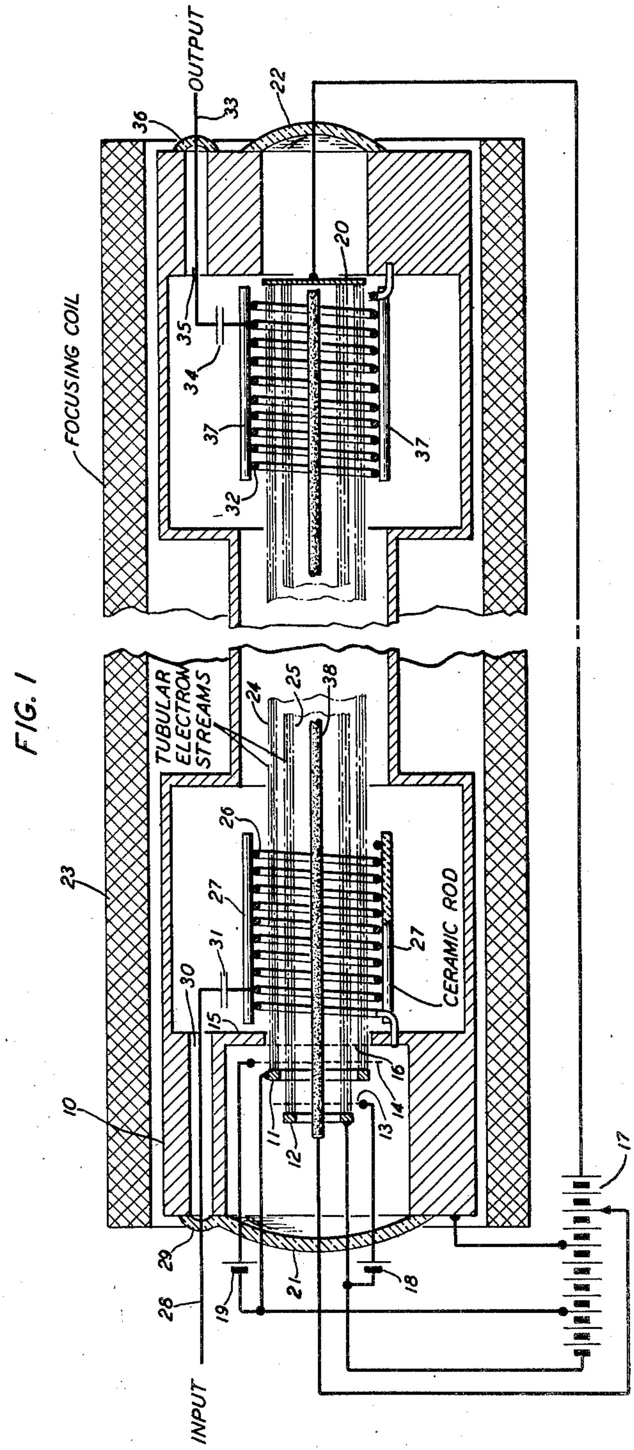
Sept. 15, 1953 A. V. HOLLENBERG 2,652,513

