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3,153,742

ELECTRON TUBE DELAY DEVICE

Filed Sept. 19, 1962

2 Sheets-Sheet 1

FIG. 1

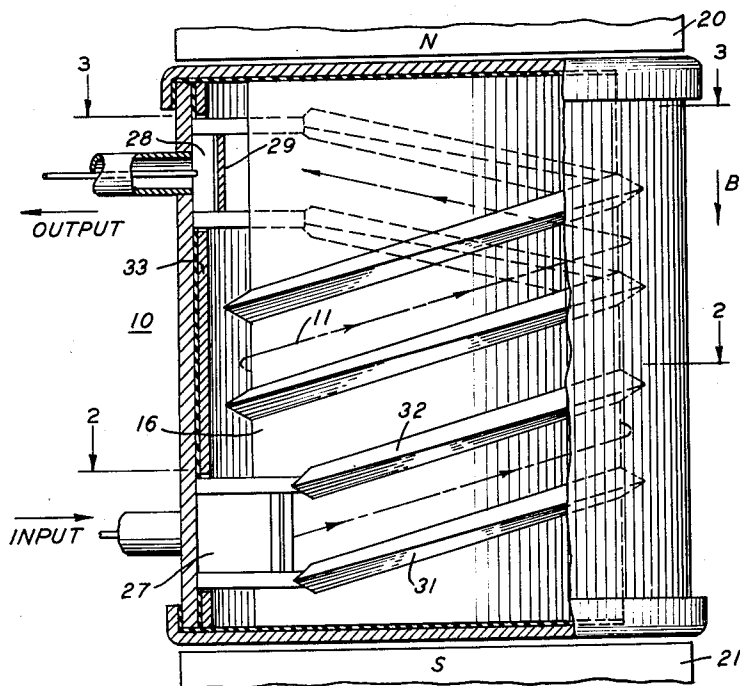
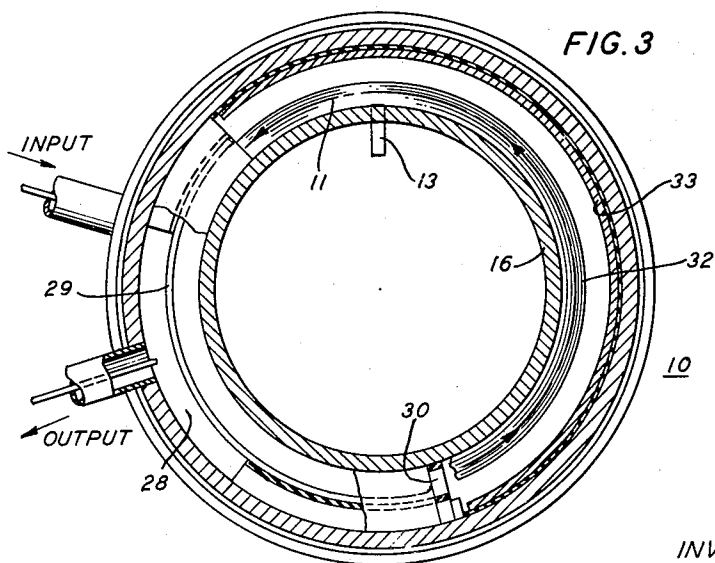


