

April 8, 1958

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2,830,271

MODULATED MICROWAVE OSCILLATOR

Filed Feb. 18, 1953

2 Sheets-Sheet 1

FIG. 1

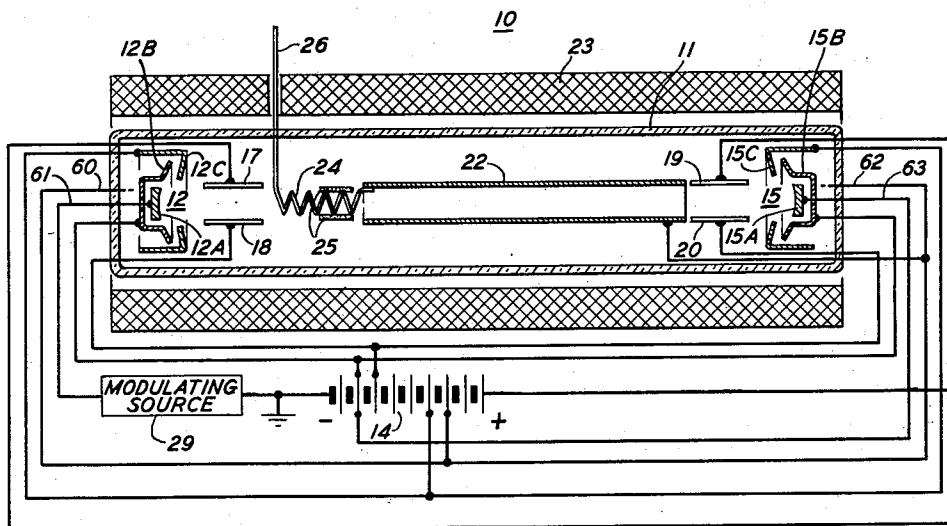
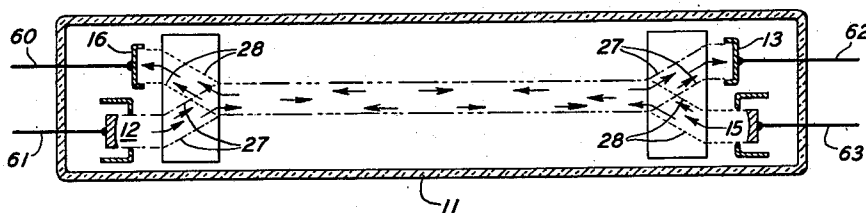


FIG. 2



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FIG. 3

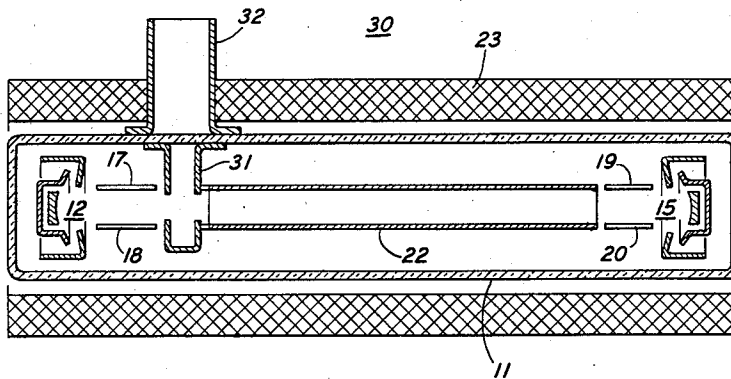
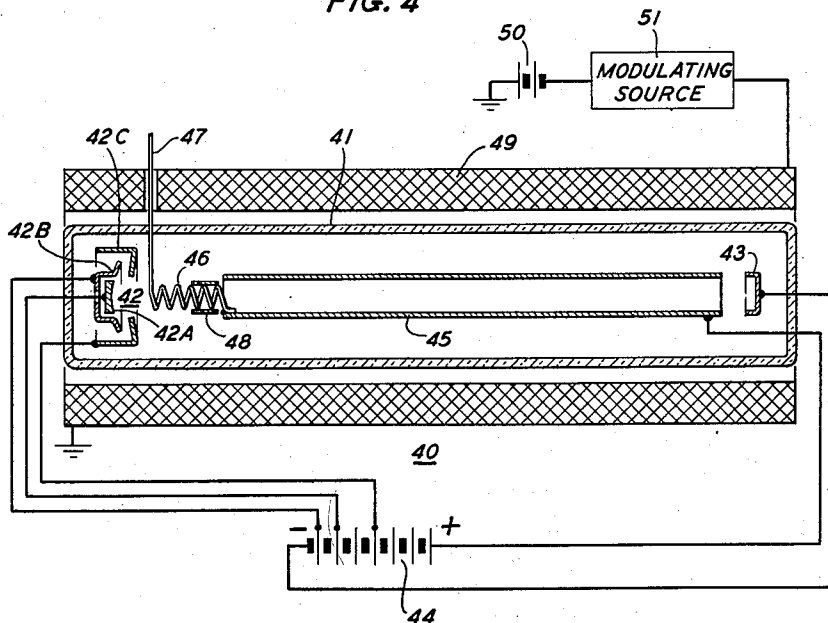


