74, 75, 76 and 77, respectively, by leads connected to suitable taps or potential divider 81. The positive potential applied to resistive coating 77 is greater than that applied to resistive coating 76 and the positive potential applied to resistive coating 75 is greater than that applied to resistive coating 74 by amounts sufficient to produce radial electric fields for balancing the centrifugal forces on the stream electrons. The average value of the potentials applied to resistive coatings 77, 76 and 75, 74, respectively, should be approximately equal to the velocity of the stream electrons expressed in electron volts. The value of the potential applied to conductive coating 79 on edge-wound helix 78 is, of course, dependent on the potentials at which resistive coatings 74, 75, 76 and 77 are maintained.

The embodiment of the electron delay tube of Fig. 5 includes an electron gun and output means located in the space provided by the transition turns at the right extremity of edge-wound helix 78 as viewed in Fig. 5 and arranged as illustrated in Fig. 7. Inasmuch as the electron gun and the means for converting the space charge condensations of the electron stream into an output signal may be the same as illustrated for the delay tube of Fig. 1, the same electron gun and signal converting means together with associated circuitry will be described in connection with the delay tube illustrated in Fig. 5. Electron gun 19, screen grid 35 and plate 36 are disposed in the space provided by one transition turn of edge-wound helix 78 so that the returning electron stream may be made to partially bypass them, a bypassed portion 110 of the electron stream combining with the new stream electrons 111 emanating from electron gun 19, as illustrated in Fig. 7. The potentials applied to the electrodes of electron gun 19, screen grid 35 and plate 36 may be the same as for the electron delay tube of Fig. 1 so that further description is not needed here.

A complete delay path for the electron stream in the described electron delay tube comprises an inner helical path 83 formed by the intervening space between the flat surfaces of edge-wound helix 69 and an outer helical path 84 formed by the intervening space between the flat surfaces of edge-wound helix 70. A transition turn of the delay path is located at each extremity of both the inner and outer helical paths 83, 84. The transition turns are provided for the electron stream at the right hand end of the edge-wound helix 78 by decreasing the radial electric field to allow the stream electrons to change from the inner helical path 83 to the outer helical path 84 and at the left hand end of helix 78, by increasing the radial electric field to cause the stream electrons to change from the outer helical path 84 to the inner helical path 83. In making the transition, the electron stream is bounded axially, with respect to the length of the tube, by the edge-wound helix 78, as shown in Fig. 5.

It is to be noted that transition elements for radially bounding the electron stream at the extremities of edge-wound helix 78 are not shown in Fig. 5 in order to avoid confusion. To illustrate more clearly the manner in which a radial boundary for the electron stream is provided, reference is made to Figs. 6 and 7. In these figures, only a portion of outer cylinder 72 sufficient to show its relative position has been illustrated. Referring to Fig. 6, elements of a transition turn from outer helical path 84 to inner helical path 83 comprise two semi-circular transition elements 85 and 86 which have appropriate widths so as to fit in between the end turn at the left extremity of edge-wound helix 78 as viewed in Fig. 5, semi-circular transition element 85 being disposed tangential to concentric cylinders 71 and 73 and semi-circular transition element 86 being disposed parallel to element 85 and tangentially to concentric cylinders 72 and 73. Transition elements 85, 86 provide means for increasing the radial electrostatic field so as to change the radius of curvature of the stream electrons from the radius of the outer helical path 84 to the radius of the inner helical path 83 and at the same time form a radial boundary for the electron stream during the transition from path 84 to path 83.

Transition elements 85, 86 may be composed of glass having resistive coatings 87 and 88, respectively, to which are applied appropriate potentials so as to change the radius of curvature of the electron stream in order to accomplish the transition. At the same time, the potentials applied to transition elements 85, 86 should have an average value so as to maintain the velocity of the electron stream substantially constant. A suitable potential is applied to resistive coating 87 of transition element 85 by a connection to the positive terminal of a potential source 89, having its negative terminal grounded. A potential less than that applied to resistive coating 87, is applied to resistive coating 88 of transition element 86 by a connection to an adjustable tap 90 of a potentiometer 91, which, in turn, is connected across potential source 89.

