April 3, 1956 A. V. HAEFF 2,740,917

ELECTRON STREAM AMPLIFIER TUBE

Filed April 12, 1952 4 Sheets-Sheet 1

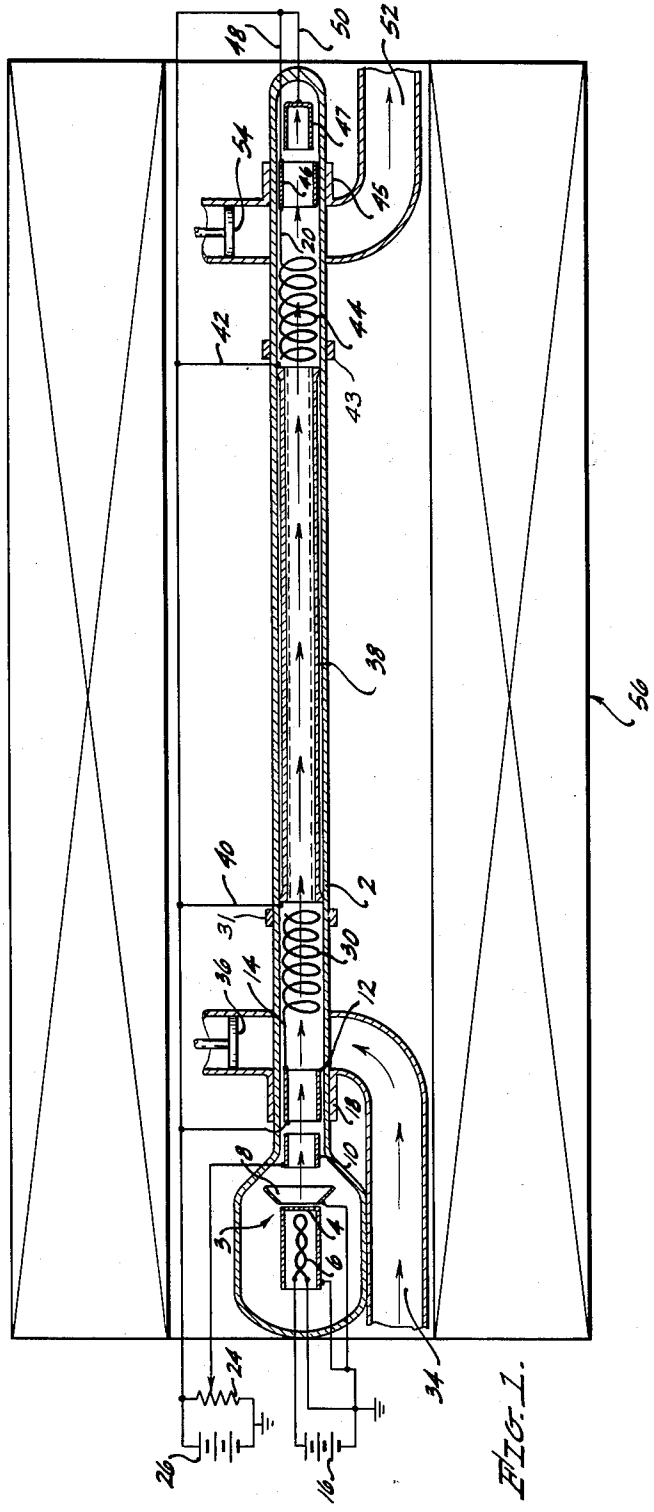


FIG. 1.

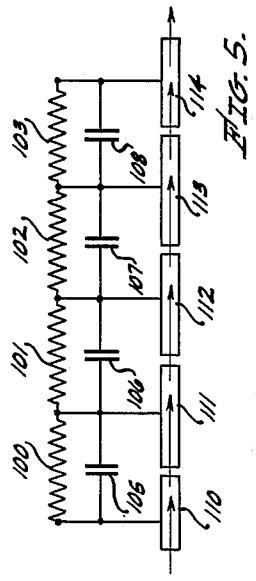


FIG. 5.

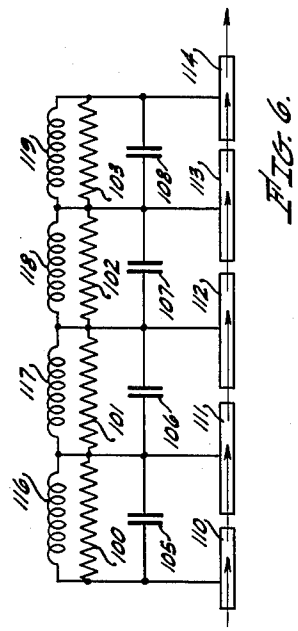


FIG. 6.

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ELECTRON STREAM AMPLIFIER TUBE

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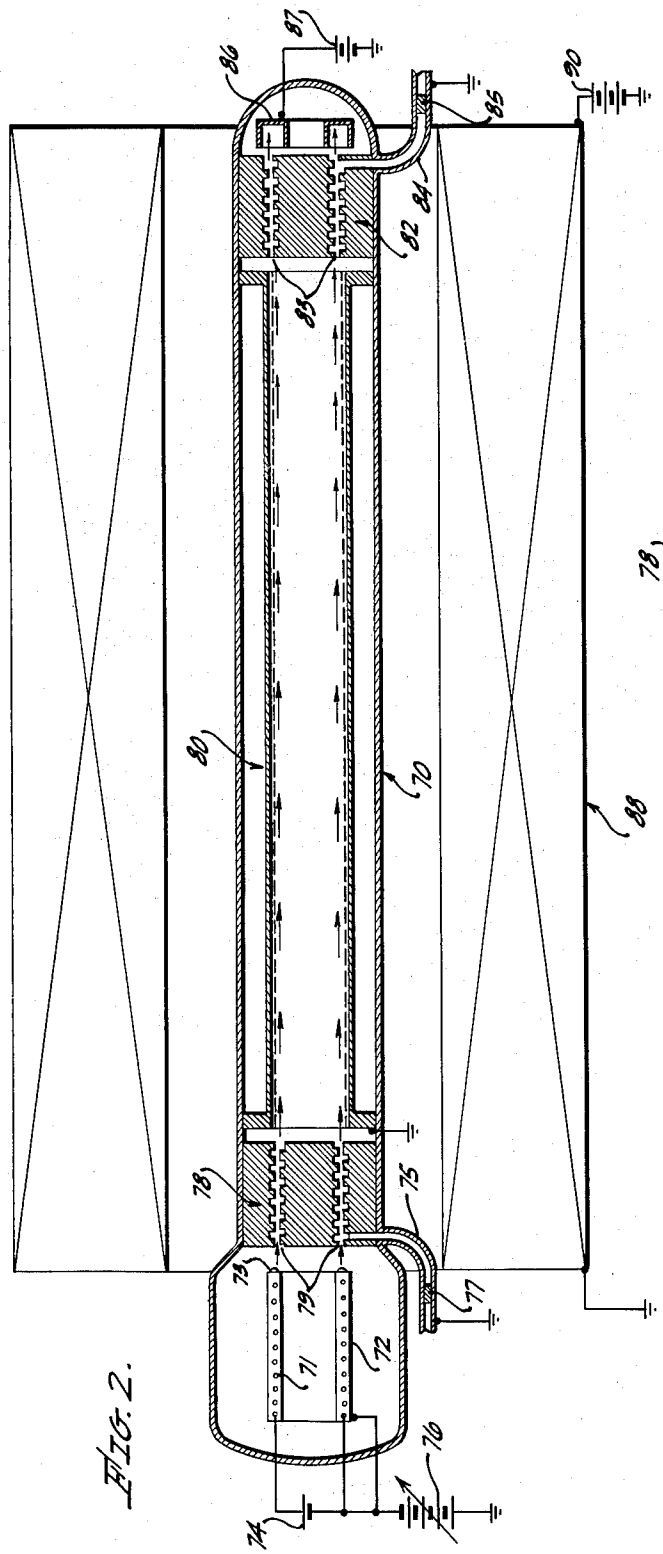


FIG. 2.