FIG. 3



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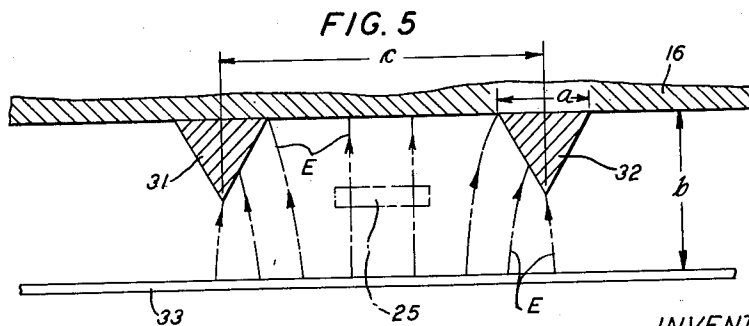
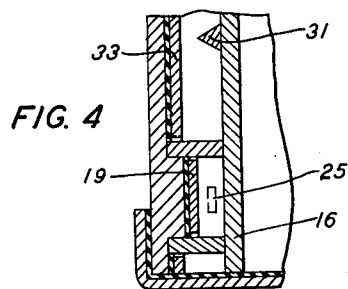
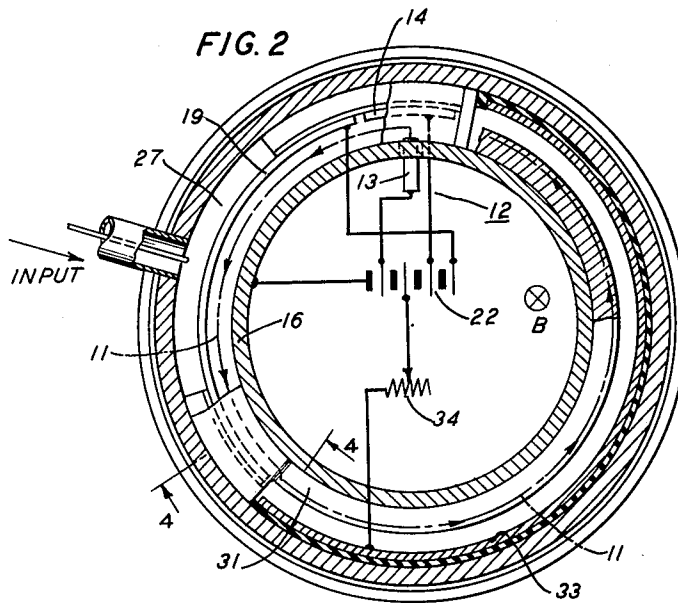
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ELECTRON TUBE DELAY DEVICE

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5 Claims. (Cl. 315—3)

This relates to apparatus for delaying electrical signals and, more particularly, to delay devices employing electron beams.

The need for efficient and flexible high microwave frequency delay lines has become increasingly apparent. The acoustic delay line, which delays the transmission of a radio wave by converting it to an acoustic wave propagating at a relatively low velocity, is probably the most widely used form of microwave delay device. When it is used at frequencies in the kilomegacycle range, however, a large attenuation loss is inevitable. Further, the acoustic delay line has a limited bandwidth, and the delay period cannot be conveniently adjusted.

Although electron beam devices have been proposed for use as delay lines, they have not been found to be acceptable primarily because of the high attenuation that accompanies the use of a low velocity electron beam. When electromagnetic wave energy is converted to electron beam space-charge wave energy the minimum beam velocity is limited by the inherent thermal velocities of the electrons so that if any appreciable delay is to be achieved the beam must be extraordinarily long. Further, modulation of the electron beam produces negative or backward velocity components on the electrons which additionally limits the minimum beam velocity.

It is an object of this invention to provide an efficient delay line for high frequency microwave energy.

It is another object of this invention to provide an easily adjustable delay line.

It is still another object of this invention to provide relatively long delays for high microwave frequency waves.

These and other objects of my invention are attained in an illustrative embodiment thereof comprising an electron gun for forming and projecting an electron beam along a path toward a collector. The electron beam is modulated near the electron gun end with microwave energy which is to be delayed, and demodulated near the collector end. Because the electron beam travels much slower than the speed of light, as will be explained later, the microwave energy is delayed for a predetermined time period between beam modulation and demodulation.

It is a feature of this invention that the electron beam be focused by crossed electric and magnetic fields. Although crossed-field focusing as such is well known, it offers particular advantages to this device in that it permits very slow beam velocities and because the beam velocity is adjustable over a wide range. Conventionally focused beams are characterized by longitudinal electron velocity deviations from the mean beam velocity caused by inconsistent emission velocities from the cathode. These velocity deviations, called thermal velocities, are manifested in crossed-field devices by orbital movements of the electrons transverse to the direction of beam flow, and therefore do not produce longitudinal beam velocity variations. For this reason the crossed-field focused beam can be projected at a much slower velocity than a conventionally focused beam without interfering with its coherency, and therefore is capable of giving a greater delay. Moreover, the beam velocity, and hence the delay of the device, can be easily adjusted merely by adjusting the electric focusing field.

It is another feature of this invention that the electron

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beam be modulated with input microwave energy in the fast cyclotron mode. This type of modulation is produced by electric fields acting on the beam in a direction transverse to the direction of beam flow. The velocities of the electrons representing the modulation energy are therefore transverse to the unmodulated velocity of the beam and do not produce longitudinal velocity variations as conventional beam modulation does. The electron beam can therefore be projected at a much slower velocity than would be possible if it were being modulated in a space-charge mode.