Transition elements 93 and 94 provide means for introducing an appropriate radial electrostatic field within the second or right-hand transition turn for controlling the portion of the electron stream that bypasses plate 36 and electron gun 19 and combines with the newly generated electron stream. Transition elements 93 and 94 have resistive coatings 95 and 96 on both flat surfaces of the elements, respectively, and are disposed as illustrated in Fig. 7. In order not to confuse the drawing, transition elements 93 and 94, together with associated circuitry, are not shown in Fig. 5. As illustrated in Fig. 7, transition elements 93 and 94 are each one-quarter circular segments disposed end to end so as to form a semi-circular structure which is positioned tangentially to concentric cylinders 72 and 73, so as to enclose screen grid 35, plate 36 and electron gun 19. Transition elements 93 and 94 also extend in an axial direction between the walls of the right-hand end turns of edge-wound helix 78. An adjustable positive potential is applied to resistive coating 95 by a connection to an adjustable tap 98 of a potentiometer 99 which is connected across a potential source 100. Similarly, resistive coating 96 is maintained at a suitable positive potential by a connection to an adjustable tap 101 of a potentiometer 102 which is connected across the potential source 100.

As previously mentioned, in the embodiment of the electron delay tube of Fig. 5, a signal is applied only for the interval of time required for the electron stream to propagate the signal once over the entire length of inner and outer helical paths 83, 84. The electron stream propagates this signal around the closed delay path for a desired integral number of times after which it is caused to appear at the output terminals. The modulated electron stream may then be collected so that the tube is cleared to receive a new signal to be delayed. Accordingly, a gating circuit 105 having input and output terminals 106 and 107, respectively, is included to provide the necessary switching means. Gating circuit 105 is connected through capacitor 47 across output circuit 40 to plate 36 and through capacitor 32 across input circuit 33 to control grid 23 of electron gun 19. The electron delay tube of the present invention requires that the signal being delayed be cleared from the electron stream before it can be modulated again by a subsequent signal to be delayed. This may be accomplished, for example, by biasing the control grid 23 negatively or by momentarily attracting all of the stream electrons to one or more of the electrodes or conducting surfaces, thereby collecting the entire modulated portion of the electron stream. Means are provided for accomplishing this in synchronism with the gating by a positive voltage impulse 114 generated by gating circuit 105 which may be impressed, for example, on resistive coating 77 by means of a lead 109 which connects resistive coating 77 to gating circuit 105.

In the operation of the delay tube of the present invention illustrated in Figs. 5 to 7, a signal to be delayed is impressed on input terminals 106 and through gating circuit 105 and capacitor 32 to control grid 23 of electron gun 19 for modulating the density of the electron stream. The electron stream is first projected from electron gun 19 along the outer helical path 84. The potentials that are applied to resistive coatings 74, 75, 76, 77 and 79 are adjusted in the same manner as are those of the delay tube of Fig. 1 so that the stream electrons follow first the outer helical path 84 and then the inner helical path 83. The average of the potentials which control the paths 83, 84 and their transition turns is preferably maintained substantially constant so as to cause a minimum disturbance to the space charge condensations propagated by the electron stream.

After traversing outer helical path 84 and the inner helical path 83, the electron stream will reach the screen grid 35 and plate 36 as shown particularly in Fig. 7. The signal propagated by the electron stream is prevented from decaying by the interaction of the space charge condensations representative of the signal propagated by the electron stream and the electric fields produced by the currents induced in the resistive coatings 74, 75, 76, 77 and 79, contiguous to the paths 83, 84. It is essential that there be no significant interaction between the portions of the electron stream following inner and outer helical paths 83 and 84. Hence, the intermediate glass cylinder 73 should attenuate the electric fields between its resistive coatings 75, 76 in order to prevent interaction between the portion of the electron stream traversing path 83 and the portion of the electron stream traversing path 84. The surface resistivity and the thickness of the coatings 75, 76 may be chosen so as to effectively shield the electric fields of the inner helical path 83 from those of the outer helical path 84. Moreover, the resistivity of resistive coatings 74, 75, 76, 77 and 78 may be chosen so as to provide a desired amount of gain for the delayed signal.

When the modulated electron stream reaches the end of inner helical path 83 at the right extremity as viewed in Fig. 5, a portion 110 of it can be made to bypass the screen grid 35, plate 36 and electron gun 19 and re-enter the outer helical path 84 by adjusting the potential applied to resistive coating 95 of transition element 93, by means of tap 98, since this potential controls the radial electric field and hence, the radius of curvature of the electron stream just prior to the termination of the inner helical path 83. Therefore, the radius of the electron stream may be controlled so that a desired portion 110 of the stream electrons may be made to bypass plate 36 and electron gun 19 for modulating the electron stream emanating from electron gun 19 and the remaining portion caused to penetrate through screen grid 35 and impinge on plate 36, thus converting the space charge condensations propagated by the electron stream into a delayed output signal which is developed across the output circuit 40 and appears at output terminals 107 of gating circuit 105.