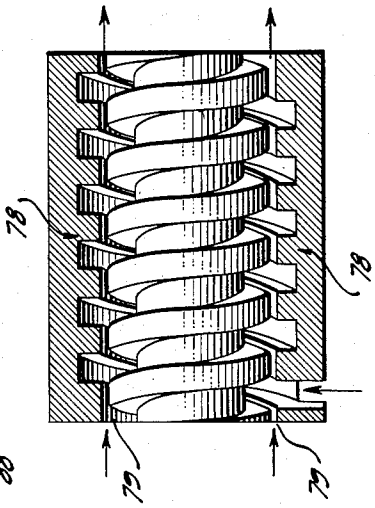


FIG. 3.

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ELECTRON STREAM AMPLIFIER TUBE

Filed April 12, 1952 4 Sheets-Sheet 3

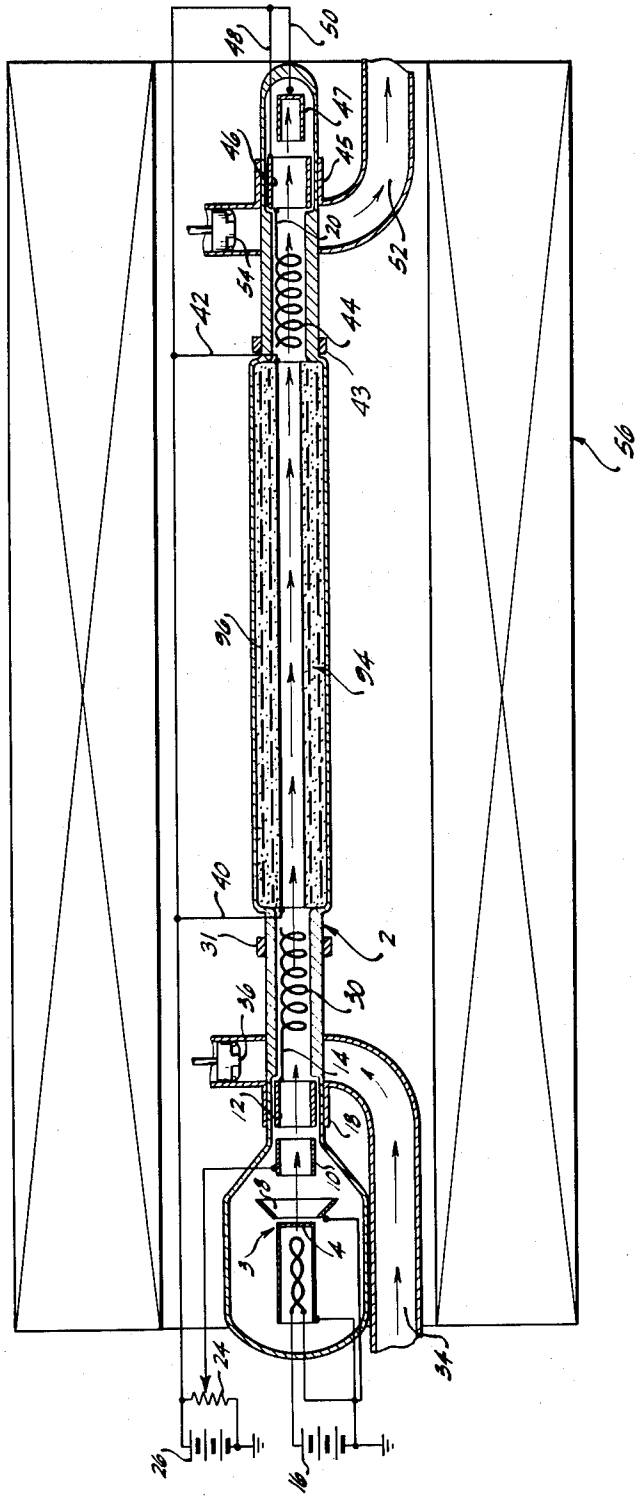


FIG. 4.

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ELECTRON STREAM AMPLIFIER TUBE

Filed April 12, 1952 4 Sheets-Sheet 4

FIG. 7.

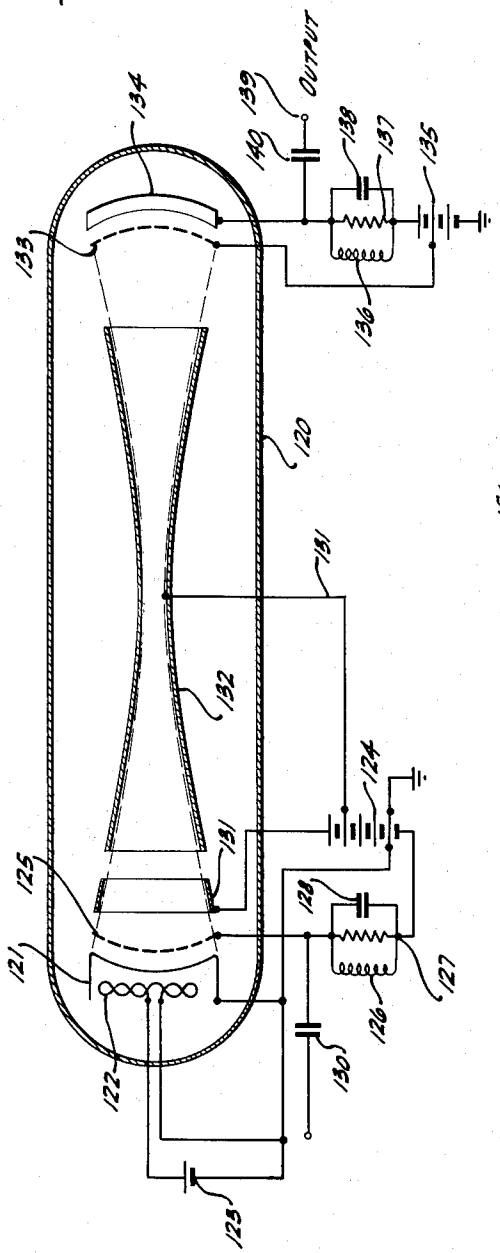
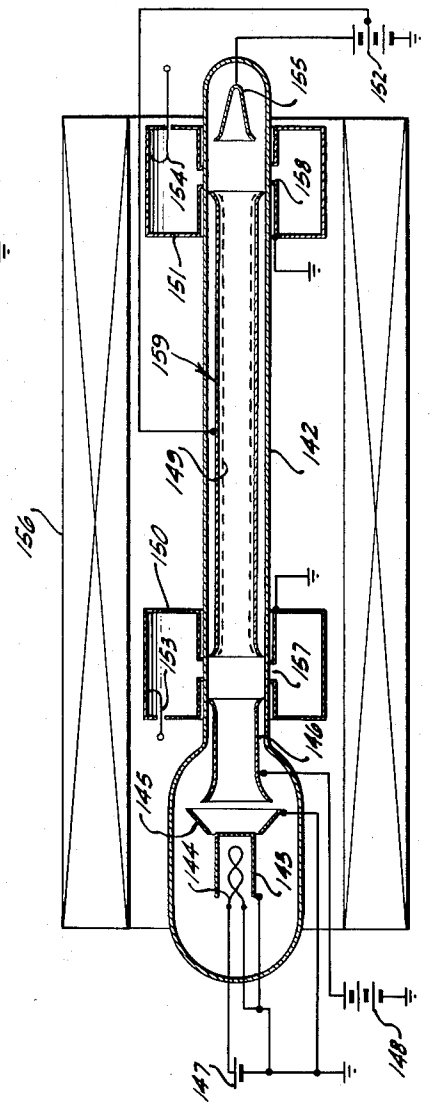


FIG. 8.