MICROWAVE AMPLIFIER

Filed Dec. 11, 1948 2 Sheets-Sheet 1



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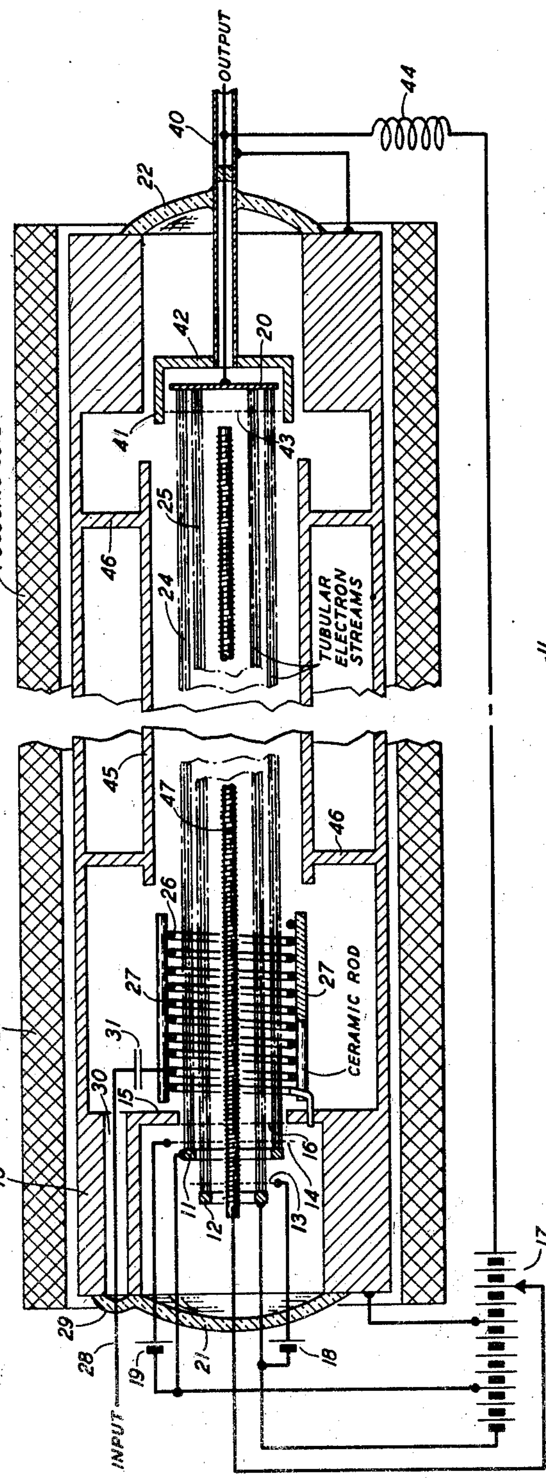

FIG. 2

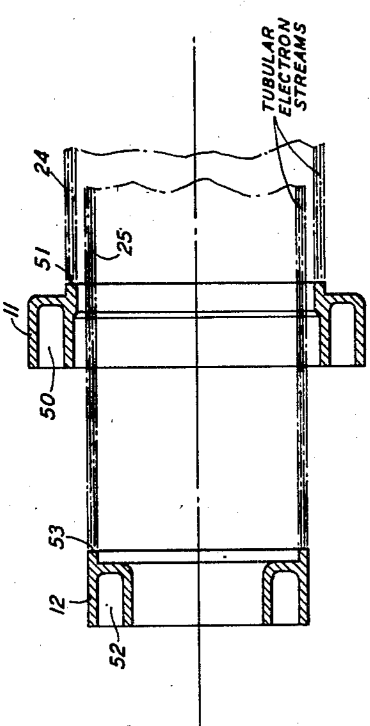

FIG. 3

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MICROWAVE AMPLIFIER

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15 Claims. (Cl. 315—3)

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This invention relates to the subject-matter of the application of W. B. Hebenstreit and J. R. Pierce, Serial No. 38,928, filed July 15, 1948. That application discloses amplifiers which utilize the interaction of a pair of closely coupled electron streams, having different average velocities, to secure gain.

One object of the invention is to secure increased gain over that obtainable in some of the embodiments of the Hebenstreit-Pierce invention.

A related object is to utilize more effectively the total electron current represented in the two interacting electron streams.

A further object is to allow the reduction of "noise" caused by the oscillation of groups of positive ions which may exist in the electron path by facilitating the removal of such ions.

According to a principal feature of the present invention, a pair of streams of charged particles (electrons, for example), which according to the Hebenstreit-Pierce invention are projected at different average velocities along a path of travel, are projected as tubular streams, one within the other. The outside transverse dimension of the inner stream is very nearly equal to the inside transverse dimension of the outer stream and the thicknesses of the stream walls are many times smaller than the respective stream transverse dimensions.

According to another feature of the invention, a high impedance rod may be inserted lengthwise of the inner beam and may be held at a potential sufficiently different from that of the vessel enclosing the streams to remove extraneous positive ions from the electron path. The tubular nature of the inner stream allows such a rod to be inserted without unduly disturbing the electromagnetic fields set up within the stream. If concentric tubular streams are employed, the rod can be situated along the common axis.

Additional objects and features of the present invention will appear upon a study of the following detailed description of several specific embodiments. In the drawings:

Figs. 1 and 2 illustrate two embodiments of the invention employing concentric tubular electron streams with a center ion removal rod; and

Fig. 3 shows details of the cathode structure of Figs. 1 and 2.

