April 19, 1960 P. M. LALLY 2,933,639

FREQUENCY SHIFTING APPARATUS

Filed Dec. 6, 1956

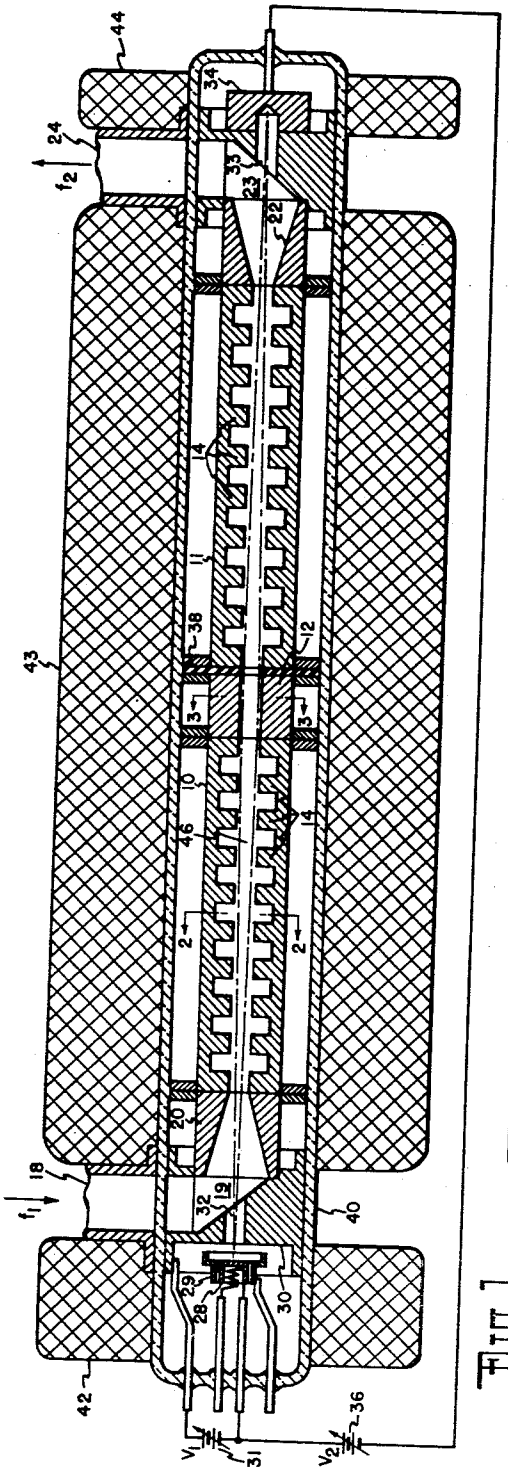


FIG. 1

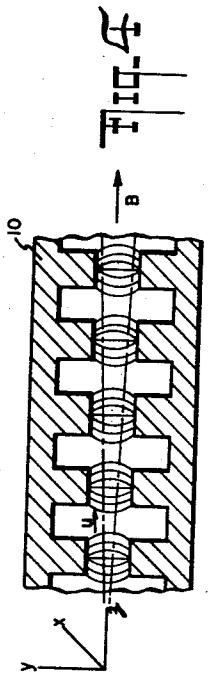


FIG. 4

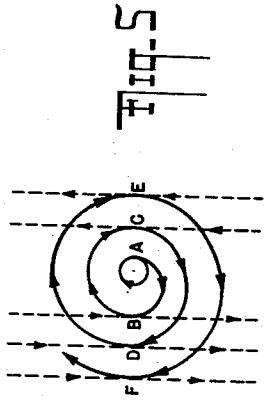


FIG. 5

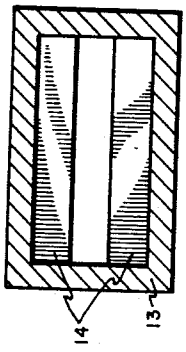


FIG. 2

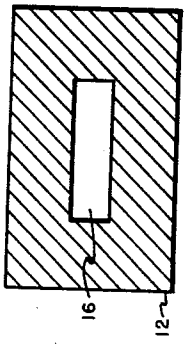


FIG. 3

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FREQUENCY SHIFTING APPARATUS

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1 Claim. (Cl. 315—3.6)

This invention relates to apparatus providing for interchange of energy between a stream of charged particles and a traveling electromagnetic wave and more particularly to a device for transmitting an electromagnetic wave differing in frequency from and responsive to a received electromagnetic wave.

