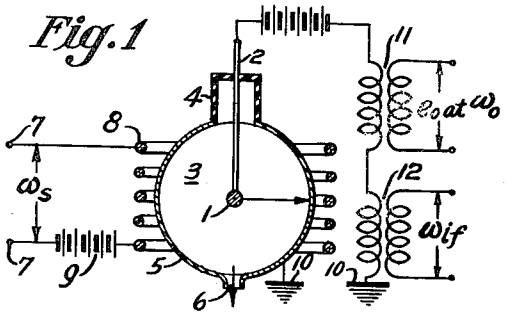
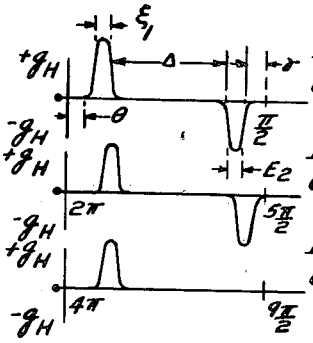
Oct. 2, 1951 J. H. COLEMAN 2,569,924

VACUUM TUBE MIXING CIRCUITS

Filed Oct. 30, 1948

Fig. 1





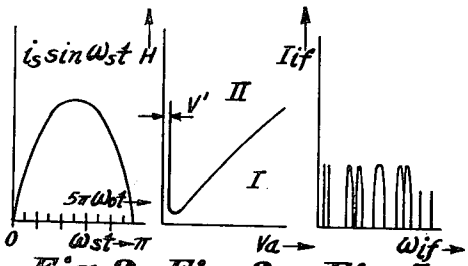


Fig. 2 Fig. 3 Fig. 5

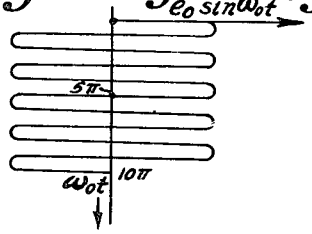


Fig. 4

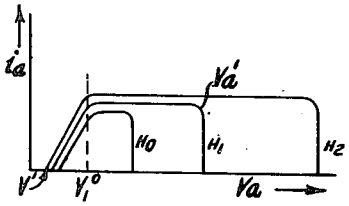
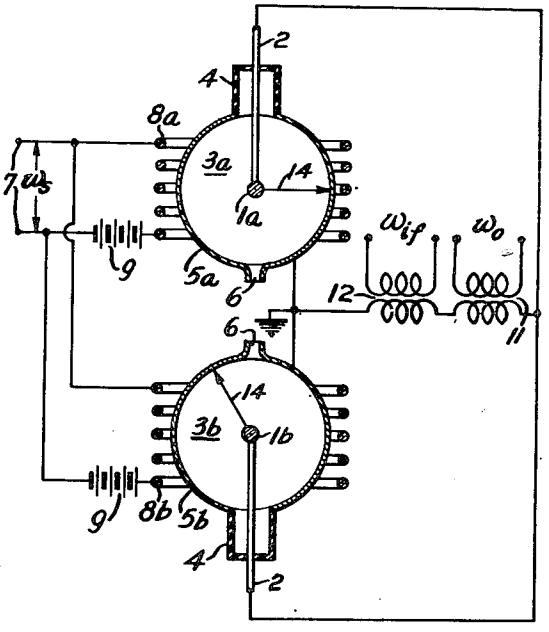


Fig. 7

Fig. 8



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VACUUM TUBE MIXING CIRCUITS

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Application October 30, 1948, Serial No. 57,461

10 Claims. (Cl. 332—57)

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This invention relates generally to vacuum tube mixing circuits and more particularly to such mixing circuits in which the cathode of the tube is "cold" and has deposited thereon a radioactive material and in which the space between the tube electrodes is subjected to a magnetic field.

It is known that certain isotopes are radioactive and emit nuclear charged particles at known rates over known periods of time and over a range of energy values or levels expressed in electron volts. Some emissions consist of positively charged or alpha particles, others of negatively charged or beta particles and others of both alpha and beta particles. With the emission of a charged particle from the nucleus of an atom, there occurs a transmutation of the atom into an atom of another element and this atom may or may not be radioactive and it may or may not be gaseous in form.