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2,740,917

ELECTRON STREAM AMPLIFIER TUBE

Andrew V. Haeff, Pacific Palisades, Calif., assignor, by mesne assignments, to Hughes Aircraft Company, a corporation of Delaware

Application April 12, 1952, Serial No. 282,000

12 Claims. (Cl. 315—3.6)

This invention relates to electron stream amplifiers, and more particularly to the electron stream amplifiers which are capable of amplifying microwave energy by means of the interaction of the electrons of a modulated electron stream with electromagnetic fields produced by currents induced in a medium contiguous to the stream by the modulated electron stream in a medium contiguous to the stream.

In a simple form, the device, in addition to the usual electron gun and collector electrodes, contains three sections. The first section is a relatively short input structure whose function is to transform signal energy into modulations of the electron stream.

The second section is a non-propagating structure including walls having a surface that presents either a resistive-capacitive, resistive, resistive-inductive or inductive impedance to the stream. Non-propagating is to be construed to mean that the structure will very highly attenuate electromagnetic waves at the signal frequency in the absence of an electron stream. In its simplest form, this structure comprises a long piece of glass tubing having a resistive coating on its inner surface. This structure, with the resistive coating on its inner surface, and other versions of this structure, which will be described more fully later in this specification, all will be generally referred to as an "impedance member" in this specification. It is, at this time, premature to define fully the meaning of this term, but it will be defined more fully later in this specification, where its significance will become more apparent in the light of the function and results produced by this member. It is to be noted, however, that the impedance member in its simplest form does not present a purely resistive impedance to the electron stream but rather a resistive-capacitive impedance due to inherent spatial capacitance along its surface. This capacitance is parasitic in nature since it acts as a low impedance path for the currents induced in the walls of the member. To counteract this effect, some of the versions of the impedance member have an artificially introduced inductance to neutralize the spatial capacitance. When this is the case, then the impedance presented to the electron stream by the walls of the member may become, for all practical purposes, resistive, resistive-inductive, or inductive. The inductance presented to the electron stream by the walls of the member may be increased in several ways, for example, by using a ferritic material or by scattering highly conductive dipoles throughout a dielectric material. As will be pointed out later, in order to obtain maximum gain, the inductance should cancel the effect of the spatial capacitance at the center operating frequency; in this case, the resistance offered by the resistive coating should be as high as possible consistent with maintaining the surface contiguous to the electron stream at a uniform quiescent potential. The original modulations of the stream are amplified through the process of interaction between the modulated electron stream and the electric fields produced by the

currents induced in the walls of the impedance member by the modulations of the electron stream.

The third section of the device is a simple output structure where the amplified signal energy in the stream is converted into a useful output signal.

In the electron stream type tube disclosed in this specification, a microwave input signal is made to modulate an electron stream which produces a series of charge condensations within the electron stream constituting a space charge wave propagated by the electron stream and corresponding to the input signal. The electron stream propagating the space charge wave is directed along contiguous to the surface of the impedance member. Charge condensations propagated by the electron stream produce corresponding electric field variations in the stream and in the contiguous walls of the impedance member. These electric fields induce currents in the portion of the wall contiguous to the electron stream which, in turn, produce electric fields which interact with the stream electrons. If the impedance presented to the stream by the wall contiguous to the stream is resistive-capacitive, resistive, resistive-inductive or inductive, the phase of the reactive field is such as to produce further "bunching" of electrons in the stream so that the space charge wave grows, i. e., increases in amplitude as it propagates along the stream. In the present invention, the passing of the electron stream in the proximity of the impedance member is actually an approximation of passing the electrons through a medium having suitable dielectric properties similar to the dielectric properties of the contiguous surface of the impedance member.

Amplification of the space charge wave, in passing in the proximity of the surface of the wall of the impedance member, is accomplished by a partial transfer of the average kinetic energy of the stream electrons to the space charge wave there are no critical requirements imposed on the velocity of the electron stream by the characteristics of the impedance member. After the stream electrons have progressed past the member, the microwave energy is removed from the electron stream by means of an output circuit coupled to the electron stream.

Some advantages of the new device can be brought out by comparing the characteristics of the more conventional amplifiers, such as traveling wave tubes, to the characteristics of the new device. In conventional traveling wave tubes, amplification of microwave signals is obtained by applying the signal to a wave-guiding structure, capable of propagating a slow traveling electromagnetic wave. An electron stream is projected contiguous to this "slow-wave" structure at a velocity slightly greater than the phase velocity of the waves on the structure. The electron stream interacts with the traveling wave in such a manner that energy is transferred from the electron stream to the traveling wave, thereby increasing the amplitude of the wave as it travels along the structure, resulting in a considerably greater signal at the output as compared to the input signal. In order to obtain high energy gain, the waveguiding structure of a traveling wave tube has to be made with considerable precision since the phase velocity of the electromagnetic waves should remain substantially constant along the length of the structure and in fixed relationship to the velocity of electrons projected contiguous to the structure. At operating voltages convenient to use, which are normally of the order of 300–3000 volts, it is somewhat difficult to achieve the necessary degree of uniformity of wave-guiding structures designed to operate in the kilomegacycle range. This is so because of very small tolerances required in the fabrication of the slow-wave structure. Considerable uniformity in electron velocity is also required in order to achieve high gain in a traveling wave tube. This is again difficult to achieve due to the pres-

ence of transverse electric fields in electron-accelerating structures and due to space charge forces produced within the stream itself.

The present invention obviates the necessity of fabricating long and very precise waveguiding structures, since the amplifying section may be a relatively simple member consisting, for example, of a piece of straight glass tubing having a resistive coating on the surface contiguous to the stream. This simple structure makes it possible to build electron stream type amplifying tubes to operate at significantly higher frequencies than is now possible with conventional traveling wave tubes. In addition, the amplification mechanism of the present invention does not require a critical adjustment of electron velocity in order to achieve high amplification. This makes it possible to use a high density electron stream, even though there may be a considerable variation in the velocity of the electrons across the stream cross-section. Another advantage of the present invention is that, in the amplifying section of the tube, signal energy is carried almost entirely by the electron stream itself and hence can propagate only in the direction of electron travel. This unidirectional energy propagation makes it possible to obtain very high gain in a single tube without danger of oscillation because of the absence of feedback through the amplifying region of the tube. Such energy feedback effects are present in conventional traveling wave tubes and are usually avoided only by artificially loading the waveguiding structure resulting in a considerable sacrifice in gain. The freedom from uncontrolled oscillation in the present device also removes the stringent requirement on the impedance matching of input and output circuits over the wide range of frequencies which is usually required in conventional traveling wave tubes and which is particularly difficult to achieve in traveling wave tubes designed for operation at very high frequencies.