At least one embodiment of the above-noted Hebenstreit-Pierce application comprises an amplifier utilizing a pair of concentric electron streams of circular cross-section, the inner of which is solid, to secure gain. It has since been shown that for a given flow of electron current, a marked increase in gain may be had if the inner stream is also tubular in nature and approximates the outer stream in size. It has been found that the gain obtainable by interaction between two electron streams having different velocities is a function of, among other things, the distance of separation between the two streams. Thus, a tubular inner beam will produce substantially greater gain than a solid inner beam having the same total current flow since more of the electrons comprising the tubular beam are thereby brought closer to those comprising the outer beam. Power dissipation and beam definition difficulties which would tend to appear if the total current flow of a solid inner beam were increased in the hope of securing increased gain are avoided.

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Referring particularly to Fig. 1, the elongated cylindrical tube envelope 10 is made of a highly conductive non-magnetic metal such as, for example, copper. The extreme left-hand end section of envelope 10 encloses a pair of axially aligned indirectly heated annular cathodes 11 and 12. The axes of cathodes 11 and 12 coincide with the central axis of envelope 10 and cathode 11 is situated to the right of cathode 12. Cathode 11 has a larger diameter than cathode 12. Both cathodes 11 and 12 have electron-emissive coatings on portions of their right-hand surfaces, the coated portion of each cathode surface being circular in shape and having a width that is many times smaller than the cathode diameter. The outside diameter of the electron-emissive surface of cathode 12 is only slightly smaller than the inside diameter of the emissive surface of cathode 11, the difference being only a small fraction of either diameter and comparable to about half the width of either cathode. A more complete description of cathodes will be given in connection with Fig. 3.

A control grid 13 is situated to the right of cathode 12 and a similar control grid 14 is located to the right of cathode 11. Envelope 10 is provided with an inward-projecting flange 15 to the right of grid 14 and an accelerating grid 16 is situated at that point.

Cathode 12 is connected to the negative terminal of a main battery 17. An auxiliary battery 18 is connected between cathode 12 and grid 13, maintaining grid 13 positive with respect to cathode 12. Cathode 11 is connected to a point on battery 17 that is positive with respect to cathode 12, and an auxiliary battery 19 is connected between cathode 11 and control grid 14, maintaining grid 14 positive with respect to cathode 11. Metallic envelope 10 is connected to a point on battery 17 that is positive with respect to both cathode 11 and grid 14. Grid 16, being connected to flange 15, is at the same potential as envelope 10.

A flat circular metallic collector plate 20 is situated at the right-hand end of tube envelope 10, is axially aligned with cathodes 11 and 12, and is connected to the most positive point on battery 17. A glass seal 21 is provided at the extreme left end of envelope 10 and a similar glass seal 22 is situated at the right-hand end, enabling the enclosure to be evacuated (by means not shown). A cylindrical focusing coil 23, supplied with direct current from a battery or other suitable source (not shown) surrounds and is axially aligned with tube envelope 10 and provides a strong longitudinal magnetic field within tube 10.

The parts thus far enumerated comprise means for projecting a pair of concentric tubular electron beams 24 and 25 lengthwise of tube 10 with different average velocities. Due to the structure of cathodes 11 and 12 and the effect of the magnetic focusing field, the walls of beams 24 and 25 are thin with respect to the beam diameters and the outside diameter of inner beam 25 is very nearly equal to the inside diameter of outer beam 24. Due chiefly to this beam formation, practically all the electrons comprising outer beam 24 are in very close proximity to practically all the electrons comprising inner beam 25 and close coupling exists.

The potential difference between cathodes 11 and 12 and accelerating grid 16 determine the electron velocities of beams 24 and 25, respectively. Since cathode 11 is at a positive potential with respect to cathode 12, the average velocity of inner beam 25 is greater than that of outer beam 24. Provided that certain quantities have the proper magnitudes, these quantities being principally velocity difference between the two streams and current density in the streams, electron streams 24 and 25 are capable of amplifying a signal that may be impressed upon either or both of them. The distance allowed for the travel of streams 24 and 25 should preferably be at least several wavelengths in the electron streams at the signal frequency; the greater the distance, the greater the amplification, up to an asymptotic limit.