It is also known that when certain materials are subjected to nuclear radiation bombardment, a number of electrons around the nucleus of the bombarded atom are knocked out of their orbits and projected into space. This phenomenon is known as secondary emission. The number of secondary electrons emitted per bombarding particle depends upon the bombarded material itself and upon angle of incidence and the velocity of the bombarding particle. In general, the less the angle of incidence of a high energy particle the less is the number of secondary emitted electrons and the less the velocity of a bombarding particle, the greater is the number of secondary emitted electrons.

These secondary emitted electrons have relatively low energy values compared with the primary emission values. Their further movements after leaving the bombarded surface depends upon their initial velocities and their initial random direction and upon the electric and electromagnetic fields in the region where they leave the bombarded surface.

When these secondary electrons strike other secondary-emission responsive materials, further secondary emissions may occur, the amount of such secondary emission depending upon the velocity of the electrons and the angles of incidence and the character of the material bombarded.

In considering the available radioactive materials, phosphorus^{32} has been selected to illustrate the invention as it is a pure beta emitter of sufficient average energy levels for the particles to reach the secondary emission responsive electrode of the tube and with sufficient energy as

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to cause secondary electron emission. Also, phosphorus^{32} becomes stable after emission and is particularly adapted to high vacuum or rarified gas tube use as its decay products are not gaseous. There are, however, a large number of other suitable radioactive substances that may be used within the scope of the invention.

The instant invention comprises an improvement on the methods and systems disclosed and claimed in copending U. S. application Serial No. 51,756 filed September 29, 1948, which basic invention contemplates the use of a source of radioactive material (deposited on the cathode) and an electrode (anode) that is secondary emission responsive to the charged particle radiation of the source, the space between the source and the electrode being under vacuum and also subjected to a magnetic field proportional in strength to and corresponding in characteristics with a potential source desired to be amplified. The amplified potentials are made available in a load circuit connected between the anode and the cathode. The basic invention also disclosed and claims the combination of the tube and associated circuits adaptable as an oscillator.

The improvement of the instant invention comprises the new modification of the basic invention of impressing on the anode and cathode, potentials originating in an independent oscillating current source, whereby the tube functions as a mixer of the frequency of the local oscillators and the frequency of the currents creating the magnetic field, to obtain currents of an intermediate frequency.

Among the objects of the invention are to provide improved methods of and means for mixing two currents of different frequencies to obtain currents of an intermediate frequency.

Another object is to provide a method of and means for initiating conduction currents in a vacuum tube by particles emitted from a radioactive source and controlling these conduction currents by variations of a magnetic field generated by a current of one frequency and controlling these conduction currents by currents of another frequency to obtain currents of an intermediate frequency.

Another object of the invention is to vary the strength of a magnetic field impressed upon a vacuum tube, which tube includes a radioactive material as its cathode, in accordance with the frequency variations of an electrical signal and utilizing the corresponding variations in the magnetic field to control the currents in the load circuit of the tube and simultaneously to impress upon the tube potentials varying at a frequency

of a local oscillator to mix the two frequencies and obtain currents of an intermediate frequency.

Other objects will be apparent from the description of the invention as hereinafter set forth in detail and from the drawings made a part hereof in which: Figure 1 is a schematic diagram of an embodiment of the invention, showing the tube, a means for the impressing on the medium of the tube of a magnetic field varying in accordance with a signal frequency, a means for impressing potentials on the cathode and anode of the tube varying in accordance with the frequency of a source of local oscillations and means for utilizing the currents of the mixed and intermediate frequency; Figure 2 is a graph showing the relation of time to instantaneous values of the currents creating the magnetic field; Figure 3 is a graph showing the relation of the magnetic field in gauss to the voltage across the tube when the tube is just non-conducting; Figure 4 is a graph showing the relation of time to the instantaneous values of the potentials impressed on the cathode and anode of the tube by the local source of oscillations; Figure 5 is a graph showing the relation of time to the instantaneous values of the currents of the intermediate frequency; Figure 6 is a graph showing the relation of time to the instantaneous values of transconductance of the tube; Figure 7 is the graph of a family of curves showing the relation of the currents in the load circuit of the tube to potentials across the tube for three intensity values of the magnetic field impressed upon the medium of the tube; and Figure 8 is a schematic diagram of the device operated in push-pull with another device.

Similar reference characters are applied to similar elements throughout the drawings.