According to another feature of this invention, the electron beam follows a helical path along a drift region between the electron gun and the collector. The helical path is advantageous for two reasons: it conserves tube length while propagating the signal wave for a long distance and giving a relatively long delay; it conserves magnet weight because magnets are not required along an extended path length. The beam is directed along this path by a helical trough-shaped negatively biased sole electrode that produces the electric focusing field with a surrounding cylindrical anode. The sides of the trough extend approximately one-half the distance to the anode while the distance between the sides of the trough is approximately equal to twice the distance between the sole electrode and the anode. Experience has shown that when these conditions are met the coherency of the beam is maintained and extensive beam impingement on the anode and sole electrodes is avoided. In fact, it appears that coherency can be maintained at beam velocities as low as one twenty-five-thousandth of the speed of light.

It is still another feature of this invention that the electric focusing fields in the input and output regions be appreciably higher than those in the drift region. It can be shown that the bandwidth of energy that is transferable to and from the fast cyclotron mode of the beam is directly proportional to the beam velocity, so that a higher beam velocity is often desirable for a greater bandwidth. The beam velocity is, of course, usually decreased in the drift region to give a greater delay.

These and other objects and features can be better appreciated from a consideration of the following detailed description, taken in conjunction with the accompanying drawing, in which:

FIG. 1 is a partially sectional view of an illustrative embodiment of my invention;

FIG. 2 is a view taken along lines 2—2 of FIG. 1;

FIG. 3 is a view taken along lines 3—3 of FIG. 1;

FIG. 4 is a view taken along lines 4—4 of FIG. 2;

and

FIG. 5 is a representation of the electric field patterns along part of the device of FIG. 1.

Referring now to FIGS. 1 and 2, there is shown an evacuated electron beam delay device 10 which is constructed to transmit an electron beam along a helical path indicated by dashed line 11. As shown in FIG. 2, the electron beam is formed and projected along its helical path by an electron gun 12 comprising a cathode 13 and an accelerating electrode 14. The beam is projected into an input region defined by a cylindrical sole electrode 16 and an anode portion 19 and is constrained to flow along path 11 by the combined focusing action of a magnetic field B produced between magnetic pole pieces 20 and 21 and an electric field produced by the sole electrode 16 and anode portion 19. The potentials on these electrodes for producing the desired electric fields are maintained by a battery 22. The general principles of crossed-field electron beam focusing and for projecting such a beam along a semi-circular path as shown in FIG. 2 are known in the art. Typically, such an electron beam is wider in one dimension than in the other, as shown in FIG. 4, wherein the electron beam is indicated by reference numeral 25.

The purpose of device 10 is to delay the transmission of a microwave signal for a substantial period of time without attenuating or distorting it. To this end, microwave energy is transferred to the electron beam by an input cavity resonator 27, transmitted at a relatively low velocity along helical path 11 and removed by an output cavity resonator 28. As can be seen in FIG. 3, the output region is substantially the same as the input region and comprises an anode portion 29 which together with sole electrode 16 produces an electric field across the beam. The beam is collected by a collector 30 which is maintained at a positive potential and which intercepts the electron path. Between the input and output regions the beam is allowed to drift along a drift region defined by sole electrode 16, a pair of helical triangular walls 31 and 32, and a cylindrical anode 33. Walls 31 and 32 form a helical trough with sole electrode 16 and force the beam to follow the helical path 11.

It can be appreciated that a relatively low beam velocity is usually desired to achieve a large delay of the signal energy. The crossed-field focused beam of the illustrated device is especially advantageous in this regard because thermal velocities of the electrons do not determine a lower limit of electron beam velocity, as is the case with other forms of beam focusing. Thermal velocities refers to the inevitable variations in emission velocities from any cathode. In conventionally focused devices the average beam velocity must be maintained high enough so that the slowest moving electrons move coherently forward without attenuating or distorting the signal modulations. With crossed-field focusing, on the other hand, it can be shown that thermal velocities are manifested by trochoidal orbiting of the electrons, and the longitudinal drift velocities of the electrons are not affected by variations in emission velocities. Hence, the longitudinal drift velocities of the electrons are more uniform than is possible with other forms of focusing.