FIG. 4



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MODULATED MICROWAVE OSCILLATOR

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8 Claims. (Cl. 332-7)

This invention relates to microwave devices which employ the interaction between a traveling wave and an electron stream over a plurality of operating wavelengths and more particularly to such devices which employ as the traveling wave a wave disturbance progressing on an electron stream.

Recently, it has been found that an electron stream can be made to interact usefully with an electromagnetic wave traveling along an electromagnetic wave circuit in a direction opposite to the direction of electron motion. In such operation, the electron stream interacts with the forward traveling spatial harmonics of the backward traveling wave. To this end, there is utilized a wave interaction circuit in which an electromagnetic wave whose group velocity is in a direction opposite to the direction of electron flow sets up spatial harmonic modes having a phase velocity in the direction of electron flow. Such devices are now generally characterized as backward wave tubes.

Backward wave tubes are now believed to be potentially very important. In particular, there have been devised backward wave tube oscillators which can be tuned electronically over a continuous range of thousands of megacycles. Such oscillators manifestly can be very useful in frequency modulation transmission systems and in various other applications. However, backward wave tubes have hitherto generally required electromagnetic wave interaction circuits which must be critically positioned and accurately dimensioned. In addition, the physical discontinuities generally associated with such interaction circuits result in wave reflections which often modify the operating characteristics of such tubes undesirably. Accordingly, it would be desirable to eliminate the need for the usual kind of interaction circuit in such backward wave tubes, particularly in backward wave tube oscillators where wave reflections are especially undesirable.

To this end, it is in accordance with the present invention to utilize an electron stream as a circuit element in a backward wave type oscillator for propagating signal energy for interaction with a second electron stream, and there is employed the principle that, under conditions to be set forth, space charge wave traveling on an electron stream can have a phase velocity in a direction opposite to that of the group velocity.

In an illustrative embodiment of the invention to be described, a microwave oscillator of the backward wave type employs interaction between a first electron stream and a space charge wave traveling along in the direction of the first electron stream on a second electron stream which is oppositely directed with respect to the first electron stream and which is oscillating under the action of a magnetic field. Oscillatory energy is abstracted from the first electron stream by a transducer element suitably positioned in coupling relation downstream along this first electron stream. By this arrangement, there is obviated the need for the customary wave interaction circuit.

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Moreover, an oscillator of this kind can be readily adapted for use as a frequency modulator by utilizing the modulating intelligence to vary any one of several of the tube parameters.

The invention will be better understood from the following more detailed description which is to be taken in conjunction with the accompanying drawings in which:

Fig. 1 shows schematically, in a vertical longitudinal cross sectional view and as an illustrative embodiment of the invention, a double stream oscillator which can be adapted for use as a frequency modulator;

Fig. 2 is a horizontal sectional view of the tube illustrated in Fig. 1 in which there is shown essentially only the elements determining the paths of the two electron streams;

Fig. 3 is a longitudinal sectional view of a modification of the oscillator shown in Fig. 1; and

Fig. 4 is a longitudinal sectional view of an embodiment of the invention which utilizes reflexing of a first electron stream to obtain an oppositely directed second electron stream.

Before describing in detail illustrative embodiments of the invention, it will be helpful to analyze first some of the principles applicable.

It is known that a stream of electrons carries energy in the direction of electron motion. It is intended additionally to show that a wave disturbance on a stream of electrons can travel in a direction opposite to the direction of electron motion. Moreover, it is further proposed that such an electron stream be made to act as a wave circuit for propagating a space charge wave for interaction with another stream of electrons.

First let there be considered a stream of electrons projected right to left through a longitudinal magnetic field. As is well known such a stream will oscillate in the magnetic field at the cyclotron radian frequency ω_c which is given by

$$\omega_c = \frac{e}{m} B \quad (1)$$

where e and m are measures of the charge and mass, respectively, of an electron and B is a measure of the strength of the longitudinal magnetic field, provided that it can be assumed that the electron stream is not so dense that the cyclotron radian frequency is modified very much by space charge effects.