Referring to Figure 1, 1 represents a source of radioactive material, supported on rod 2, which is the cathode of a tube shown generally at 3. Rod 2 is mounted in a conventional manner in tube 3 through insulator 4. The anode 5 forms the envelope of the tube. The tube is kept under vacuum, (a residual pressure of less than 10^{-3} mm. Hg), by a conventional pump (not shown) communicating with exhaust connection 6. The envelope of the tube is permeable to an electromagnetic field created by currents from alternating current source 7 flowing through solenoid 8. The magnetic field is biased by electric source 9. Aluminum has been found to be a suitable material for anode 5. Anode 5 is grounded at 10.

The anode-cathode or load circuit of the tube consists of the secondary of transformer 11, the primary of transformer 12, and biasing electric source 13. The secondary of transformer 11 and the primary of transformer 12 are connected in series with each other and source 13. A terminal of the primary of transformer 12 is grounded at 10, and hence connected to anode 5, and the other end of the load circuit, the positive terminal of electric source 13, is connected to source 1.

The primary of transformer 11 is connected to the output of a local oscillator (not shown) and the terminals of the secondary of transformer 12 are the terminals of the intermediate frequency circuit.

When alternating currents flow through solenoid 8 from source 7, such as currents created by received signals at one frequency, and currents flow through the primary of transformer 11 at another frequency, tube 3 functions as a mixer tube and currents flow through transformer 12 at an intermediate frequency, as will be disclosed in detail hereinafter.

When there is no magnetic field present in the space between the source 1 and anode 5, the paths of the primary radiation particles from source 1 are straight lines from source 1 to anode 5, as shown by arrow 14. As the angles of incidence of the paths of the particles to the anode 5 are practically zero, the particles are captured or collected by anode 5 with little secondary electron emission. This is particularly true of the high energy particles from source 1.

If a unidirectional magnetic field is impressed on the medium of the tube and the field is increased, the primary charged particles from source 1 are deflected more and more, inversely as the velocity of individual particles. Some of the particles of high velocities will continue to follow the path of a straight line from source 1 to anode 5, but the paths of a large proportion of the medium velocity particles will be deflected and thereby increasing the angles of incidence and thus cause substantial secondary electron emission to be emitted from the surface of anode 5.

The secondary electrons are emitted from anode 5 at relatively low velocities compared with the primary particles, but they are likewise affected by the magnetic field and the electric field between source 1 and anode 5, the electrons being of relatively low velocities, their paths are deflected to a corresponding great extent. The particles are accelerated towards source 1, as source 1 is of a positive potential and anode 5 is of negative potential.

Whether these secondary electrons reach source 2 will depend upon their velocities and the strength of the magnetic field. The strength of the magnetic field and the voltage between source 1 and anode 5 may be adjusted to such values that the secondary electrons are cut off from reaching source 1 and are deflected to pass by source 1. The equation defining the conditions under which the secondary electrons will cut off from or miss source 2 is

$$H=2\sqrt{2}\cdot\sqrt{\frac{m}{e}}\cdot\frac{r}{R}2\sqrt{V} \qquad (1)$$

where e is the charge of particle, H is the magnetic field, m is the mass of the particle, r is the radius of the source 1, R is the radius of anode 5 and V is the potential of source 1, all in C. G. S. units (see Hull, Physics Review 1921, volume 18, page 35).

When this cut off condition is reached, the electrons passing by source 1 continue on their curved paths and strike anode 5, causing further secondary electron emission from anode 5. As the electrons that pass by source 1 are of relatively low velocities, the number of secondary electrons emitted per individual electron striking anode 5, is relatively high. Thus a copious supply of free electrons are trapped within the space of anode 5 and source 1.

Because the secondary electrons are cut off from source 1, and are deflected successively by anode 5, the paths of the electrons are lengthened until, after several reflections from anode 5, their paths become longer than the mean free path for collision with the residual molecules of the medium and ionization of the medium occurs.

When the medium is ionized, there will also be a flow of the positively charged ions toward the anode 5, as anode 5 is of a negative potential. The bombardment of anode 5 by these ions will

cause further secondary emission from anode 5. Thus large conduction currents flow across the tube and through the load circuit as long as source 1 is positive with respect to anode 5.

It has been found by observations that when the magnetic field is reversed in direction, the same phenomenon exists. With a reversed magnetic field, the paths of the particles are deflected in the opposite direction but to the same degree for corresponding values of field strength.