The potential applied to resistive coating 96 of transition element 94 controls the radial electric field and hence, the radius of curvature of the stream electrons **110** bypassing the screen grid **35**, plate **36** and electron gun **19** so as to project them along the outer helical path **84** in such a manner that they combine with the electron stream emanating from electron gun **19**. As described in connection with the electron delay tube illustrated in Fig. 1, the potential of resistive coating **79** on edge-wound helix **78** is maintained sufficiently negative with respect to the region where the stream electrons are flowing by a connection to an appropriate tap of potentiometer **81** (see Fig. 5) connected across potential source **82** in order to constrain and guide the stream along the delay path.

As previously specified, the portion **110** of the stream electrons bypassing screen grid **35**, plate **36** and electron gun **19** is made to re-enter outer helical path **84** by adjusting the potential applied to resistive coating **95** of transition element **93** by means of tap **98**. The portion **110** of the stream electrons then combines with the electrons emanating from electron gun **19**, thereby modulating the newly launched electron stream in accordance with the delayed signal. The manner in which an unmodulated electron stream is modulated by another modulated electron stream through the action of space-charge fields is described in detail in an article entitled, "The Electron-Wave Tube," by Dr. Andrew V. Haeff, which was published in the Proceedings of the I. R. E. Volume 37, No. 1, pages 4–10, January 1949. The signal to be delayed, in the form of modulations or space charge condensations of the electron stream, may then be circulated as many times as desired around the delay path of the tube. After the signal has been delayed by a desired amount, gating circuit **105** connects the output terminals **107**, to the output circuit **40**, for a period of time equivalent to that required for the signal to completely traverse the delay path and commencing an integral number of periods after the signal was initially impressed on the tube.

Before applying a subsequent signal to be delayed to the electron delay tube, it is necessary that the previously applied and delayed signal be cleared from the tube, that is, it is necessary that all intelligence in formation propagated by the circulating electron stream be eliminated.

As previously pointed out, this may be accomplished by having gating circuit **105** produce a sufficiently positive potential or pulse **114** for an interval of time equal to the time required for the electron stream to traverse the delay path of the tube and applying this potential by means of lead **109** to resistive coating **77** of cylinder **71** so as to upset the dynamic balance of the modulated stream electrons, thus collecting the modulated electron stream. This potential, of course, may be produced in synchronism with the gating operation performed by gating circuit **105**.

In Figs. 8, 9 and 10 there is illustrated an additional modification of an electron delay tube in accordance with the invention. In this embodiment, both magnetic and electrostatic fields are utilized to cause the electron stream to flow along a spiral path commencing at the center of the spiral and proceeding outwards along the spiral. The time required for the electron stream to propagate space charge condensations over the length of this spiral constitutes the desired delay time. In the case of the delay tubes illustrated in Figs. 1 and 5, the time delay was obtained by making the electron stream travel along the locus of a helix. The basic principles in all the delay tubes illustrated in the drawings remain the same, however, that is, an electron stream is modulated by a control grid whereupon it is guided along a long delay path contiguous to a resistive surface or surfaces in order to prevent detrimental attenuation or to provide amplification of the modulations of the electron stream.

More specifically, referring to the electron delay tube of Figs. 8 to 10, there is illustrated an envelope **120** shaped in the form of a flat circular cylinder for providing the necessary evacuated chamber for the tube. A spiral **122** fabricated from an insulating material such as, for example, mica is mounted between two flat circular insulating discs **124** and **126** within the envelope **120** for the purpose of providing a spiral path between the spiral **122**. Resistive coatings **128** and **130** are deposited on the circular discs **124**, **126**, respectively, between the walls formed by spiral **122** as shown by the enlarged cross section of the spiral path illustrated in Fig. 9. Resistive coatings **128**, **130** may be in electrical contact with one another by a suitable conductive connection. Resistive coatings **132** and **134** are deposited on opposite flat sides of spiral **122** as shown in Fig. 9 and are electrically insulated from one another and from resistive coatings **128**, **130**. Fasteners **136**, **137**, **138** and **139** are shown, by way of example, to illustrate how spiral **122** may be mounted between insulative discs **124** and **126**. By means of leads **131** (Fig. 8), suitable potentials are applied to resistive coatings **128**, **130** and **132** and **134**.

An electron gun **19**, screen grid **35** and plate **36**, (Fig. 10), together with associated circuitry, may be the same as illustrated and described for the delay tubes of Figs. 1 and 5. As shown in Fig. 10, the electron gun **19** is disposed at the beginning of the spiral path formed by spiral **122** and the screen grid **35** and plate **36** are disposed at the termination of the spiral path so as to intercept the electron stream produced by electron gun **19**. The position of the electron gun **19** is such that the electrons projected from the gun have a small outward radial component.