If an observer moves with the electrons, the phase of the oscillations to such an observer will be such that the oscillations constitute a wave of amplitude given by

$$e^{j(\omega_0 t - \beta z')} \quad (2)$$

where β is the phase propagation constant of the oscillatory wave and z' is measured with respect to the observer positive in the direction of travel of the electrons. Now let

$$z' = z + u_0 t \quad (3)$$

where u_0 is the average speed of the electron stream and z is measured with respect to a fixed frame of reference. This means that in the z coordinate system the electrons move in the $-z$ direction with the speed of u_0 . In a z coordinate system, the wave now varies as

$$e^{j(\omega_0 t - \beta(z + u_0 t))}$$

This can be written as

$$e^{j((\omega_0 - \beta u_0)t - \beta z)} \quad (4)$$

Accordingly, in the fixed coordinate system, the radian frequency of the wave disturbance traveling on the electron stream will be given by

$$\omega = \omega_0 - \beta u_0 \quad (5)$$

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In terms of ω and ω_c the phase propagation constant β is given by

$$\beta = \frac{\omega_c - \omega}{u_0} \quad (6)$$

With respect to the fixed coordinate system, the various quantities will then vary as

$$e^{j\omega t} e^{-j\beta z} \quad (7)$$

Now, if ω_c is greater than ω the wave disturbance on the electron stream is moving to the right, while the electrons go to the left. The speed u with which the wave goes to the right is given by

$$u = \frac{\omega}{\beta} = \frac{u_0}{\frac{\omega_c}{\omega} - 1}$$

Now let us suppose there is projected a second electron stream moving to the right in a direction opposite to that of the first stream but sufficiently near to or interpenetrating the first stream so as to be in electromechanical coupling relation therewith and having a speed u_1 which is close to the speed of the wave disturbance u . Under such conditions, the interaction of the electric fields of the two streams will result in amplification of this wave disturbance and accordingly, oscillations of this frequency will be sustained. Therefore, to achieve oscillations at a particular radian frequency ω , the second electron stream is projected past the first electron stream at a speed u_1 , such that this speed u_1 is approximately equal to the speed u associated with a wave disturbance of radian frequency ω . In this way from the noise on the first electron stream there is selectively amplified the wave disturbance of the desired frequency, and oscillations at this frequency are established. The radian frequency ω of these oscillations will be given by

$$\omega = \frac{\omega_c}{1 + \frac{u_0}{u_1}} \quad (8)$$

Fig. 1 shows schematically, by way of example, for purposes of illustration, a double stream oscillator 10 in accordance with the invention. An evacuated elongated tubular enclosure 11 which, for example, can be a glass envelope, houses the various tube elements. At the left-hand end of the enclosure, there is positioned a first electron gun 12 which can be of conventional design for emitting a cylindrical electron stream for projection longitudinally along the major portion of the length of the enclosure 11 for eventual collection by a suitable target or collector electrode 13 positioned at the right-hand end of the enclosure (shown in the view of Fig. 2). Such an electron gun customarily includes an electron emissive cathode surface, a heater unit, an intensity control element and an electrode system for forming and accelerating the electron stream. However, for purposes of simplicity, it will be convenient to illustrate such an electron gun 12 schematically by the cathode 12A, the control element 12B, and the accelerating anode 12C. The control element 12B and the anode 12C are maintained at suitable potentials with respect to cathode 12A by means of lead-in conductors which are tapped to a suitable voltage source 14. At the right-hand end of the enclosure, there is positioned a second electron gun 15 which can be of the type used at the left-hand end and, accordingly, which is similarly shown as the cathode 15A, the control element 15B, and the accelerating anode 15C, disposed for emitting an electron stream which is projected longitudinally the major portion of the length of the enclosure 11 for eventual collection by collector electrode 16 positioned at the left-hand end of the enclosure (shown in Fig. 2). The various operating potentials are applied by lead-in conductors suitably tapped to voltage source 14. At opposite ends of the region between electron sources 12