The above-mentioned amplification has been described in detail in the previously noted Hebenstreit-Pierce application and will be described here only briefly. Although the actual mechanism of energy interchange between closely coupled electron beams of different average velocities appears to be rather complicated and involved, amplification may be considered, for purposes of explanation, to take place as follows. A signal is somehow impressed upon one of the streams. A large number of methods and devices for so impressing a signal were disclosed in the Hebenstreit-Pierce application and one such device will be later described as adapted for use in the present amplifier. The signal, as impressed upon the stream may, for example, take the form of electron density modulation. Through electron interaction, a signal corresponding to that impressed upon the first stream appears in the second. The resulting disturbance on the second stream produces, through electron interaction, another disturbance on the first stream, thus causing the initial disturbance to be reinforced. The increased disturbance on the first stream in turn causes reinforcement of the one appearing in the second stream. The reinforcing process continues as the electron streams progress along their allotted path of travel and the amplified signal may be removed at or near the end of the path.

As was noted above, in order to utilize the amplification powers inherent in a pair of such streams, suitable means must be provided for modulating one or both streams near their source by the wave to be amplified, and for abstracting the amplified wave energy from one or both streams near the end of their travel.

The example of such modulating means shown in Fig. 1 comprises a conductive wire helix 26 supported on ceramic rods 27 or on the inside surface of a ceramic cylinder. The helix 26 embraces both streams 24 and 25 for a distance near the beginning of their travel path. An input lead 28 is brought in through a glass seal 29 and a hole 30 bored lengthwise in tube envelope 10 from its left end through to a larger diameter inner space beyond flange 15. Input lead 28 is coupled to a suitable point on helix 26 through a coupling condenser 31, the tapping point on the helix and the size of condenser 31 being chosen to give an impedance match between the external input circuit and the helix. A suitable matching termination is provided at the right-hand end of helix 26 by spraying a thin layer of conducting material on ceramic rods 27 at or near their right-hand ends. Helix 26 is connected to tube envelope 10 and is at the same potential. Its inside diameter is somewhat greater than the outside diameter of outer stream 24.

For very small differences between the velocities of beams 24 and 25, the velocity of propagation of a wave along helix 26 may, for example, be made the mean between the beam velocities. For larger velocity separations, the velocity of one stream may be adjusted to equal the velocity of propagation along helix 26.

The means shown in Fig. 1 for taking out the amplified signal is likewise a helix 32 surrounding electron beams 24 and 25 near the end of their travel, just short of collector 20. Helix 32 is similarly connected to the external, in this case the output, circuit by an output lead 33. Output lead 33 is coupled to a suitable point on helix 32 through a coupling condenser 34, and is taken out through a hole 35 bored lengthwise in tube envelope 10 from its right end through to an inner space to the left of collector 20. Hole 35 is provided with a glass seal 36. As before, helix 32 is supported on ceramic rods 37 and a suitable matching termination is provided at the left-hand end of helix 32 by spraying a thin layer of conducting material on the supporting rods 37 at or near their left-hand ends. As before, helix 32 is connected to tube envelope 10 and is at the same potential. The inside diameter of helix 32 is also slightly greater than the outside diameter of outer stream 24.

In Fig. 1, as in Fig. 2 to follow, the electrical rather than the mechanical aspects of the device have been stressed, and no attempt has been made to show how the various elements would be supported in relation to each other or how their assembly would be provided for, since it is thought that all such features can be supplied in an obvious manner from the mechanical side of the vacuum tube art. It is only pointed out here that suitable supports will be necessary in a practical embodiment for holding the parts in proper spaced relation to one another and for allowing for application to them of the necessary voltages. The tube can be evacuated in the usual manner. The diameter of tube envelope 10 may, if desired, be reduced somewhat over the portion which encloses that part of the path of travel of beams 24 and 25 lying between helices 26 and 32.

In the operation of devices of the character shown in Fig. 1, it is found that a certain number of positive ions are present because of the practical impossibility of completely removing all extraneous gas from the tube. When positive ions exist in the path of the interacting electron streams 24 and 25, groups of them tend to oscillate at certain frequencies and produce "noise." It is, therefore, highly desirable to remove as many ions as possible from the path of the streams. For this purpose, a ceramic rod 38 is inserted along the axis of tube 10 extending from a point just to the left of cathode 12 to a point just to the left of collector 20. Being of a ceramic material, the resistance of rod 38 is so high that for all practical purposes it may be considered to be an insulator. A very thin layer of conducting material such as, for example, colloidal graphite (aquadag) or finely divided metal is sprayed onto the surface of rod 38. The resistance of rod 38 is then still very high in comparison with a straight piece of wire of similar length, but is reduced from that of the unsprayed rod sufficiently to make the total potential drop due to ion currents (which are generally of the order of microamperes) along the entire length of rod 38 small in comparison with the potential difference between rod 38 and envelope 10. The left-hand end of rod 38 is connected to a variable tap on battery 17.