In a frequency changing device a wave is received at a first frequency and retransmitted at a second frequency differing from said first frequency by a predetermined amount. In prior art frequency changing devices, such as those used in microwave relays, it is customary to provide an interaction process between the received microwave signal and the signal produced by an auxiliary oscillator located at the relay point. One sideband is selected from the output signal of the interaction process for retransmission, the frequency of the sideband differing from that of the received signal by an amount equal to the frequency of the local signal or an harmonic thereof. Two types of interaction processes are commonly employed, one of which employs nonlinear mixing of the received signal and the local signal by methods well known in the art, and the other of which employs the synchrodyne principle as disclosed in U.S. Patent No. 2,519,369 to W. W. Hansen and J. R. Woodyard and assigned to the same assignee as the instant invention. In the latter process an electron beam velocity modulated by the received signal is also phase modulated by the local signal, one sideband of the process being selected for retransmission. Frequency changers of the types described require complex electronic circuitry and include as a necessary element the aforementioned auxiliary oscillator. Furthermore, such prior art devices had no inherent selectivity, but would act to shift the frequency of all received signals. Selectivity could only be achieved by applying the received or output signals to a frequency selective device, such as a resonant cavity. It was desired therefore to provide a frequency changing device simple in operation, having no auxiliary oscillator, and one which rejected undesired received signals.

It is therefore a principal object of this invention to provide an improved frequency changing device.

It is a further object of this invention to provide a more reliable frequency changing device simple in circuitry and operation.

It is a further object of this invention to provide a frequency changing means employing but one electron discharge device.

It is a further object of this invention to provide a frequency changing circuit employing no auxiliary oscillator.

It is a further object of this invention to provide a novel electron discharge device to effect an interchange of energy between a stream of charged particles and a traveling electromagnetic wave.

It is a further object of this invention to provide a novel electron discharge device to effect an interchange of energy between a stream of charged particles and an electromagnetic wave traveling at substantially different velocities with respect to each other.

It is a further object of this invention to provide a frequency selective frequency changing device.

In accordance with the principles of the present invention there is provided an electron discharge device employing a novel type of interaction between an electron stream and a slow electromagnetic wave. The device employs a pair of slow wave structures disposed in tandem and provided with axial apertures for passage therethrough by an electron stream. The slow wave structures are adapted to propagate waves with substantially transverse electric fields. A magnetic focusing field is provided along and directed parallel to the axes of the slow wave structures. An electron drift tube interconnects the slow wave structures. An input electromagnetic wave is coupled to the first slow wave structure and propagates therealong. An electron beam is projected through the apertures of the slow wave structures. The beam velocity in the first structure is adjusted to a particular value substantially different from that of the slow wave. The electrons move in helical paths of increasing radii about the axis at the cyclotron frequency, continually absorbing energy from the input electromagnetic wave. The electron beam then passes through the drift tube, which prevents passage of the input wave, and enters the second slow wave structure rotating about the axis thereof at the cyclotron frequency. In the second structure the axial velocity of the electrons is changed, thereby changing the frequency of the slow wave with which they can interact. The spiraling electrons induce a wave on the second slow wave structure whose frequency differs from that of the input wave by an amount determined by the velocity difference of the electron beam in the two slow wave structures. Means is provided for removing the induced wave from the second slow wave structure.

This invention will be described with reference to the following drawings wherein:

Fig. 1 is a cross-sectional drawing of the preferred embodiment of the invention;

Fig. 2 is a sectional drawing taken on line 2—2 of Fig. 1;

Fig. 3 is a sectional drawing taken on line 3—3 of Fig. 1;

Fig. 4 is a drawing showing the electron field configuration of a wave traveling along a slow wave structure of the type employed in the embodiment of Fig. 1; and

Fig. 5 is a drawing showing the transverse motion of electrons within the electron stream of the embodiment of Fig. 1.