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and 15, there are positioned on opposite sides of the paths of electron flow the two pairs of deflection plates 17 and 18, and 19 and 20. Plates 17 and 18 are maintained positive and negative, respectively, with respect to the accelerating anode 12C by suitable lead-in conductors tapped to voltage source 14. Similarly, plates 19 and 20 are maintained positive and negative, respectively, with respect to the anode 15B by suitable lead-in conductors tapped to voltage source 14. Along the major portion of the tube length intermediate the two sets of deflecting plates, there extends a hollow cylindrical electrode 22 axially aligned with the two coextensive electron paths, which provides a drift space region for the two electron streams. This electrode 22 is maintained at positive potentials with respect to cathodes 12A and 15A by a suitable lead-in conductor connected to voltage source 14. At the left-hand end of electrode 22 also axially aligned with the electron streams there is positioned an output coupling, or transducer, element, which, for example, is a helical conductor 24 preferably terminated at its right-hand end in its characteristic impedance and having its other end leading off to a suitable output coupling connection 26. To effect the desired termination of the right-hand end of the helical conductor 24, there is inserted coated on dielectric support rods 25, lossy material such as Aquadag. This helix is preferably maintained at the D.-C. potential of the electrode 22 by electrical connection thereto. The tube is immersed in a longitudinal magnetic field of strength B provided by an external solenoid 23.

Fig. 2 will be helpful in explaining the functions of pairs of deflecting plates 17 and 18, and 19 and 20 and the preferred relative positioning of electron guns 12 and 15 to collectors 16 and 13, respectively. In this figure, the envelope of the electron beam emitted from electron gun 12 is shown by the broken lines 27 while the envelope of the electron beam emitted to the left from the electron gun 15 is shown by the dotted lines 28. Fig. 2 is the view seen looking from the top of the page at a horizontal longitudinal section of the view shown in Fig. 1. The electric fields set up between deflecting plates 17 and 18 and plates 19 and 20 in conjunction with the longitudinal magnetic field B provided by the external solenoid 23 act to deflect the electron beams emitted from the electron guns 12 and 15 in a direction transverse to both the electric and magnetic fields as shown. Each cathode and its associated collector are positioned on opposite sides of the tube axis. By this expedient the paths of the two electron streams can be substantially coextensive along the tube axis for the major portion of their lengths whereby electromechanical coupling between the two streams is effected, while at the same time the two electron streams can be kept relatively distinct at their respective path ends to minimize the reflexing of electrons. The strength of the deflecting fields and the positioning of the various affected elements are adjusted, accordingly. The cylindrical electrode 22 also is positioned to surround both paths of the electron flow long their substantially coextensive region. The potential on this electrode with respect to that of each cathode serves as the accelerating voltage primarily determining the velocity of each of the two electron streams. The longitudinal magnetic field B tends to suppress undesirably large transverse components of electron velocity except at the regions of beam deflection adjacent the deflecting plates 17 and 18 and 19 and 20.

The operation is in accordance with the principles set forth above. To provide oscillations of a desired radian frequency ω , the strength of the magnetic field B and the magnitudes of the velocities u_0 and u_1 of the two electron streams are adjusted so that

$$\omega = \frac{\omega_c}{1 + \frac{u_0}{u_1}} \quad (9)$$

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where, as described above, the cyclotron radian frequency ω_c is given by

$$\frac{e}{m}B$$

Moreover, for improved efficiency, the output coupling element 24 is preferably adjusted to offer a high impedance to waves of radian frequency ω . Where operation is to be over a band of frequencies, the element 24 is adjusted to offer a high impedance to waves having a radian frequency ω_m where ω_m is the radian frequency of the center of the band. A helix coupling element is advantageous since it offers both a high impedance to the electron stream and additionally is efficient over a wide frequency band. The pitch of this helical conductor is adjusted to provide an axial wave velocity to oscillatory waves propagating therealong sufficiently close to the velocity of the electron stream being emitted from electron gun 15 from which energy is to be abstracted so as to provide conventional traveling wave type interaction therebetween. Alternatively, where broad band operation is less important, it is possible to employ as the coupling element a resonant cavity suitably apertured for passage of the electron stream and resonant at the desired frequency of oscillations. An oscillator 30 of this kind is shown in Fig. 3 in which the coupling element is a resonant cavity 31 which is excited by the velocity modulations on the electron stream and which thereafter supplies the oscillatory energy to a hollow wave guide external coupling connection 32 to which it is capacitively coupled through the glass envelope. In other respects, this tube resembles that shown in Fig. 1, and accordingly, similar reference numerals are used to designate corresponding elements.