If the variable tap of battery 17 is so adjusted that rod 38 is held at a potential different from that of envelope 10 and helices 26 and 32, positive ions will tend to be removed. If rod 38 is positive with respect to envelope 10, it will tend to repel positive ions, driving them outward from the electron path to helices 26 and 32 or envelope 10. If, on the other hand, rod 38 is negative with respect to envelope 10, it will tend to attract ions, pulling them inward out of the electron path. The effectiveness of rod 38 in removing ions from the electron path is dependent to a large extent upon the difference in potential, positive or negative, between it and tube envelope 10. However, since a large difference in potential between rod 38 and envelope 10 will tend to disturb streams 24 and 25 by attracting or repelling them, as the case may be, it is necessary to arrive at a compromise. It has been found that rod 38 will remove ions and that the tube will operate satisfactorily if rod 38 is maintained at a potential substantially equal to that of cathode 12 or at a potential positive with respect to envelope 10 by approximately the amount that envelope 10 is positive with respect to cathode 11.

The diameter of rod 38 is many times smaller than the inside diameter of inner electron stream 25 in order to avoid unduly disturbing the radio frequency field set up by the streams 24 and 25 to any appreciable extent.

In an experimental model of the device shown in Fig. 1 having a total length of about twelve inches, the following direct operating voltages were found to give satisfactory results: cathode 12, ground; grid 13, ten volts positive; cathode 11, twenty-five volts positive; grid 14, thirty-five volts positive; envelope 10, fifty-five volts positive; collector 20, some potential greater than fifty-five volts positive; rod 38, either ground or eighty-five volts positive.

In Fig. 2, component parts of the device shown have been given reference numerals corresponding to similar parts shown in Fig. 1. The chief structural difference between the device shown in Fig. 1 and that shown in Fig. 2 is that the latter has a different type of signal abstracting means and a different type of ion removal rod.

Referring to Fig. 2, the inner conductor of a coaxial line 40 is connected to collector 20 and coaxial line 20 is taken out of the tube through glass seal 22. A short hollow metal cylinder 41 surrounds and is axially aligned with collector 20. Its right-hand end extends somewhat to the right of collector 20 and is connected by a metal flange 42 to the outer conductor of coaxial line 40. The left-hand end of cylinder 41 extends somewhat to the left of collector 20 and holds a grid 43 between cathodes 11 and 12 and collector 20. The outer conductor of coaxial line 40 is at the same potential as tube envelope 10 and the inner conductor is connected through a radio frequency choke 44 to the most positive point on battery 17. In practice, choke 44 may be a quarter wave line.

As an alternative to the reduced diameter of tube envelope 10 between helices 26 and 32 in Fig. 1, Fig. 2 shows a hollow metal inner cylinder 45 which has an inside diameter corresponding to that of the reduced diameter section of envelope 10 in Fig. 1. Cylinder 45 is concentric with envelope 10, is held in place by a number of annular ribs 46 connecting it to envelope 10, and is situated in the space between helix 26 and grid 43. This arrangement and the one shown in Fig. 1 are examples of means providing such reduced diameters and may be used alternatively if a reduced diameter section is desired.

In Fig. 2, a ceramic rod 47 is situated along the axis of tube 10 and extends from a point just to the left of cathode 12 to a point just to the left of grid 43. A fine wire helix is wound upon rod 47 throughout its length, causing rod 47 to present a high impedance to the radio frequency field set up within streams 24 and 25 and a low direct current resistance to ion currents. The low resistance to ion current flow renders the total potential drop along the entire length of rod 47 small in comparison with the voltage of battery 17. The helix should be so wound upon rod 47 that the velocity of propagation of a wave along it is different from the velocity of propagation of the impressed signal along streams 24 and 25. The left-hand end of rod 47 is connected to a variable tap on battery 17. If it is desired to omit the helix from one or more sections of rod 47, some provision should be made to maintain the remaining sections having the helix at approximately the same potential.

The operation of the embodiment of the invention shown in Fig. 2 is much the same as that of Fig. 1. A signal is impressed upon one of two concentric tubular electron streams 24 and 25 and is amplified due to energy interchanges between electrons of the two streams. In Fig. 2, energy is removed from streams 24 and 25 by a gap 43—20. Rod 47 operates to remove positive ions from the electron path in the same manner as does rod 38 of Fig. 1.