The preferred embodiment of this frequency changing device comprises a pair of wave transmission structures **10** and **11** disposed in tandem and having a drift tube **12** interposed between them, as shown in Fig. 1. Structures **10** and **11** each comprise a rectangular waveguide section **13** (Fig. 2) and a plurality of inwardly extending conductive members **14**. Structures **10** and **11** are each adapted to propagate an electromagnetic wave with a substantially transverse electric field at a velocity substantially less than that of the velocity of light; for example, of the order of $\frac{1}{10}$ the velocity of light. Structures of this type are termed slow wave structures and are described in U.S. patent application Ser. No. 253,343 by L. M. Field, now Patent No. 2,808,532. Drift tube **12** (Fig. 3) is apertured to permit passage of an electron beam. However, the aperture **16** in drift tube **12** is not sufficient in transverse extent to permit passage of the electromagnetic waves which propagate in structures **10** and **11**. In this regard, drift tube **12** functions as a waveguide beyond cutoff.

An input signal comprising electromagnetic energy of frequency f_1 is coupled into the device by means of an input waveguide section **18**. The input signal is coupled from input section **18** through a waveguide bend section

19, through a waveguide transition 20, and into the left end of slow wave structure 10. Electromagnetic energy of frequency f_2 induced in slow wave structure 11 is coupled out from the right end thereof, through a waveguide transition 22, through a waveguide bend section 23, and into an output waveguide section 24. Energy coupled to output waveguide section 24 is termed the output signal. The output signal is delivered at a frequency f_2 which differs from the frequency f_1 of the input signal by a predetermined frequency shift.

A stream of electrons is generated in an electron gun comprising an indirectly heated cathode 28, a focusing cylinder 29, and an apertured anode 30. The electron stream is accelerated to a velocity u_1 determined by the voltage V_1 of a first direct voltage source 31 connected between cathode 28 and anode 30. The electron stream travels toward the right in the figure through an aperture 32 in anode 30, and along the respective axes of waveguide transition 20, slow wave structure 10, drift tube 12, slow wave structure 11, and waveguide transition 22. The electron stream finally passes through an aperture 33 in waveguide bend section 23 and impinges on a conductive collector 34. A second direct voltage source 36 of voltage V_2 is connected between cathode 28 and collector 34, which is electrically connected to structure 11, and serves to operate the structure 11 at a potential different from that of structure 10. An apertured insulator 38 electrically isolates slow wave structure 11 from drift tube 12. An evacuated dielectric envelope 40 encloses and supports the portions of the device through which the electron stream must travel. Electrodes extend through envelope 40 in vacuum sealed relation thereto to couple voltages to the elements therein for heating the cathode and accelerating the electron stream. A plurality of solenoids 42, 43, 44 provide a steady magnetic field along the axis of the structure and directed parallel thereto for immersing the electron stream. The magnetic field provides for focusing the electron stream ad for exciting interaction between the electrons and waves traveling on the slow wave structures.

The electron stream 46 originates at the electron gun end of the device as a thin, sharply defined beam. As the beam travels toward the right through slow wave structure 10, it interacts with the transverse electric field components of the wave of frequency f_1 traveling therein. The resultant interaction increases the tangential velocity of the individual electrons of the stream, thereby enlarging the cross-section of the beam. The enlarged beam then passes through drift tube 12 and enters slow wave structure 11, where its axial velocity is changed due to direct voltage source 36. As the electron stream travels to the right in slow wave structure 11, it induces a wave of frequency f_2 to travel along said structure in synchronism, this wave gradually absorbing energy from the electron stream. This absorption of energy decreases the tangential velocity of the individual electrons of the stream, thereby reducing its cross-sectional area. The induced wave is delivered to output waveguide section 24. The electron stream terminates in collector 34.

The theory of operation of this invention may be explained as follows: Consider an electron traveling to the right (+z direction) in the slow wave structure 10 of Fig. 4. The particular electromagnetic wave of interest has substantially transverse electric fields, as shown. The transverse electric field of a wave due to the input signal acting on the electron located at any point z along the z-axis of the slow wave structure is given by

$$E_y = E_{10y} \epsilon^{j\left(\omega_1 t - \frac{\omega_1 z}{v_1}\right)} \quad (1)$$

where E_{10y} is a reference value of transverse electric field; $\omega_1 = 2\pi f_1$, where f_1 is the frequency of the input signal; and v_1 is the phase velocity along the z-axis of the particular wave in slow wave structure 10.