An examination of the Equation 9 shows that the radian frequency ω of the oscillations may be varied by changing the magnitude of any of three parameters ω_c , u_0 and u_1 . In practice, it is generally most convenient to vary the magnitude of either u_0 or u_1 , the velocities of the two electron streams. The velocity of each stream is determined by the accelerating voltage acting thereon, and accordingly, changes in this accelerating voltage will result in corresponding changes in the oscillatory frequency. There then results an oscillator whose operating frequency can be tuned electronically by varying the accelerating voltage acting on either stream. In an important aspect, the invention relates to a frequency modulator in which a signal voltage whose amplitude varies in accordance with modulating intelligence is inserted in series with the steady D.-C. accelerating voltage acting on one electron stream to provide an output whose frequency is a measure of the modulating intelligence. To this end, in Fig. 1 there is shown inserted in series with the accelerating voltage applied between the cathode 12A and the cylindrical electrode 22 a source 29 of signal voltage controlled by modulating information. It is found preferable to modulate the electron stream which is not coupled to the transducer element 24 so that maximum coupling can be maintained between the transducer element 24 and the stream to which it is coupled.

It is in accordance with another embodiment of the invention to employ a single electron source and to reflex the electron stream originating from this source to provide effectively an oppositely directed second electron stream. Fig. 4 shows an oscillator 40 adapted for operation of this kind. At one end of the evacuated glass envelope 41, there is positioned an electron source 42 comprising a cathode 42A, an intensity control grid 42B, and an accelerating anode 42C, for forming and projecting an electron stream along the longitudinal axis of the tube. At the opposite end of the envelope 41 and in target relationship with the cathode 42A is the reflex electrode 43, which is maintained at a potential suitably negatively with the cathode 42A as required for reflex operation, by lead-in conductors connected to a voltage source 44. A

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hollow cylindrical electrode 45 axially positioned around the path of electron flow forms a drift space of the major portion of the region between the electron gun and the reflex electrode. This electrode 45 is maintained at a potential positive both to the cathode 42A and the reflex electrode 43 by a lead-in conductor tapped to the voltage supply source 44 whereby there is provided an accelerating voltage for the electron flow. Preferably between the electron gun 42 and the electrode 45 and along the path of electron flow there is positioned an output coupling or transducer element which, for example, is a helical conductor 46 wound to a pitch to provide an axial velocity of waves propagating therethrough equal to that of the electron flow therepast. The electron gun end of the helix 46 leads off to a suitable output coupling connection 47 and the opposite end, which preferably is connected electrically to the electrode 45 whereby the helix is maintained at the same D.-C. potential, is terminated in the characteristic impedance of the helix by the insertion of lossy material sprayed on dielectric support rods 48. The tube is immersed in a longitudinal magnetic field of strength B provided by an external solenoid 49.

The principles of operation are similar to those set forth above. In this case, however, the function of the second electron stream is served by the reflexed electron stream. This reflexed electron stream has the same speed as the first electron stream, so that the parameters u_0 and u_1 appearing in expression 9 are equal.

Accordingly, the expression for the radian frequency ω of the oscillations becomes

$$\omega = \frac{\omega_c}{2} \quad (11)$$

Tuning is effected by varying the strength of the magnetic field B which can be accomplished by changing the current through solenoid 49 which is controlled by the voltage source 50. For frequency modulation operation, the solenoid current is varied in accordance with modulating intelligence by means of a modulating source 51 in series with voltage source 50.

It should be evident at this point that the several embodiments described above are merely illustrative of the general principles of the invention. Various alternative arrangements can be devised by one skilled in this electronic devices art without departing from the spirit and scope of the invention.

Reference is made to my United States Patent No. 2,635,206, issued April 14, 1953, and United States Patent No. 2,730,647, issued January 10, 1956, which similarly relate to radio frequency apparatus utilizing two oppositely directed electron streams.

What is claimed is:

1. In combination, a hollow enclosure, an electron emitter at each of two opposite ends of the enclosure for forming an electron stream, an electron collector at each of said two opposite ends for collecting the electron stream originating from the emitter at the opposite end, the electron paths between the two emitters and collectors being substantially coextensive along the major portion of each of the paths whereby the two electron streams are therealong electro-mechanically coupled for electrical interaction therebetween, an electrode positioned along a coextensive portion of each of the two paths for forming a drift space region therealong extending over a major portion of the interaction region of said streams, a coupling element positioned at substantially the end of one path and at the end of said drift space for abstracting oscillatory energy from its associated electron stream.