Although the different types of ion removal rods have been described only in connection with the respective embodiments of the invention in which they are shown, they are substantially interchangeable and may be used alternatively.

Details of the cathode structure of Figs. 1 and 2 are shown in Fig. 3. In Fig. 3, cathodes 11 and 12 are axially aligned and are spaced along the common axis, cathode 11 being shown situated to the right of cathode 12. Cathode 11 comprises a short hollow metal cylinder which is circular in transverse cross-section. The inside diameter of the cylinder is of the same order of magnitude as the outside diameter and the cylinder contains an annular recess 50 for the purpose of accommodating a heating coil. Recess 50 opens to the left in Fig. 3. A portion of the cylinder is of somewhat reduced inside diameter and extends slightly beyond the right-hand end of the rest of the cylinder. The right-hand surface 51 of that section is narrow with respect to the cathode diameters and is coated so as to cause it to emit electrons when heated. Cathode 12 is somewhat similarly constructed and includes a similar annular heating coil recess 52 which opens to the left. However, the outside diameter of cathode 12 is slightly less than the inside diameter of surface 51 of cathode 11. A portion of the cylinder comprising cathode 12 extends somewhat beyond the right-hand end of the rest of the cylinder and has the same outside diameter as the rest of the cylinder. The right-hand face 53 of that section is coated similarly to surface 51 of cathode 11 and is also narrow with respect to the cathode diameters.

The following emitting surface dimensions for cathodes 11 and 12 have been found to give satisfactory results and are given by way of example: outside diameter of surface 51, .460 inch; inside diameter of surface 51, .400 inch; outside diameter of surface 53, .370 inch; inside diameter of surface 53, .310 inch.

While the electron-emissive surface of each cathode has been shown as consisting of the area between two concentric circles, it is contemplated that areas of other shapes may be used if desired. For example, the curves defining the area need not be circular, but may take the form of ellipses or may even be irregular in nature.

Although the invention has been described largely with reference to several specific embodiments, various other embodiments will occur to those skilled in the art. In particular, many of the numerous devices for impressing a signal upon the electron streams and for extracting the amplified signal which were disclosed in the previously noted Hebenstreit-Pierce application may be used to advantage. The invention itself is to be limited only by the spirit and scope of the appended claims.

What is claimed is:

1. A microwave amplifier which comprises an elongated enclosure defining a path of travel for charged particles, electrode means at one end of said path to direct a pair of closely coupled hollow cylindrical streams of charged particles, one stream within the other, lengthwise along said path at discretely different average velocities, whereby said streams of charged particles interact electromechanically with each other to produce gain as they progress along said path, electrode means at the other end of said path to collect substantially all of the charged particles of both of said streams, coupling means to supply a signal to be amplified to at least one of said streams, and coupling means to withdraw amplified signal energy from at least one of said streams.

2. An amplifier in accordance with claim 1 in which said streams are essentially circular in cross-section and in which the difference between the average diameters of said streams is at least several times smaller than either diameter.

3. An amplifier in accordance with claim 1 in which said streams are essentially circular in cross-section, in which the outside diameter of the inner stream is substantially the same as the inside diameter of the outer stream, and in which the thicknesses of the stream walls are at least several times smaller than the respective stream diameters.

4. An amplifier in accordance with claim 1 in which both the difference between the average transverse dimensions of said streams and the thicknesses of the stream walls are at least several times smaller than either transverse dimension.

5. A microwave amplifier which comprises an elongated enclosure defining a path of travel for electrons, electrode means at one end of said path to direct a pair of closely coupled hollow cylindrical electron streams, one within the other, lengthwise along said path at different average velocities, whereby said streams interact electromechanically with each other to produce gain as they progress along said path, electrode means at the other end of said path to collect substantially all of the electrons of both of said streams, coupling means operable at one region along said path to impress a signal to be amplified on at least one of said streams, and coupling means operable at another region along said path to extract amplified signal energy from at least one of said streams.

6. A microwave amplifier which comprises an elongated enclosure defining a path of travel for electrons, electrode means at one end of said path to direct a pair of closely coupled hollow cylindrical electron streams in which the electromechanical coupling is substantial between substantially all of the electrons of one stream and substantially all of the electrons of the other lengthwise along said path at different average velocities, electrode means at the other end of said path to collect substantially all of the electrons of both of said streams, input coupling means at the upstream end of said path to impress a signal to be amplified on at least one of said streams, and output coupling means at the downstream end of said path to withdraw amplified signal energy from at least one of said streams.