It can be shown that the velocity v_0 of a crossed-field electron beam is given by the equation:

$$v_0 = \frac{E}{B} \quad (1)$$

where E is the intensity of the electric focusing field and B is the flux density of the magnetic focusing field. This equation applies to all of the electrons in spite of variations in emission velocity. Since the velocity is directly proportional to the electric focusing field, it can be changed by adjusting the voltage on anode 33. As shown in FIG. 2, this is done by adjusting a potentiometer 34 which can be conveniently calibrated in terms of beam velocity or time of delay.

Another feature of my invention that permits large time delays is the type of beam modulation that is used: cavity resonator 27 modulates the beam with input power in the fast cyclotron mode. A detailed discussion of fast cyclotron mode modulation of crossed-field focused electron beams is given in my copending application Serial No. 28,918, filed May 13, 1960. Briefly, cyclotron wave modulation utilizes the principle that any electron in a magnetic field will rotate in response to a force transverse to the magnetic field at a frequency given by:

$$\omega_c = B \frac{e}{m} \quad (2)$$

where ω_c is referred to as the cyclotron frequency, B is the magnetic flux density, and e/m is the charge-to-mass ratio of the electron.

Referring to FIG. 2, microwave energy in resonator 27 generates R-F. electric fields between anode portion 19 and sole electrode 16 which are transverse both to magnetic field B and to the direction of beam flow. As long as the frequency of the R-F. fields approximates the cyclotron frequency, the microwave energy in the resonator 27 will be converted to rotational electron kinetic energy. Since the electron velocity components representing signal

modulation are entirely transverse to the direction of flow of the beam, they are not affected by low average beam velocities. In contradistinction, conventional space-charge wave modulations are defined by longitudinal electron velocity variations and are distorted and attenuated if the electron beam is slowed to a low velocity.

Resonator 27 is resonant at the cyclotron frequency and is preferably one-half wavelength long at the cyclotron frequency. The input signal frequency is shown as being conducted to the resonator by a coaxial cable, and is contained within a frequency band that is preferably centered about the cyclotron frequency. The bandwidth of frequencies that is transferable to the beam varies in direct proportion to the beam velocity. Hence, anode portion 19 is maintained at a higher potential than anode 33 to maintain a high beam velocity in the input region. Likewise, anode portion 29 is maintained at a relatively high voltage.

As is known, energy that is on the beam in the cyclotron frequency band is inherently transferred to input resonator 27 and output resonator 28. This not only permits convenient demodulation of the beam, but it permits "stripping" of spurious fast cyclotron wave noise on the beam, so that delay of the signal is accomplished without coupling electron beam noise to the signal.

In the drift region the electric focusing field is normally lower than in the input and output regions to maintain a low beam velocity and so the spacing between the anode and sole electrode may be greater in the drift region as is shown. Even at low beam velocities there is little danger of extensive beam impingement on the anode or sole electrode in the drift region because of the high magnetic field that is normally needed to meet the requirements of Equation 2. Whenever the device is operated in the kilomegacycle frequency range the magnetic field needed to fulfill Equation 2 necessarily confines beam expansion because the radii of the orbiting electrons are inversely proportional to the magnetic field. Hence, the magnetic field requirements for focusing purposes are compatible with those for cyclotron wave modulation. It should be pointed out that a change in beam potential as that which occurs between the drift region and the input and output regions may theoretically cause deleterious mixing of cyclotron and synchronous waves. This mixing can be avoided by using an adiabatic transition which is discussed generally in my Patent No. 2,999,959, granted September 12, 1961. Serious mixing will normally not occur if the ratio of change of electric field in one cyclotron wavelength to total electric field is less than one-tenth. Unless the potential change is made extremely abrupt, this condition will normally be inherently fulfilled.

The beam is directed along helical path 11 by a helical trough that is defined by walls 31 and 32. The helical path is advantageous for two reasons: it conserves tube length while propagating the signal wave for a long distance and giving a relatively long delay; it conserves magnet weight because magnets are not required along an extended path length. As best seen in FIG. 5, walls 31 and 32 have equilateral triangular cross sections which, with anode 33, produce an electric field E having components which exert inward forces on the beam. Experience has shown that the coherency of the beam is best maintained under all conditions if thickness a of the base of the triangular cross section is half the separation b between the sole plate and the anode and if the distance c between walls 31 and 32 is equal to twice the separation b . Under these conditions the electron beam will maintain its coherence and follow path 11 even at extremely low velocities. After traversing the drift region the beam enters the high-potential high-velocity output region where it is demodulated by output resonator 28 and collected by collector 30, as explained previously.