In applying the invention to a practical operating condition, the constants of circuits and sources of electrical energy, such as the resistances of coils, the magnetic field produced by different coils under different current conditions, available voltages, etc. are known or may be determined by conventional methods.

The operating characteristics of the tube for any range of operating conditions may likewise be determined in the same manner as for any conventional tube, that is, a series of observations are made for the various values of the variables over the desired ranges and the results of these observations are plotted as the characteristic curves of the tube. These curves are then available for selecting any desired particular operating condition.

The cut-off characteristics of the device, that is, the conditions of operating values at which the device becomes conductive, is determined by observing the values in the elements of the circuit (Figure 1) such as the maximum strength of the magnetic field (H) in gauss required for the several values of the voltage across the tube, V_a, at which the anode current is just zero, that is, when the tube is just conducting or just not conducting. A typical plot of a set of related values is shown in Figure 3, where H is the value of the magnetic field in gauss for corresponding values of V_a, the anode voltage in volts, the anode current being zero, that is, the tube being just non-conductive. The non-conductive region (I) and the conducting region (II), see Figure 3, and hence the cut-off characteristics, are thereby determined.

Likewise, the magnetic field may be successively held constant (H_0, H_1, and H_2, respectively) and the anode current (i_a) observed for values of anode voltage, V_a. The results of such a test are shown in Figure 7.

It will be noted in Figure 7 and in Figure 2 that the cut-off voltage V^1, is the minimum anode voltage at which there is no conduction currents for any value of magnetic field H.

To analyze what takes place when currents alternating at an angular velocity, ω_s, are impressed on solenoid 7 and currents alternating at an angular velocity, ω_0, the instantaneous values of the current through solenoid 8 ($i_s \sin \omega_s t$), Figure 2, and the instantaneous values of the voltage across the tube ($e_0 \sin \omega_0 t$), Figure 4, are plotted coaxially with Figure 3, that is, the horizontal origin-line of Figure 3 is drawn as an extension of the horizontal origin-line of Figure 2 and the vertical origin-line of Figure 4 is drawn as an extension of the vertical origin-line of Figure 3. In the figures, $\omega_0 = 10\omega_s$.

It will be noted that the ordinates in Figure 3 are proportional to the ordinates in Figure 2 and the abscissa in Figure 3 are proportional to the abscissa in Figure 4. It is, therefore, possible to find by cross plotting the instantaneous values of the resulting alternating currents and hence the angular velocity of their alternations or their frequency. These latter values are plotted in

Figure 5, the maximum points on the plotted values forming the envelope of the intermediate frequency currents.

Another approach to the explanation of the reactions taking place in the circuit at various instants of time is by a mathematical analysis of the device.

As the conduction currents are varied in accordance with the magnetic field, the transconductance (g_H) may be defined as $g_H = \delta i/\delta H$ and is sketched in Figure 6 for the three time sequences of $\omega_0 t = n\pi/2$, where n equals 1, 5 and 9, the conductance being zero when source 1 is negative, that is, when n equals 2, 4 etc. The current-voltage characteristic curves for three magnetic fields are sketched in Figure 7, as previously explained.

A general mathematical expression for the output current can be obtained by:

$$i = g_H e_0 \sin(\omega t + \theta) \tag{2}$$

where either g_H or θ can be considered time dependent and represented by the usual Fourier series over the proper limits:

$$g_H = \epsilon a_n \cos n\omega_s t \tag{3}$$

and

$$\theta = \epsilon q_n \cos n\omega_s t \tag{4}$$

Thus, on considering a time variation in g_H and neglecting the phase factor, the following equation is obtained:

$$i = e_0 \sin \omega_0 t \epsilon a_n \cos n\omega_s t \tag{5}$$

$$= A_0 e_0 \sin \omega_0 t + \frac{e_0}{2} \epsilon a_n (n\omega_s + \omega_0) t - \frac{e_0}{2} \epsilon a_n \sin (n\omega_s - \omega_0) t \tag{6}$$