7. An electronic amplifying device in accordance with claim 6 in which the length of the portion of said path over which the said electromechanical coupling is substantial is at least several wavelengths in the electron streams.

8. An amplifying space discharge device which comprises an elongated conducting envelope defining a path of travel for electrons, charged particle projection means positioned at one end of said enclosure, charged particle collection means positioned at the other end of said enclosure, means including charged particle acceleration means positioned between said projection means and said collection means to direct a pair of hollow cylindrical streams of charged particles, one stream within the other, at different average velocities along substantially the entire length of said path from said projection means to said collection means in an electromechan-

ically interacting relationship with each other, a rod-like conducting element situated centrally within said streams and extending along said path, and circuit means coupled to said rod-like conducting element for maintaining it at a direct potential substantially different from said envelope.

9. An amplifying space discharge device which comprises an elongated conducting envelope defining a path of travel for electrons, charged particle projection means positioned at one end of said enclosure, charged particle collection means positioned at the other end of said enclosure, means including charged particle acceleration means positioned between said projection means and said collection means to direct a pair of hollow cylindrical streams of charged particles, one stream within the other, at different average velocities along substantially the entire length of said path from said projection means to said collection means in an electromechanically interacting relationship with each other, a rod-like conducting element situated centrally within said streams and extending along said path, said rod-like element having an impedance per unit length at the signal frequencies at least several times that of a uniform metallic conductor, circuit means coupled to said rod-like element for maintaining it at a direct potential substantially different from said envelope, means operative at one region along said path for impressing an alternating signal on at least one of said streams, and means operative at another region along said path for extracting an alternating signal from at least one of said streams.

10. An amplifier in accordance with claim 8 in which said streams are substantially circular in cross-section and are concentric, and in which said rod-like conducting element is elongated, disposed along the common axis of said streams, and has an over-all transverse dimension at least several times smaller than the diameter of either of said streams.

11. An amplifier in accordance with claim 8 in which the over-all transverse dimension of said rod-like conducting element is at least several times smaller than the over-all transverse dimension of either of said streams.

12. A space discharge device comprising electron projection means and electron collection means spaced apart to define a path of travel for electrons, means to direct a pair of substantially tubular electron streams, one within the other, along said path from said projection means to said collection means in an energy interchanging relationship, whereby said electron streams interact to produce gain as they progress along said path, a rod of insulating material situated within said streams and along said path, said rod having a transverse dimension at least several times smaller than the transverse dimension of either of said streams and having a thin layer of conducting material on its outer surface, whereby the resistance of said rod is at least several times that of a uniform metallic conductor, and means coupled to said rod for maintaining it at a potential substantially different from that of said path defining means.

13. A space discharge device comprising electron projection means and electron collection means spaced apart to define a path of travel for electrons, means to direct a pair of substantially tubular electron streams, one within the other, along said path from said projection means to said collection means in an energy interchanging relationship, whereby said electron streams interact to produce gain as they progress along said path, a rod of insulating material situated within said streams and along said path, said rod having a transverse dimension at least several times smaller than the transverse dimension of either of said streams and having a fine metallic wire wound around it over at least a portion of its length, and means coupled to said rod for maintaining it at a potential substantially different from that of said path defining means.

14. A space discharge device in accordance with claim 13 which includes means coupled to at least one of said streams for impressing an alternating signal upon it and means coupled to at least one of said streams for extracting an alternating signal from it, and in which the impedance at the signal frequency of said rod with said wire wrapped around it is at least several times that of a uniform metallic conductor.

15. An amplifying space discharge device comprising an evacuated metallic enclosure, electron projection means and electron collection means spaced apart within said enclosure to define a path of travel for electrons, means to direct a pair of substantially tubular electron streams, one within the other, along substantially the entire length of said path from said projection means to said collection means in an energy interchanging relationship, whereby said streams interact to produce gain as they progress along said path, means operable at one region along said path for impressing a signal on at least one of said streams, means operable at another region along said path for extracting a signal from at least one of said streams, a high impedance elongated rod-like element situated within said streams and along said path, and means coupled to said rod-like element for maintaining it at a potential substantially different from that of said metallic enclosure, whereby an electric field is established between said rod-like element and said metallic enclosure which tends to remove positively charged particles from the paths of said electron streams.

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