In addition to the foregoing advantages, the disclosed impedance wall tubes also provide gain and have a frequency response comparable to that of prior art ultra high frequency amplifiers without the accompanying structural complications.

It is, therefore, an object of this invention to provide a method and apparatus for amplifying a space charge wave by passing a modulated electron stream contiguous to a surface of an impedance member.

Another object of this invention is to provide an electron stream amplifier tube capable of amplifying microwave signal energy of broad bandwidth, the amplification being accomplished by passing a signal-modulated electron stream contiguous to the surface of a member that presents an impedance to the electron stream whereby the relationship between the velocity of the electron stream and the characteristics of the member are such as to permit the operation of the tube over a wide range of electron stream velocities.

A further object of this invention is to provide a stream type amplifier tube wherein the walls of an impedance member present an inductive admittance to the electron stream by means of "imbedded" inductive elements within the wall structure thereby canceling the inherent spatial capacitance of the surface of the walls.

A still further object of this invention is to provide a stream type amplifier tube wherein the admittance presented to the electron stream by an impedance member including a resistive surface is made resistive-inductive in nature by incorporating material therein that exhibits a higher permeability at the operating frequency than that of free space, thereby to present a higher impedance to the electron stream than is possible with a resistive surface alone, due to its inherent capacitance.

Still another object of this invention is to provide a stream type amplifier tube having an impedance member which produces a signal-amplifying effect on a modulated electron stream, the impedance member having a resistive-inductive surface positioned contiguous to the electron stream between the input and output circuits of the tube.

An additional object of this invention is to provide an electron tube including an impedance member having an inductive reactance wall capable of amplifying microwave signals propagated by an electron stream, the tube being readily adaptable to a variety of input and output circuits for coupling to and from the electron stream of the tube, these circuits taking such forms as a beam-modulating grid, resonant cavity, a short helical waveguide section, or a short helical coil.

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 drawings, in which several embodiments of the invention are illustrated, by way of examples. 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.

Figs. 1, 2, 4, 7 and 8 are diagrammatic sectional views of first, second, third, fourth and fifth embodiments of the invention with associated circuitry;

Fig. 3 is a cross-sectional view of the input helical wave-guide section for the embodiment illustrated in Fig. 2; and

Figs. 5 and 6 are equivalent circuit diagrams.

Referring now to the drawings, wherein like reference characters designate like or corresponding parts throughout the several views, there is shown in Fig. 1, one embodiment of the impedance wall amplifier tube. An envelope **2**, whch provides the necessary evacuated chamber, consists of a long cylindrical structure with an enlarged portion at the left extremity as viewed in the drawing. Within the enlarged portion of envelope **2**, there is an electron gun **3** comprising a cathode **4** with a heater **6**, a focusing electrode **8**, an anode **10**, and an electrode **12**. Heater **6** is connected across a source of potential, such as battery **16**, the negative terminal of which can be connected to cathode **4**, as shown. Cathode **4** and focusing electrode **8** are connected together and are, in turn, connected to ground.

Anode **10** is connected to the movable arm of a potentiometer **24** which is connected across a source of potential **26**, which has its negative terminal connected to ground and its positive terminal connected to electrode **12**. Potentiometer **24** is used for controlling the current of the electron stream, a potential of 500 volts with respect to ground being representative of the potential normally applied to anode **10**, while the potential applied to electrode **12** is of the order of 1000 volts.

An input helix **30** is maintained in a fixed position by evacuated envelope **2**, its left extremity being connected by a lead **14** to electrode **12**, while its right extremity is terminated in the vicinity of **38** by a coating **31** of absorbing material, such as aquadag, applied on the outside of envelope **2** about the last few turns of the helix **30**. Helix **30** is axially aligned with the electron stream emitted from electron gun **3**, and has an inner diameter that is substantially equal to the inner diameter of the electrode **12** so that the stream electrons pass as close to the helix as possible without being intercepted by the latter. A material, such as tungsten, is suitable for making the helix, the main prerequisite being that it retain its form, especially with respect to its pitch and diameter.

An input waveguide **34** is mounted so that lead **14**, connecting input helix **30** to electrode **12**, is located approximately one-quarter wavelength from the shorted end of the waveguide, as indicated in the drawing. Lead **14** is also placed so as to be parallel to the electric field in the waveguide **34**. A matching element **36** provides a means

to adjust the distance from lead 14 to the end of the input waveguide 34 so that the voltage induced in lead 14 can be adjusted to an optimum value.

Cylindrical collar 18 is concentric with electrode 12 for a distance of roughly one-quarter wavelength. Since the stub formed by collar 18 and electrode 12 is open circuited at the far end with respect to the waveguide, an apparent shorting plane is produced at the inner surface of the waveguide.

The impedance member 38 is tubular in form and axially aligned with the input helix, the inside diameters of the two being approximately equal. Member 38 may be made of glass with a resistive coating of tin oxide disposed on its inner surface. Resistive coatings of this type are generally thinner than the skin depth of a radio-frequency wave in a lossy dielectric material, hence the radio-frequency resistance of the resistive coating approximates its direct-current resistance. Thus, a resistive coating of tin oxide is equivalent to the resistive surface of a lossy dielectric material at frequencies where the skin depth of the material approximates the thickness of the resistive coating and the direct-current resistances of the lossy dielectric material and and the coating are comparable.

For obtaining maximum gain, the surface resistivity must be chosen to have a value depending upon the desired operating frequency, the velocity of the electron stream and the dielectric constant of the material on which it is disposed. By surface resistivity is meant the actual resistance per square centimeter of surface area to an electrical wave. In the case of a resistive coating of tin oxide on glass, the direct-current resistance per square centimeter approximates the value of surface resistance given to the wave since its thickness is less than the usual skin depth encountered at the frequencies used. In the case of a thick material, the surface resistivity is the resistance per square centimeter of a sheet of the material having a thickness equal to the skin depth. The choice of surface resistivity of the wall required for obtaining maximum amplification per unit length of the tube depends upon the operating frequency, the separation between the electron stream and resistance wall, the electron velocity, and the dielectric constant of the wall. In normal practice, values of surface resistivity will be found to range from 500 to 10,000 ohms per square centimeter. A typical value of surface resistivity for the inner surface of member 38 is of the order of 1000 ohms per square centimeter. The coated glass member may be replaced with other resistive elements, such as a carbon tube or other thick tubular structures possessing the correct surface resistivity. The member 38 is usually maintained at a potential approximately equal to that of the accelerating electrode 12. For convenience, the same battery 26 is used to apply a potential of the order of 1000 volts with respect to ground through leads 40 and 42 to both ends of member 38.

The output portion of the impedance wall amplifier tube comprises an output helix 44 connected by a lead 20 to an electrode 46 and a collector electrode 47, all maintained at a potential approximately equal to the potential of electrode 12. Again, for the sake of convenience, the same potential source is used to impress a potential of the order of 1000 volts with respect to ground on output helix 44 and electrode 46 through lead 48, and to impress a like potential on collector electrode 47 through lead 50. As was mentioned in connection with the input helix 30, tungsten is a suitable material out of which to make the output helix 44. The helix 44 may be terminated in a manner similar to helix 30 by applying a coating 43 of absorbing material such as aquadag on the outside of envelope 2 around the first few turns of helix 44 adjacent to member 38.