2. In combination, a hollow enclosure, an electron emitter at each of two opposite ends of the enclosure for forming an electron stream, an electron collector at each of said two opposite ends for collecting the electron stream originating from the emitter at the opposite end, the electron paths between the two emitters and collectors being substantially coextensive along the major por-

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tion of each of the paths whereby the two electron streams are therealong electro-mechanically coupled for electrical interaction therebetween, an electrode positioned along the coextensive portion of each of the two paths for forming a drift space region therealong extending over a major portion of the interaction region of said streams, and a helical conductor positioned at the end of one electron path and at the end of said drift space and having a pitch adjusted to provide an axial wave velocity for oscillatory wave propagating therealong substantially equal to the velocity of the associated electron stream.

3. In combination, a hollow enclosure, first and second electron emitters at each of two opposite ends of the enclosure for forming first and second electron streams respectively, first and second electron collectors at each of said ends for collecting the electron means originating from the second and first emitters respectively, the electron paths between the two emitters and collectors, being substantially coextensive along a major portion of each of the paths whereby the two electron streams are therealong electro-mechanically coupled for electrical interaction therebetween, an electrode positioned along the coextensive portion of each of the two paths for forming a drift space region therealong extending over a major portion of the interaction region of said streams, a helical conductor positioned at the end of the electron path associated with the first stream and at the end of said drift space and having a pitch adjusted to provide an axial wave velocity substantially equal to that of the first electron stream, and circuit means to be supplied with modulating intelligence for varying the direct current velocity of the second electron stream in accordance with the modulating intelligence.

4. In combination, means for forming two electron streams, the paths of flow of the two streams being substantially coextensive and the direction of flow opposite along a major portion of each of said paths whereby the two electron streams are therealong electro-mechanically coupled for electrical interaction therebetween, a conductive element surrounding a major portion of said paths along their interaction length for providing an electric field for accelerating said electron streams, and a coupling element at substantially the end of one path and at the end of said conductive element for abstracting oscillatory energy from the electron stream associated with said last-mentioned path.

5. In combination, means for forming two oppositely directed electron streams, the paths of flow of the two streams being substantially coextensive along the major portion of each of said paths whereby the two electron streams are therealong electro-mechanically coupled for electrical interaction therebetween, a conductive element surrounding a major portion of said paths along their interaction length for providing an electric field for accelerating said electron streams, a coupling element positioned at substantially the end of one path and at the end of said conductive element for abstracting oscillatory energy from the electron stream associated with said last-mentioned path, and circuit means to be supplied with modulating intelligence for varying the direct current velocity of one electron stream relative to the direct cur-

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rent velocity of the other electron stream in accordance with the modulating intelligence.

6. In combination, means for forming two oppositely directed electron streams, the paths of flow of the two streams being substantially coextensive along the major portion of said paths whereby the two electron streams are therealong electro-mechanically coupled for electrical interaction therebetween, a conductive element surrounding a major portion of said paths along their interaction length for providing an electric field for accelerating the electron streams, a helical conductor positioned at substantially the end of one path and at the end of said conductive element for abstracting oscillatory energy from the first of the two electron streams, and circuit means to be supplied with modulating intelligence for varying the direct current velocity of the second electron stream relative to the direct current velocity in the first electron stream in accordance with the modulating intelligence.

7. In combination, means for forming two oppositely directed electron streams, the paths of flow of the two streams being substantially coextensive along the major portions of each path whereby the two electron streams are therealong electromechanically coupled for electrical interaction therebetween, a conductive element surrounding a major portion of said paths along their interaction length for providing an electric field for accelerating the electron streams, a transducer element positioned at substantially the end of one path and at the end of said conductive element for abstracting oscillatory energy from the electron stream associated with said last-mentioned path, means for providing a magnetic field along said paths of flow, and means for varying the strength of the magnetic field in accordance with modulating intelligence for modulating the frequency of oscillations.

8. In radio frequency apparatus, means for forming a first electron stream of velocity u_0 , means for providing a magnetic field along the path of flow of said stream whereby the electrons oscillate with cyclotron frequency ω_c , a transducer element positioned downstream along said stream and adjusted for abstracting oscillatory energy of frequency ω therefrom, and means for forming and projecting a second electron stream in a direction opposite to that of said first stream along a path substantially coextensive with the path of said first stream and having a velocity u , given by the expression:

$$\frac{u_0}{\left(\frac{\omega}{\omega_c} - 1\right)}$$

said streams being electro-mechanically coupled for electrical interaction therebetween over a major portion of the paths of flow of said streams, and a conducting element surrounding a major portion of said paths for providing an electric field for accelerating said streams.

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