In summary, it can be appreciated that several salient features of my invention cooperate to give large delays with efficiency and flexibility: crossed-field focusing per-

mits very low beam velocities because it eliminates the thermal velocity problem and it permits easy adjustment of delay; cyclotron wave modulation is unaffected by low beam velocities because it is defined solely by transverse electron motion; specific drift tube structure constrains the beam to follow a helical path which conserves both tube length and magnet weight.

The device shown in the figures should be considered as being only an illustrative embodiment of the invention. For example, the pitch of helical electron path 11 can be reduced from that shown in order to reduce the spacing between magnetic poles 20 and 21 and thereby further conserve the weight of the magnets. Numerous other modifications may be made by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. An electron tube delay line comprising:
 - means for forming and projecting an electron beam;
 - means for focusing the beam, for maintaining a uniform velocity of the component electrons, and for establishing a fast cyclotron mode of wave propagation comprising means for producing crossed electric and magnetic fields along the beam path;
 - the magnetic field being substantially transverse to the path of flow of the electron beam;
 - means comprising an input cavity resonator for transferring signal wave energy to the fast cyclotron mode of the beam;
 - said input cavity resonator being resonant at a frequency substantially equal to the product of the flux density of the magnetic field and the charge-to-mass ratio of an electron;
 - means comprising an output cavity resonator for extracting signal wave energy from the beam;
 - the input and output resonators being separated by a drift region;
 - the electric focusing field intensity in the drift region being substantially lower than the electric focusing field intensity in the input and output resonators, whereby the beam travels at a substantially lower velocity in the drift region than in the resonators.
2. The electron tube delay line of claim 1 wherein:
 - the drift region is defined by a helical trough-shaped negatively biased sole electrode surrounded by a cylindrical positively biased anode;
 - the walls of the trough being separated by a distance substantially equal to twice the distance between the sole electrode and the anode;
 - and wherein the magnetic field is substantially parallel with the common axis of the anode and sole electrode.
3. The electron tube delay line of claim 1 further comprising:
 - means for manually adjusting the intensity of the electric focusing field in the drift region thereby adjusting the velocity of the electron beam.
4. An electron tube delay line comprising:
 - means for forming and projecting an electron beam;
 - means for producing crossed electric and magnetic fields along the beam path;
 - means comprising an input cavity resonator for modulating the electron beam in the fast cyclotron mode;
 - means comprising an output cavity resonator for demodulating the beam;

the input and output resonators being resonant at a frequency substantially equal to the product of the flux density of the magnetic field and the charge-to-mass ratio of an electron;

the input and output resonators being separated by a drift region defined by a cylindrical sole electrode coaxially surrounded by a cylindrical anode;

a pair of interleaved helical walls wrapped around the outer surface of the sole electrode for constraining the beam to follow a helical path through the drift region;

the walls extending approximately half the distance between the sole electrode and the anode and being separated by approximately twice the distance between the sole electrode and the anode;

the electric focusing fields in the input and output resonators being of substantially higher intensity than the electric focusing fields in the drift region;

and a potentiometer connected to the sole electrode.

5. An electron tube delay line comprising:

- means for forming and projecting an electron beam;
- means for focusing the beam, for maintaining a predetermined velocity of the component electrons, and for establishing a fast cyclotron mode of wave propagation comprising means for producing crossed electric and magnetic fields along the beam path;
- said electric and magnetic fields each being substantially unidirectional;
- the magnetic field being substantially transverse to the beam path;
- said beam flowing successively through an input region, a drift region, and an output region;
- means comprising an input coupler for transferring signal wave energy to the fast cyclotron mode of the beam;
- means comprising an output coupler for extracting signal wave energy from the fast cyclotron mode of the beam;
- the input coupler being located entirely within the input region and the output coupler being located entirely within the output region;
- the beam being subjected only to said unidirectional crossed electric and magnetic fields in the drift region;
- the electric focusing field intensity in the drift region being substantially lower than the electric focusing field intensity in the input and output regions, whereby the beam travels at a substantially lower velocity in the drift region than in the input and output regions.

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