The construction of the output waveguide 52 is identical to that of the input waveguide 34. It has a matching element 54 similar to matching element 36 in the input waveguide. A cylindrical collar 45 runs concentric with electrode 46 for a distance of approximately one-quarter wavelength producing an apparent shorting plane on the inner surface of output waveguide 52. Although a rather specific means has been disclosed for coupling signal energy to and from the disclosed impedance wall amplifier tube, other methods, such as replacing the input and output waveguides with coaxial lines, may be used. Also, as will be described later, the input and output helices can be replaced by resonant cavities or a grid can be used to directly modulate the stream of electrons at the input, and a screen and anode similar to those of a tetrode can be used to extract the signal energy from the electron stream at the output end. In addition, the disclosed invention need not be restricted to the particular geometrical configuration described as the electrons can be made, for example, to flow along any desired curved path merely by the utilization of appropriate electrostatic and magnetic fields.

A solenoid 56 is axially positioned symmetrically about the complete length of the glass enevelope 12. An appropriate direct-current is maintained in solenoid 56 so as to produce a magnetic field which may be of the order of 500 gauss running axially with the length of the tube. The purpose of this magnetic field is to keep the electron stream focused or constrained throughout the length of the tube.

In its operation, an input microwave signal is applied through input waveguide 34, inducing a signal potential on the lead 14 connecting the input helix 30 to the electrode 12. The matching element 36 is adjusted to give maximum signal voltage at the input helix 30. As in conventional traveling wave tubes, the axial phase velocity of the traveling wave through the helix is determined by the pitch and diameter of the helix and is a fraction of the velocity of light. The velocity of the electron stream is usually adjusted so that it is slightly greater than the phase velocity of the wave in passing through the helix. The interaction of the electron stream and the wave on the helix results in a density and velocity modulation of the electron stream. The modulated electron stream after passing the helix enters the tubular member 38. The exposed inner surface of member 38 has resistance and dimensions such that a propagated electric wave is very highly attenuated in the absence of electrons. Member 38 is referred to a non-propagating structure insofar as it will attenuate a signal by of the order of 40 decibels as compared to 3 to 5 decibels attenuation by the helix of a conventional traveling wave tube. It is also to be noted that, due to the electrical discontinuities between helices 30, 44 and the member 38, the overall attenuation in the absence of the electron stream from input 34 to output 52 of the tube of Fig. 1 is of the order of 80 decibels.

Hence it is seen that nearly all of the energy transmitted along the axis of the member 38 is in the form of a space charge wave propagated by the electron stream. Signal energy exists in a space charge wave in the form of electron bunching. Axial current induced by the bunched electron stream in the walls of member 38 produce electric fields which act on the stream electrons so as to increase still further the electron bunching. An increase in electron bunching is equivalent to an increase in the signal amplitude. Thus, the magnitude of signal on the electron stream continuously increases as the stream electrons move along contiguous to the resistive surface of member 38. As the amplified space charge wave emerges from the far end of the member 38, it induces voltage on the helix, thereby transforming a portion of the signal energy in the electron stream into the form of an electromagnetic wave on the output helix. The stream electrons, as they proceed toward electrode 46, continue to impart energy to the growing wave on the helix. After transferring most of the signal power from the stream to the helix, the electrons finally are collected in collector elec-

trode 47. The electric field induced by the electromagnetic wave on lead 20 of the output helix is parallel with the electric field of the fundamental mode desired to be excited in the waveguide; hence, amplified signal energy is transferred from the output helix 44 to the output waveguide 52.

An analysis of the problem of obtaining maximum gain in an impedance wall amplifier tube indicates that the electrons should pass as closely as possible to the walls of the amplifying member 38, the gain being a maximum if it were possible to pass electrons through a solid medium. In actuality, this is not possible, but an approximation may be made by visualizing the electrons in the form of streams going through a myriad of small holes in the solid medium.

For a current density and an electron velocity within the ranges encountered in practice, it is possible to obtain appreciable amplification in this type of tube in which the electrons are projected through a medium having conductivity and an absolute dielectric constant, ($\epsilon_0\epsilon_1$). For example, at a current density of 0.1 ampere/square centimeter, with an average electron velocity of 1000 volts, and using optimum value of conductivity, the estimated gain is of the order of 1 decibel per centimeter length of the amplifying section.

Not only is the gain quite high at the frequency of optimum operation, but high gain is available over a wide frequency band. For example, calculations show that in a tube with a theoretical electronic gain of 40 decibels, having an estimated overall gain of 35 decibels, the amplification would be down to 32 decibels at 51 percent and at 151 percent of optimum frequency, the tube having a bandwidth of 102 percent. Optimum frequency, ω, is defined as the frequency at which the quantity

$$\frac{\sigma}{\omega\epsilon_0\epsilon_1}$$

attains its optimum value (equal to about $\sqrt{3}$ on the basis of elementary theory) with fixed values of conductivity, σ, and absolute dielectric constant ($\epsilon_0\epsilon_1$). Again from the elementary theory, the maximum gain at the optimum frequency is

$$\text{Gain}\ \frac{(\text{decibels})}{\text{centimeter}} = 8.7\ \frac{J_0\ (\text{ampere/square centimeter})}{3\epsilon_1 V_0^{3/2}\ (\text{kilovolts})^{3/2}}$$

wherein J_0 is the current density of the electron stream, V_0 the potential through which the stream electrons are accelerated, and ϵ_1 the real part of the relative dielectric constant. It is apparent from the foregoing analysis that the electron stream in a resistive medium, as described in the disclosed embodiment of the impedance wall amplifier tube, is capable of supporting a wave which will greatly amplify initial modulation on the stream over an exceedingly wide frequency band. At the same time there is no critical requirement on the electron stream velocity as is the case in conventional traveling wave tubes.

An additional embodiment of the disclosed invention is illustrated in Fig. 2. An envelope 70 furnishes the necessary evacuated chamber required for the tube. Evacuated envelope 70 consists of a long tubular structure with an enlarged portion at the left extremity as viewed in the figure. A circular source of electrons, including a cylindrical cathode 72, a circular electron-emitting surface 73, and a heater 71, is axially aligned with the long tubular portion of the envelope. Heater 71 is connected across a source of potential 74, which has its negative terminal of which is connected to cathode 72. Cathode 72 is maintained at a negative potential with respect to ground by a source 76. The potential of source 76 may be of the order of —1000 volts.

An input helical waveguide section 78, positioned axially in line with cathode 72, is provided with a cylindrical path 79 for the electrons emitted by cathode 73. The input waveguide is illustrated on an enlarged scale in Fig. 3, where the inner portion of the guide is illustrated in side elevation. The cylindrical slit or path 79 is axially aligned with cathode 72. An input waveguide 75 is connected to the end of waveguide 78 nearest to cathode 72. A seal 77 retains the vacuum within envelope 70.