The Fourier coefficients are then determined by

$$a_n = \frac{2}{\pi}\int_{\theta}^{\theta+\xi_1} g_H \cos n\omega_s t \delta\omega_s t + \frac{2}{\pi}\int_{\theta+\xi_1+\Delta}^{\theta+\xi_1+\Delta+\xi_2} g_{H_2} \cos n\omega_s t \delta\omega_s t \tag{7}$$

where

$$\theta = \sin^{-1}\frac{V^1}{e_0}$$

V^1 being the low voltage cut-off

$$\xi_1 = \sin^{-1}\frac{V_a^0 - V^1}{e_0}$$

$$\Delta = \sin^{-1}\frac{V_a^1 - V_a^0}{e_0}$$

$$\xi_2 = \sin^{-1}\frac{V_a - V_a^1}{e_0}$$

The conversion transconductance, represented in the usual manner by:

$$gc_n = \frac{i_{if}}{e_s} = \frac{a_n}{2}$$

can be seen in the first approximation from Figure 6b. For this particular case

$$a_n r \frac{2}{H} g_H \text{ (max)}$$

$$gc_n r \frac{1}{\pi} g_H \text{ (average)}$$

This value of transconductance approaches the theoretical maximum of ordinary vacuum tubes (see I. R. E., E. W. Herold, April 1946). The average value of gc_n will of course be somewhat lower in normal operation.

The disclosed device can be used with any con-

ventional circuits which match the stated characteristics for frequency mixing or conversion. For example, a push-pull arrangement can be used as shown in Figure 8.

Referring to Figure 8, the mediums in tube 3a and in tube 3b are subjected to a magnetic field varying in accordance with the frequency of the currents from source 7. The voltages produced along the secondary of transformer 1 are impressed upon source 1a and source 1b. When source 1a is positive and tube 3a is conductive, source 1b is negative and tube 3b is non-conductive, and vice versa. The anodes 5a and 5b are connected together and grounded at 10. The primary of transformer 12 is connected in series with the secondary of transformer 11 and forms the load circuit of the two tubes.

The reactions in the tubes and circuits are the same as previously disclosed in connection with Figure 1. It is immaterial whether solenoids 8a and 8b are connected in series or in parallel as the direction of the magnetic field along the central axis of the tubes is not critical. As previously explained, the cut-off of secondary electrons reaching the cathode (source 1) occurs at the same value of the electromagnetic field, the paths of electrons being deflected either to one side or the other but in either case missing the source 1 at the same value of strength of the electromagnetic field.

There is thus disclosed a mixing circuit in which the medium in a tube (or tubes) having a radioactive source as a cathode and a secondary electron emission responsive anode, is subjected to a magnetic field varying in accordance with the frequency characteristics of one source of currents, the anode-cathode potentials are varied in accordance with the frequency characteristics of a second source of currents and currents of an intermediate frequency are made available in the load circuit of the tube, which circuit consists of three elements: the secondary of a transformer the primary of which is connected to the said second source of currents, the primary of a transformer the secondary of which is the output of the intermediate frequency currents and a source of biasing electric source, these three elements being connected in series with each other and connected as a unit between the anode and the cathode.

I claim as my invention:

1. The method of mixing two currents of different frequencies to produce currents of an intermediate frequency comprising: providing a source of nuclear charged particle radiation in a rarified gaseous medium, positioning in said medium and adjacent said source a secondary electron emission responsive material, impressing upon said medium an alternating magnetic field corresponding in frequency to that of one of said two currents, impressing upon said source and said material electric alternating potentials corresponding in frequency to that of the other of said two currents, and collecting the currents of said intermediate frequency from a circuit associated with said source and said material.

2. The method of mixing two currents of different frequencies to produce currents of an intermediate frequency comprising: providing a source of nuclear charged particle radiation in a rarified gaseous medium, positioning in said medium and adjacent said source a secondary electron emission responsive material, impressing upon said medium an alternating magnetic field corresponding in frequency to that of one of said two currents, impressing upon said source and said material electric alternating potentials corresponding in frequency to that of the other of said two currents, the said potentials on said source and said material being 180 degrees out of phase with each other, and collecting the currents of said intermediate frequency from a circuit associated with said source and said material.

3. The method of mixing two currents of different alternating frequencies to produce currents of an intermediate frequency comprising: providing a rarified gaseous-medium high vacuum tube having as its cathode a source of nuclear charged particle radiation and as its anode a secondary electron emission responsive material and having a load circuit therebetween, impressing upon said medium an alternating magnetic field corresponding in frequency to that of one of said two currents, impressing upon said anode and said cathode through said load circuit electric potentials corresponding in frequency to that of the other of said two currents, and collecting the currents of said intermediate frequency through said load circuit.