The electron is moving along the z-axis with a velocity u_1, so that in Equation 1

$$z = u_1 t \quad (2)$$

and

$$E_y = E_{10y} \epsilon^{j\omega_1 t\left(1-\frac{u_1}{v_1}\right)} = E_{10y} \epsilon^{j2\pi f_1 t\left(1-\frac{u_1}{v_1}\right)} \quad (3)$$

Therefore, the electron is subjected to a transverse electric field of frequency

$$f_1\left(1-\frac{u_1}{v_1}\right) \quad (4)$$

The frequency indicated in Equation 4 is that "seen" by the electrons as they pass wavefronts of constant phase or are passed by such wavefronts.

Simultaneously with being acted on by the transverse electric fields, the electrons are subjected to the axially directed magnetic field of magnetic flux density B. This field would normally accomplish focusing (holding the beam together) by inducing electrons having transverse velocity components to describe helical paths as they traveled along the z-axis. In the transverse (x—y) plane the electrons would describe circles of constant radius in the absence of the transverse electric fields. The frequency of rotation of an electron in a uniform magnetic field is independent of the electron's velocity, being given by

$$f_c = \frac{Be}{2\pi m} \quad (5)$$

where e/m is the charge to mass ratio of the electron. The frequency f_c of Equation 5 is known as the cyclotron frequency of the electrons in the magnetic field B.

The y-component of velocity of the spiraling electrons is therefore given by

$$u_{1y} = u_{1y0} \epsilon^{j2\pi f_c t} \quad (6)$$

where u_{1y0} is a reference value of y-directed velocity. Maximum energy will be absorbed by the electron from the transverse electric field if the force of the field on the electron is always accelerating. This can only be so if the transverse velocity of the electron is in synchronism with the transverse electric field; i.e., if the exponential terms in Equations 3 and 6 are equal

$$f_c = f_1\left(1-\frac{u_1}{v_1}\right) \quad (7)$$

Therefore, Equation 7 expresses the condition for interaction between the electron stream and the transverse electric field components of the traveling wave. For a given magnetic field, B, the electron stream can be made to absorb energy from the wave due to the input signal by adjusting the stream velocity u_1 to satisfy Equation 7. Equation 7 may be modified to

$$f_c \lambda_1 = v_1 - u_1 \quad (8)$$

where λ_1 is the guided wavelength of the wave of frequency f_1. Thus, for a particular value u_1, the electron stream will interact with but one frequency component of the input signal.

As the electrons absorb energy from the wave, they travel in helical paths of increasing radius. The value of u_{1y0} increases but the cyclotron frequency, f_c, remains constant. An end or transverse picture of typical electron paths is shown in Fig. 5. The small loop A is the path of an electron rotating at cyclotron frequency as it travels along the tube axis and not subjected to any transverse electric fields. The flat spiral is the path of a corresponding electron moving in synchronism with a traveling transverse electric field and subject to successive acceleration forces at points B, C, D, E, F. The accelerating electric field at these successive points, and its direction is shown by the dotted lines in Fig. 5. An electron subject to but not in synchronism with a traveling transverse electric field will be subjected to random ac-

celeration and deceleration forces, will not absorb energy from the wave, and will continue to move in a helical path of small radius. The radius of the helical path is a measure of the energy the electron has absorbed from the field.

The electron stream now passes through the drift tube **12** of Fig. 1, where it is shielded from interaction with the traveling waves. The input signal f_1 cannot pass through the drift tube to slow wave structure **11**. The electrons continue to move in the helical paths of relatively large radii that they assumed after interaction with the input signal traveling wave. These electrons are now accelerated to a different axial velocity u_2, and enter slow wave structure **11**. The transverse velocity of the spiraling electrons continues to be that given by Equation 6.

Noise and shock excitation will excite slow wave structure **11** at all frequencies. However, one of these waves will build up because it operates in synchronism with the spiraling electrons. This wave, of frequency f_2, will subject an electron moving with velocity u_2 to a transverse electric field.

$$E_y = E_{20y} \epsilon^{j2\pi f_2 t\left(1-\frac{u_2}{v_2}\right)} \tag{9}$$

where v_2 is the phase velocity along the z-axis of this wave.