A tubular member 80, having a resistive surface, is positioned axially in line with the cathode 72 and slit 79, member 80 having an inside diameter slightly greater than the outside diameter of slit 79. Member 80 comprises a glass tube, the inner surface of which is provided with a resistive coating of tin oxide, for example. Methods for depositing a resistive coating are known, and, hence, further description would be unwarranted. A suitable surface resistivity for tubular member 80 is of the order of 1000 ohms per square centimeter. Other materials having the specified resistivity can be used, the main consideration being that the stream electrons pass in the near proximity of a surface or wall having a resistivity in the range previously specified for the particular frequency and dielectric constant used.

An output helical waveguide section 82, similar in shape and form to the input helical waveguide section 78, is positioned axially in line with tubular member 80 at the opposite end of envelope tube 70. Both output and input waveguides are made of a nonferrous conducting material, such as copper, silver or silverplated copper.

An output waveguide 84 is connected to the output helical waveguide section 82 on the side nearest to a circular collector electrode 86 which is disposed so as to intercept the electron stream. A seal 85 retains vacuum within the tube. The waveguides 78 and 82, and tubular member 80 may all be maintained at a common ground potential by appropriate ground connections thereto so the average velocity of the stream electrons after their initial acceleration will be unaffected. Collector electrode 86 is maintained at a potential that is sufficiently positive with respect to the potential of the output waveguide 82 so as to suppress any secondary emission due to the stream electrons impinging on the collector electrode surface. An appropriate potential to effect this result is applied to collector electrode 86 by means of a connection to a potential source, such as a battery 87.

A solenoid 88, positioned symmetrically about the complete length of the envelope 70 and connected to a source 90, produces a magnetic field parallel to the axis of the tube having a flux density of the order of 500 gauss. As before, the purpose of this magnetic field is to keep the electron stream focused or constrained throughout the length of the tube.

Since the theory of operation of the tube, illustrated in Fig. 2, is essentially the same as the theory of operation of the tube illustrated in Fig. 1, only a brief explanation of its functioning is necessary. With potentials applied to the tube elements, as specified, electrons will be emitted from cathode 72 and accelerated toward slit 79. Since circular slit 79 is in alignment with cylindircal cathode 72, a cylindrical stream of electrons will be formed which, due to the axial alignment of all the elements, will proceed on through circular slit 79, tubular member 80, circular slit 83, to collector electrode 86, where the remaining kinetic energy of the stream electrons is dissipated. The magnetic field produced by solenoid 88 keeps the circular electron stream focused or constrained to substantially its original cross-sectional dimensions throughout the length of the tube.

The microwave signal to be amplified is applied through input waveguide 75. The dimensions of the waveguide should be such that the rate of change of phase velocity with respect to frequency is relatively small so as to operate the tube in as broadband a region a possible. For constructive interaction between the stream and the guided wave, the electron velocity should be just greater than the axial component of phase velocity of the guided wave. In other words, the velocity of

the stream electrons is adjusted by the potential of battery **76** so that they travel a distance equal to the pitch of the helix while a wave in the waveguide traveling at its phase velocity progresses one complete revolution. This synchronous relationship between the stream electrons and the microwave signal enables the stream electrons to be modulated by an electric field of the same phase each time they pass through a section of waveguide. The slit going through the center of the waveguide has little effect on the transmission characteristics of the waveguide as it is in a region where the boundary current is normally zero for the fundamental transverse electric mode of propagation.

After being modulated with the signal by the input helical waveguide section **78**, the stream electrons proceed on through tubular member **80**. The effect of the hollow cylindrical electron stream in passing near the resistive surface of the wall of tubular member **80** is essentially the same as for a solid electron stream passing through a tubular member having resistive walls, as described in connection with the tube illustrated in Fig. 1. Currents are induced in the resistive surface and these currents produce electric fields which act on the stream electrons to increase the electron bunching. Since the bunching of the electrons is representative of the amplitude of the space charge wave contained within the electron stream, the amplitude of the space charge wave increases as the stream electrons progress through the tubular member **80**.

The electron stream containing the space charge wave of increased amplitude passes through the tubular member **80**, and enters the circular slit **83** of output helical waveguide section **82**. The amplified space charge wave is synchronized with the output waveguide so as to excite a circuit wave in the output helical waveguide section **82**, the energy so induced being available at output waveguide connection **84**. The stream electrons continue on through circular slit **83** to impinge on circular collector electrode **86** where their kinetic energy is dissipated. The potential on collector electrode **86** may be maintained slightly positive with respect to the potential of helical waveguide section **82** to prevent secondary emission effects.

Still another embodiment of the disclosed invention is illustrated in Fig. 4. The structure of the tube is the same as for the tube illustrated in Fig. 1 except that an inductive wall member **94** is used in lieu of the impedance member **38** which has a wall having a resistive surface.

Inductive wall member **94** can be made of an artifical dielectric material having resonance in the vicinity of the operating wavelength. Such a material can be made by imbedding numerous pieces of metal in a dielectric material, such as the type illustrated by dipole **96**. In order to make the artificial dielectric material respond to a broader bandwidth, the dipoles can be cut to different wavelengths throughout a specified band of frequencies and randomly scattered throughout the dielectric material.

An alternative means of obtaining a distributed inductance in inductive wall member **94** is to use a thick wall made of ferritic material. Ferritic materials will be defined as those materials having a relative permeability constant substantially greater than unity. The permeability of some ferritic materials has the characteristic of going through the equivalent of a parallel resonance in a rather narrow frequency band, making it necessary to use a particular ferritic material having a resonance in the region of the frequency spectrum where amplification is desired. The width of this narrow frequency band would determine the bandpass characteristics of the tube for the particular ferritic material used. Since the permeability constant of different ferritic materials goes through resonance at different frequencies, a broader response can be obtained by blending two or more of the ferritic materials together having resonance characteristics in the vicinity of the frequency range desired. The specific ferritic materials used are dependent upon the frequency and bandwidth to be amplified.

The general functioning of the impedance wall amplifier tube illustrated in Fig. 4, having an inductive wall member, is similar to that of the amplifier tube illustrated in Fig. 1, and, hence, will not be repeated.

To explain more adequately the advantages of the inductive wall member over the resistive wall member, a comparison will be made between their equivalent circuit diagrams. Fig. 5 represents the equivalent circuit diagram of tubular member **38** which has resistive walls. Resistors **100**, **101**, **102** and **103** represent, in lumped parameter form, the series resistance of member **38**. Tubular elements **110**, **111**, **112**, **113** and **114** represent the electrical coupling of the electron stream to the walls. In addition to the foregoing, there is also a distributed series capacitance represented as lumped capacitors **105**, **106**, **107** and **108**.

The equivalent circuit diagram of inductive wall member **94** is shown in Fig. 6. As before, resistors **100**, **101**, **102** and **103** represent, in lumped parameter form, the series resistance of the member; tubular elements **110**, **111**, **112**, **113** and **114** represent the electrical coupling of the electron stream to the walls; and capacitors **105**, **106**, **107** and **108** represent the distributed series capacitance. In addition to the foregoing parameters, the inductive wall member has series inductance represented in lumped parameter form by inductors **116**, **117**, **118** and **119**, these inductors being connected in parallel with resistors **100**, **101**, **102** and **103**, respectively.

In adjusting parameters in electron stream tubes for maximum amplification, essentially the same rules apply as in video amplifier circuits: That is, the impedance is maintained as high as possible consistent with the frequency bandwidth desired. Referring to Fig. 5, it can be seen by inspection that admittance presented to the electron stream consists of conductance plus capacitive susceptance. To increase the gain of the tube, it is necessary to cancel the capacitive susceptance. One means of accomplishing this is the use of inductance, as shown in Fig. 6. For this combination, the admittance, as seen by the electron stream at the lower frequencies with respect to resonance, is now resistive-inductive. When such a structure is analyzed, it will give higher gain relative to a comparable resistive-capacitive wall if the inductance is adjusted to compensate for capacitive susceptance.