4. The method of mixing two currents of different frequencies to produce currents of an intermediate frequency comprising: providing a pair of sources of charged particle radiation in two separate rarified gaseous mediums, positioning in each of said mediums a secondary electron responsive material adjacent said sources, impressing upon said mediums an alternating magnetic field corresponding in frequency to that of one of said two currents, maintaining the said materials at the same potential, impressing upon said sources alternating electric potentials corresponding in frequency to that of the other of said two currents, whereby conduction currents are generated within said tubes at a frequency intermediate the said two frequencies, and collecting the said conduction currents.

5. The method of mixing two currents of different frequencies to produce currents of an intermediate frequency comprising: providing a pair of sources of charged particle radiation in two separate rarified gaseous mediums, positioning in each of said mediums a secondary electron responsive material adjacent said sources, impressing upon said mediums an alternating magnetic field corresponding in frequency to that of one of said two currents, maintaining the said materials at the same potential, impressing upon said sources alternating electric potentials corresponding in frequency to that of the other of said two currents, the said potentials on said sources being 180 degrees out of phase with each other, whereby conduction currents are generated within said tubes at a frequency intermediate the said two frequencies, and collecting the said conduction currents.

6. Apparatus for mixing two currents of different frequencies to produce currents of an intermediate frequency comprising: a rarified gaseous-medium tube, a source of nuclear charged particle radiation within said tube, a secondary electron emission responsive material within said tube and adjacent said source, means for impressing upon said medium a magnetic field alternating in accordance with the frequency of one of said two currents, means for impressing upon said source and said material electric potentials alternating in accordance with

the frequency of the other of said two currents, whereby conduction currents are generated within said tube corresponding to predetermined modulation products of said different frequencies, and means for collecting the said conduction currents.

7. Apparatus for mixing two currents of different frequencies to produce currents of an intermediate frequency comprising: a rarified gaseous-medium tube, a source of nuclear charged particle radiation within said tube, a secondary electron emission responsive material within said tube and adjacent said source, means for impressing upon said medium a magnetic field alternating in accordance with the frequency of one of said two currents, means for impressing upon said source and said material electric potentials alternating in accordance with the frequency of the other of said two currents, the said potentials on said source and said material being 180 degrees out of phase with each other, whereby conduction currents are generated within said tube corresponding to frequency intermediate said different frequencies and means for collecting the said conduction currents.

8. Apparatus for mixing currents from two sources of different frequencies to produce currents of an intermediate frequency comprising: a rarified gaseous medium tube, a source of nuclear charged particle radiation within said tube, a secondary electron emission responsive material within said tube and adjacent said source, a solenoid surrounding said medium and connected to one of the said two current sources, a first transformer the primary of which is connected to the other of said two current sources, a second transformer the primary of which and the secondary of said first transformer being connected in series with each other and between said nuclear source and said material, the terminals of the secondary of said second transformer being terminals of said intermediate frequency currents.

9. Apparatus for mixing two currents of different frequencies to produce currents of an intermediate frequency comprising: a pair of rarified gaseous medium tubes, each of said tubes having therein a source of nuclear charged particle radiation and a secondary electron emission responsive material adjacent thereto, means for impressing upon said mediums a magnetic field alternating at a frequency corresponding to that of one of said two currents, means for impressing upon the said sources of said tubes electric potentials alternating at a frequency corresponding to that of the other of said two currents, means for connecting together the said materials of said tubes, whereby conduction currents are generated within said tubes corresponding to a frequency intermediate said different frequencies, and means for collecting said conduction currents.

10. Apparatus for mixing two currents of different frequencies to produce currents of an intermediate frequency comprising: a pair of rarified gaseous-medium tubes, each of said tubes having therein a source of nuclear charged particle radiation and a secondary electron emission responsive material adjacent thereto, means for impressing upon said mediums a magnetic field alternating at a frequency corresponding to that of one of said two currents, means for impressing upon the said sources of said tubes electric potentials alternating at a frequency corresponding to that of the other of said two currents, the said potentials on said sources being 180 degrees out of phase with each other, means for connecting together the said materials of said tubes, whereby conduction currents are generated within said tubes corresponding to a frequency intermediate said different frequencies and means for collecting said conduction currents.

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