Maximum energy will be absorbed by the wave from the spiraling electron if the force of the transverse field on the electron is always retarding. This can only be so if the transverse velocity of the electron and the transverse electric field of the wave are in synchronism, i.e. if the exponential terms in Equations 6 and 9 are equal

$$f_c = f_2\left(1-\frac{u_2}{v_2}\right) \tag{10}$$

Therefore, with an electron beam adjusted to interact with the wave of frequency f_1 traveling on slow wave structure **10**, a wave of frequency f_2 will be induced on slow wave structure **11**. By combining Equations 7 and 10 the relationship between f_1 and f_2 can be obtained

$$\frac{f_2}{f_1} = \left(\frac{1-\frac{u_1}{v_1}}{1-\frac{u_2}{v_2}}\right) \tag{11}$$

If the slow wave structures are identical and broadband; that is, they propagate waves of a broad frequency range at constant velocity, Equation 11 can be simplified to

$$\frac{f_2}{f_1} = \left(\frac{1-\frac{u_1}{v_1}}{1-\frac{u_2}{v_1}}\right) \tag{12}$$

In this instance the frequency shift between input and output signals is dependent solely on the electron beam velocities, or upon the ratio of accelerating voltage V_2 to accelerating voltage V_1. In operation, the value of V_1 and correspondingly u_1 must be adjusted for synchronism with an input wave of the frequency to be passed (Equation 7), and then the value of V_2 and correspondingly u_2 is adjusted to obtain the desired frequency shift for the output signal.

In these equations, the presence of an apparent negative sign if u is greater than v may be ignored. The equations were arbitrarily set up to give a positive sign with v greater than u. In the event u is greater than v, the parenthetical terms should read

$$\left(\frac{u}{v}-1\right)$$

In summary, the theory of operation of this invention is as follows: A stream of electrons is accelerated by a first voltage source and directed along a path parallel to the direction of an applied magnetic field. An input signal is applied to a slow wave structure disposed adjacent the path of the stream. Waves having substantial transverse electric field components propagate along the structure parallel to the stream path. The velocity of the stream is adjusted by the first voltage source so that the electrons interact with one component of the input wave, and travel in helices of increasing radius as they absorb energy from the synchronous wave. The electron stream then passes through a field-free region, retaining the energy absorbed from the particular waves as tangential velocity of the individual electrons. However, the stream retains no "memory" of the frequency of the wave from which it absorbed the energy, the electrons spiralling at the cyclotron frequency. The stream is then further accelerated or decelerated and projected into a path opposite a second slow wave structure. A wave is induced on this structure, the frequency of which is that necessary to cause synchronous interaction with the rotating electrons. The amount of additional acceleration given the beam determines the value of this new frequency and, consequently, the frequency shift of the device.

Although this invention has been described, as employing different electron stream velocities in slow wave structures **10** and **11**, it is within the spirit of this invention to achieve frequency shifting by variation of other parameters. For example, the magnetic field may have different magnitudes along the axes of respective slow wave structures **10** and **11**. The output frequency would then differ from the input frequency by an amount dependent on the relative magnitudes of two magnetic fields. In a similar manner, the two slow wave structures may be designed with different electrical or physical characteristics so that the velocity vs. frequency characteristics of the two structures differ. In such device although the magnetic fields and electron stream velocities are the same in both structures the output frequency will differ from the input frequency.

The invention has been described as employing a novel interaction of an electron stream and a traveling electromagnetic wave. It is within the scope of this invention that the traveling electromagnetic wave may be one traveling wave component of a standing electromagnetic wave of the type which occurs in periodically loaded wave transmission devices.

While the invention has been described in its preferred embodiment, it is to be understood that the words which have been used are words of description rather than of limitation and that changes within the purview of the appended claim may be made without departing from the true scope and spirit of the invention in its broader aspects.

What is claimed is:

A frequency changing device comprising means for projecting an electron stream along an axis, first and second wave transmission structures disposed adjacent said axis and in tandem along said axis, each of said structures being adapted to propagate respectively along said axis first and second waves having electric field components perpendicular to said axis, said first and second waves each being of different frequency f_1, means for providing a steady magnetic field along said axis and directed parallel thereto in each of said first and second wave transmission structures, said steady magnetic field in each of said structures immersing said electron stream and thereby imparting to said electron stream a helical motion about said axis, said helically moving electron stream having a frequency of rotation about said axis of f_c, wherein the velocity u_1 of said electron stream along said axis in each of said wave transmission structures is related to the phase velocity v_1 and the frequency f_1 of a respective one of said first and second waves substantially in accordance with the expression

$$\frac{u_1}{v_1} = 1 - \frac{f_c}{f_1}$$

means for accelerating said electron stream to a first

velocity adjacent said first wave transmission structure, and means to accelerate said electron stream to a second velocity adjacent said second wave transmission structure, said first and second velocities being different.

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