Fig. 7 illustrates an additional embodiment of the invention with electrostatic focusing of the electron stream. From what is disclosed in Fig. 7, it follows that the invention may be practiced either with or without the magnetic field created by the solenoid. All that is necessary is that the electrons emitted by the cathode are accelerated and, by using a suitable electron optical system, are directed, in a stream form, in the direction of the input portion of the tube for proper modulation and the concomitant "bunching" of this beam in response to the input signal. This modulated beam is then made to travel through the impedance member in the manner described in connection with Figs. 1 through 6. The main difference between the structure of this tube and the previously described tubes, therefore, resides in the fact that an electrostatic focusing is used in this case which, depending on the electron optics used, may produce a converging beam illustrated in Fig. 7, or a substantially parallel beam, which generally will have a tendency to diverge because of the mutual repulsion of electrons and their thermal velocities. The degree of final divergence is a function of the kinetic energy imparted to the electrons at the time they are accelerated by the acceleration electrodes. All of the above is well known in the art and is mentioned here to stress the

fact that the invention is equally applicable to all known types of electron streams so long as these streams have sufficient electron density and initial kinetic energy to be suitable as an amplification vehicle. As will become more apparent from what follows, all that is necessary is to make the shape of the impedance member conform with the shape of the beam. As will be pointed out later, the beam cross-section may also be of elliptical, rectangular or other suitable form.

Referring again to Fig. 7, a cathode **121**, mounted in an evacuated envelope **120**, has the shape of a cylindrically concave electron emitting surface for facilitating subsequent focusing of the emitted electrons. If cathode **121** is maintained at ground potential, the potentials of other electrodes are referenced with respect to the cathode. Thus, heater **122** is connected to cathode **121**, an intensity grid **125** is at a slightly negative potential with respect to the cathode, and a focusing and accelerating electrode **131** is at a high positive potential so as to impart sufficiently high initial kinetic energy to the stream electrons. Grid **125** is positioned in front of and parallel to the electron emitting surface of cathode **121**; it is a cylindrically concave grid having a radius of curvature approximately equal to the distance to the virtual focal point of the electron stream, so that the current modulation wave fronts, as they progress along the resistive walls, will travel equal distances and subsequently impinge on a surface shaped to correspond with the shape of the wave fronts. The actual biasing potential supplied by battery **124** to grid **125** which may be of the order of −2 volts is applied to grid **125** through a parallel resonant combination of an inductor **126**, a resistor **127**, and a capacitor **128**. Resistor **127** is used for flattening the frequency response characteristics of the parallel resonant circuit. An input signal is applied to grid **125** through a capacitor **130**.

An electrostatic focusing electrode **131** is positioned symmetrically in front of grid **125**, the value of the potential applied to it being of the order of 200 volts.

Since in the illustrated example, the electron stream is a converging and then diverging stream because of the illustrated electron optics, the impedance member **132** is made to conform to the geometrical configuration of the stream. The stream may have a cross-section that is circular, elliptical, rectangular, or other configuration, as previously mentioned.

As stated previously, numerous other geometrical configurations can be used without departing from the spirit of the invention so long as the configuration of the impedance member is such that it has a surface that is contiguous to a boundary of the electron stream.

As described previously, member **132** may be primarily resistive or inductive with the parameters having the same optimum values as in the previous cases. As before, member **132** is maintained at a suitable positive potential with respect to cathode **121** by connecting it over conductor **131** to battery **124** to maintain the velocity of eletcrons in the beam at the optimum value. This optimum potential may be of the order of +100 volts with respect to the potential of the cathode.

A screen **133** and a plate **134** are positioned at the extremity of member **132** so as to intercept the electron stream projected between resistive walls of member **132** from cathode **121**. Screen **133** and plate **134** have parallel surfaces which are cylindrically concave on the side exposed to the electron stream so as to equalize the total distance traveled by individual electrons of the stream from grid **125** to plate **134**. A positive potential with respect to ground is applied to screen **133** by means of a connection to an appropriate terminal of a battery **135**. Similarly, a positive potential with respect to ground is applied to plate **134** by battery **135** through a parallel combination of an inductor **136**, a resistor **137** and a capacitor **138**, the values of which may correspond to the values of the respective elements **126**, **127** and **128** on the input side in order to obtain the same frequency bandwidth in the output circuit as well as in the input circuit. The potential of screen **133** is maintained negative with respect to that of plate **134** so as to suppress secondary emission of electrons from plate **134**. The potential applied to screen **133** may be of the order of +120 volts and the potential applied to plate **134** may be of the order of +200 volts. The output signal is available at a terminal **139** which is connected through a capacitor **140** to plate **134**.

The amplifier tube illustrated in Fig. 7 functions as follows: The electrons emitted by cathode **121** are accelerated by electrode **131**, so as to produce an electrostatically focused electron stream having a rectangular cross-section and narrowing down to a thin sheet at the focal point. The input signal is applied to grid **125** through capacitor **130**, grid **125** modulating the electron stream and producing bunching of the electrons or varying the electron density of the beam in accordance with the applied signal. The input signal is applied across the parallel combination of inductor **126**, resistor **127** and capacitor **128**, which is resonant at the center of the operating frequency range.

The modulated electron stream is then projected between the resistive walls of member **132** whose length is of the order of several wavelengths, i. e., the distances between the "crests" of modulation along the stream is a small fraction of the length of the resistive walls of member **132**.

As previously explained, the space charge wave propagated by the electron stream increases in amplitude as the stream progresses from the input to the output end of the member **132** along the resistive walls.

The electron stream propagating the amplified space charge wave continues from its entry between the resistive walls of member **132** through screen **133**, and finally impinges on plate **134**, where it produces an amplified signal voltage across the output impedance. The output signal is available at terminal **139** which is connected to plate **134** through capacitor **140**.

Although the tube described in Fig. 7 illustrates the use of a resistive wall amplifying section, it can, of course, be replaced by any of the previously described inductive wall amplifying sections without changing the mode of operation.

Fig. 8 illustrates a tube of the present invention wherein the use of resonant cavities for coupling the input and output signals to and from the electron stream, respectively, is illustrated. As in the previously described tubes, an electron gun, including cathode **143**, focusing electrode **145** and accelerating and focusing electrode **146** for producing an unmodulated electron stream, is positioned in the left extremity of an evacuated envelope **142**. The tube also includes the impedance member **159** which may be either a resistive or an inductive wall element of the type described in connection with the prior tubes, a resistive coating **149** being illustrated in the described tube. A collector **155**, a solenoid **156**, and a source of positive potential **152**, are also provided, the latter keeping collector **155** and the resistive coating **149** at the proper positive potentials. An input resonant cavity **150** is positioned between electrode **146** and the left extremity of impedance member **159**, as viewed in the drawing. This cavity resonator represents a ring-shaped member of circular configuration when the beam produced by the electron gun has a circular cross-section and is elongated either in the vertical or horizontal plane, if the electron beam produced by the gun has a larger dimension in one plane than in the other. The same type of resonant cavity **151** surrounds the electron stream exterior to envelope **142** at the right extremity of the tube. Both cavities **150**, **151** are tuned to resonate at the center frequency of the input signal frequency range. The input cavity is excited in the conventional manner by means of an input loop **153**. Useful output signal appears on the output loop

154 placed within the output resonant cavity 151. Both resonant cavities are provided with slits 157 and 158 for producing an effective coupling between the respective resonant cavities and the electron stream. The resistive coating 149 is terminated prior to covering the coupling slits 157 and 158 to avoid loading of the input and output cavities 150, 151.