For the electron delay tube of Figs. 8 to 10, it is necessary to provide a progressively decreasing magnetic field from the center of the spiral path toward its outer evolution, the lines of force of the magnetic field being essentially normal to the insulating discs **124** and **126**, that is, normal to the plane of the paper in Fig. 10. Referring to Fig. 8, a magnetic field of this type is provided by disposing the evacuated envelope **120** containing the elements previously described between conical pole faces **141** and **142** of a low reluctance magnetic circuit **143**, such as, for example, a magnetic circuit composed of soft iron.

Envelope **120** is disposed between conical pole faces **141**, **142** so that the air gap increases in an outward direction along spiral **122**. A magnetomotive force is applied to magnetic circuit **143** by means of a solenoid **144** which is energized by a connection to contact arm **145** of a potentiometer **146** connected across a potential source **147**. The magnetomotive force applied to magnetic circuit **143** is, of course, controlled by the magnitude of the current allowed to flow through solenoid **144**.

As is commonly known, the magnetic flux density is directly proportional to the reluctance of the path. Consequently, the magnetic flux density, in proceeding from the center of pole faces **141**, **142** of the magnetic circuit **143** to their outer periphery, becomes decreasingly less dense because of the increasing reluctance.

In order to operate the described embodiment of electron delay tube, the electron stream is launched along the spiral path **149** by electron gun **19**. The electron stream is directed along the spiral path **149** to screen grid **35** and plate **36** by the combined effect of the magnetic field between pole faces **141**, **142** and a radial potential gradient produced by the potentials applied to resistive coatings **132**, **134**.

Since the electron flow emanating from electron gun **19** is not collimated, all of the electrons cannot be initially projected along the spiral path **149** in the same direction. Consequently, the individual electrons will follow different spiral paths whereby the initial directions of the spiral paths are distributed through an angular range which may be referred to as the divergence of the stream electrons upon leaving the electron gun **19**. The effect of the radial electric field and axial magnetic field is to cause the electron stream to be confined to the spiral path and to have "focal points" whenever two or more individual spirals intersect. The simultaneous use of the radial electric field and axial magnetic field makes it easier to guide the electrons along the spiral path and at the same time, to keep the beam focused. Since it is desirable and convenient to maintain the same spacing and the same voltage difference between the adjacent turns of the spiral, the magnetic field is "shaped" by proper configuration of the pole-pieces to confine the electron beam to the particular dimensions of the spiral within the tube. In addition to the foregoing, the average potential applied to resistive coatings **132**, **134** will determine the velocity of the stream electrons and the potential applied to resistive coatings **128**, **130** is adjusted so as to constrain the stream electrons within the center region of the spiral path **149**.

Other phases of the operation of the described embodiment of electron delay tube are similar to the operation of the embodiments of the delay tubes illustrated in Figs. 1 and 5.

From the foregoing description of the present invention, it is seen that when the current or density of an electron stream is modulated with a signal, the signal is propagated along the electron stream in the form of space charge condensations. Since the electron stream is contiguous to one or more resistive surfaces which have predetermined values of surface resistivity, the gain of the signal is controlled by the adjustment of the voltage beam current, as in the resistive wall amplifier described in the aforementioned Haeff application. The actual time required for the signal in the form of space charge condensations propagated by the electron stream to travel from the input to the output of the electron delay tube represents the time delay. The velocity of the electron stream and that of the signal are approximately equal, hence, the time delay of the tube is essentially determined by the length of the delay path and the velocity of the stream electrons. In the described embodiments of the invention, helical or expanding spiral delay paths have been disclosed so as to provide a tube occupying a minimum volume. Also, one illustrated embodiment of the electron delay tube provides a re-entrant delay path for the electron stream making it possible to circulate the signal through the tube an integral number of times, thus increasing the delay time of the tube.

What is claimed as new is:

1. An electron delay tube capable of delaying very high and ultra high frequency signals, said electron delay tube comprising first and second concentric cylinders forming an annular evacuated chamber, first and second resistive layers disposed on opposite surfaces of said first and second concentric cylinders, respectively, a conductive edge-wound helix extending radially in said annular chamber between said first and second concentric cylinders and electrically insulated from said first and second resistive layers, the intervening space between said first and second concentric cylinders and the flat surfaces of said edgewound helix forming a helical chamber, means for producing an electron stream and projecting it into said helical chamber, means for modulating the density of said electron stream with an input signal, means connected to said first and second resistive layers and to said conductive edge-wound helix for maintaining predetermined potentials thereon for directing said modulated electron stream through said helical chamber, and output means disposed at the termination of said helical chamber for converting said density modulations of said electron stream into a delayed output signal.

2. The electron delay tube as defined in claim 1 including external feedback means connected between said output means and said means for modulating the density of said electron stream for feeding back said delayed output signal from said output means to said means for modulating the density of said electron stream to increase the delay of said input signal.

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