In its operation, the tube illustrated in Fig. 8 functions similarly to the previously described tubes having axial magnetic fields, except for the input and output coupling means to the electron stream. A signal is applied to input loop 153 which excites resonant cavity 150, thereby to produce an electric field across the circular slit 157 which penetrates sufficiently far into the electron stream to modulate it in accordance with the applied signal. As in the prior embodiments, the modulations of the electron stream are amplified in passing through impedance member 159 because of the interaction between the modulations propagated by the electron stream and electric fields produced by currents induced in resistive coating 149 by the modulations. As the modulated electron stream emerges from the portion of the tube having resistive coating 149 and passes the circular slit 158 of the output resonant cavity 151, electric fields are generated across the circular slit 158 by the modulation of the stream, setting up an electric field within the cavity corresponding to the applied signal. Output loop 154 is used to remove the signal energy from the output cavity 151.

Since resonant cavities usually have an appreciable capacitance, the frequency response of this tube, as a whole, may be narrower than the frequency response of the amplifying section alone. However, because of higher impedances of resonant cavities for a given electron stream, tubes using cavities will produce a higher overall gain at the center frequency than the impedance wall tubes previously described. It is obvious that any type of impedance wall structure, described previously, can be used in connection with the resonant cavity mode of coupling, and hence their use in combination with the described input and output resonant cavities is encompassed by this invention.

In summarizing the principles of operation of the disclosed embodiments of the present invention, it is seen that in every case a modulated electron stream is projected contiguous to the surface of a non-propagating impedance member for a minimum distance of several wavelengths thereby increasing the modulation of the stream. The surface of the impedance member may present a resistive-capacitive, resistive, resistive-inductive, or inductive impedance to the electron stream. In the case of the resistive surface, the resistance may be provided either by a material having lossy dielectric characteristics or by a resistive coating on glass. The impedance member is non-propagating in the sense that, in the absence of the electron stream, it highly attenuates electromagnetic waves having a free space wavelength in the operating range of the tube. The increased modulation of the electron stream is then converted to a useful amplified signal in the output circuit. Although the helical means have been described with which to modulate and remove signal energy from the electron stream, which is a preferred method in tubes designed for very high frequencies of the order of thousands of megacycles. The specification also discloses other means, such as resonant cavities in one case, and grid structure in another case, which also are available for performing these functions at lower frequencies in combination with the disclosed method of amplification. Therefore, the invention is not restricted to any specific type of input or output circuitry that may be used. What is essential for practicing the disclosed invention is to pass the modulated electron stream adjacent to a lossy material surface, either of resistive or inductive type, for increasing the modulation and thus produce the desired amplification in the overall system.

I claim:

1. An electron stream tube for amplifying a microwave signal, said tube comprising means for producing an electron stream, means for modulating said electron stream with the microwave signal to launch a concomitant space charge wave propagated by the electron stream, means for directing said modulated electron stream along a predetermined path, a substantially non-propagating member having a surface disposed contiguously along said predetermined path for a minimum distance of several wavelengths of said space charge wave, said member presenting an impedance to said stream at said surface to enable said space charge wave to induce electric currents in said member which generate electric fields which, in turn, interact with said electron stream to produce amplification of said space charge wave, and output means coupled to said electron stream for converting said amplified space charge wave to a microwave output signal.

2. An electron stream tube for amplifying a microwave signal, said tube comprising an evacuated envelope, means for producing an electron stream within said envelope, input means for modulating said electron stream with a microwave input signal, means for directing said modulated electron stream along a predetermined path within said envelope, a substantially non-propagating member including a wall having a surface extending contiguously along said path for a distance of at least several modulations of said electron stream, said wall presenting an impedance to said electron stream to amplify said modulations, and output means coupled to said electron stream for converting said amplified space charge wave into an electromagnetic output signal.

3. The electron stream tube as defined in claim 2 wherein the surface of the wall of said substantially non-propagating member has a surface resistivity in the range of from 500 to 10,000 ohms per square centimeter.

4. The electron stream tube as defined in claim 2 wherein said substantially non-propagating member including a wall having a surface comprises a glass structure having a surface, and a resistive coating disposed on the surface of said glass structure.

5. The electron stream tube as defined in claim 4 wherein said resistive coating is of tin oxide.

6. The electron stream tube as defined in claim 2 wherein the wall of said substantially non-propagating member is composed of a dielectric material having a plurality of dipole elements distributed throughout said dielectric material.

7. The electron stream tube as defined in claim 2 wherein the wall of said substantially non-propagating member has a conductivity substantially equal to $\omega\epsilon_0\epsilon_1\sqrt{3}$ where ω is the angular frequency of the signal frequency range, ϵ_0 is the absolute dielectric constant of free space, and ϵ_1 is the real part of the relative dielectric constant of said wall.

8. The electron stream tube as defined in claim 2 wherein the wall of said substantially non-propagating member is composed of ferritic material for making the impedance inductive presented to said electron stream at the surface of said wall.

9. A wave-type amplifier tube comprising means for producing an electron stream, means for modulating said electron stream with a microwave input signal, a non-conducting tubular element disposed concentrically about and contiguous to said modulated electron stream, a resistive coating disposed on the inner surface of said element, whereby the initial modulations of said electron stream induce electric currents in said resistive coating which generate electric fields which, in turn, interact with said electron stream to amplify the initial modulations thereof, and output means coupled to said electron stream for converting the amplified modulations of said electron stream into an electromagnetic output signal.

10. An electron stream tube for amplifying microwave signals, said tube comprising means for producing an

electron stream, means for directing said electron stream along a predetermined path, input means responsive to a microwave input signal for modulating said electron stream, a non-conductive tubular member disposed concentrically about said predetermined path, the inner surface of said member being contiguous to said electron stream, a resistive coating disposed on said inner surface, whereby the modulations of said electron stream induce currents in said resistive coating which generate electric fields which interact with said electron stream to effect amplification of said modulations, and output means for converting the amplified modulations of said electron stream into an electromagnetic microwave output signal, said input means, said tubular member, and said output means being disposed along said path in the direction of electron flow in the order named.

11. The electron stream tube as defined in claim 10 wherein said tubular member additionally includes means for cancelling the spatial capacitance immediately adjacent said resistive coating.

12. An electron stream tube for amplifying a microwave signal, said tube comprising means for producing an electron stream, means for modulating said electron stream with a microwave input signal to launch a concomitant space charge wave propagated by said electron stream, means for directing said modulated electron stream along a predetermined path, a non-propagating member having a surface disposed contiguously along said predetermined path for a minimum distance of several wavelengths of said space charge wave, said member presenting an impedance to said electron stream at said surface, said member being substantially the only means providing amplification of said space charge wave, whereby said space charge wave induces currents in said member which generate electric fields which, in turn, interact with said electron stream, and output means coupled to said electron stream for converting the amplified space charge wave into a microwave output signal.

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