Oct. 25, 1949. G. G. BRUCK ET AL 2,486,001

FREQUENCY-STABILIZING SYSTEM

Filed Feb. 12, 1946 2 Sheets-Sheet 1

FIG. 1.

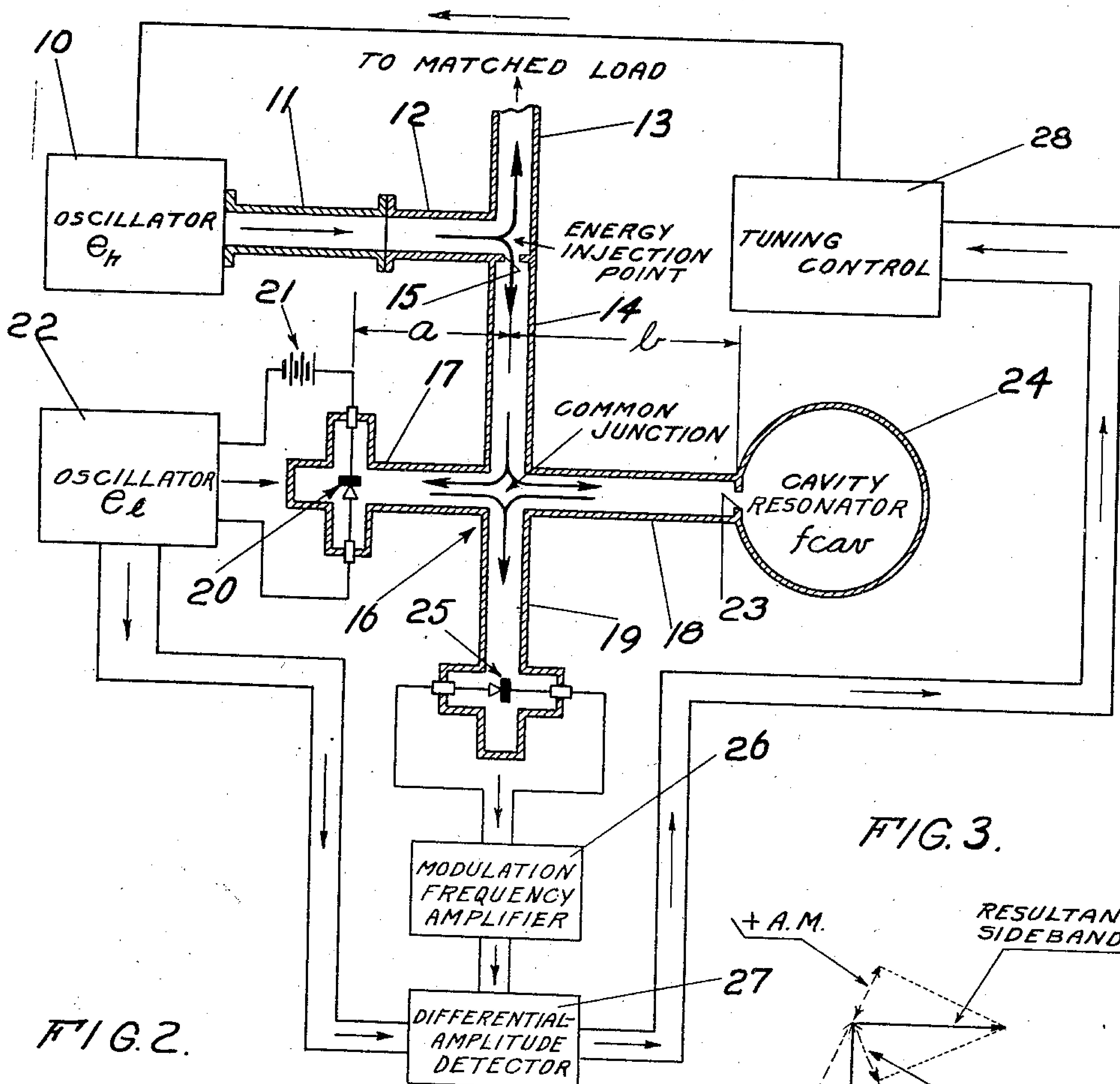

FIG. 3.

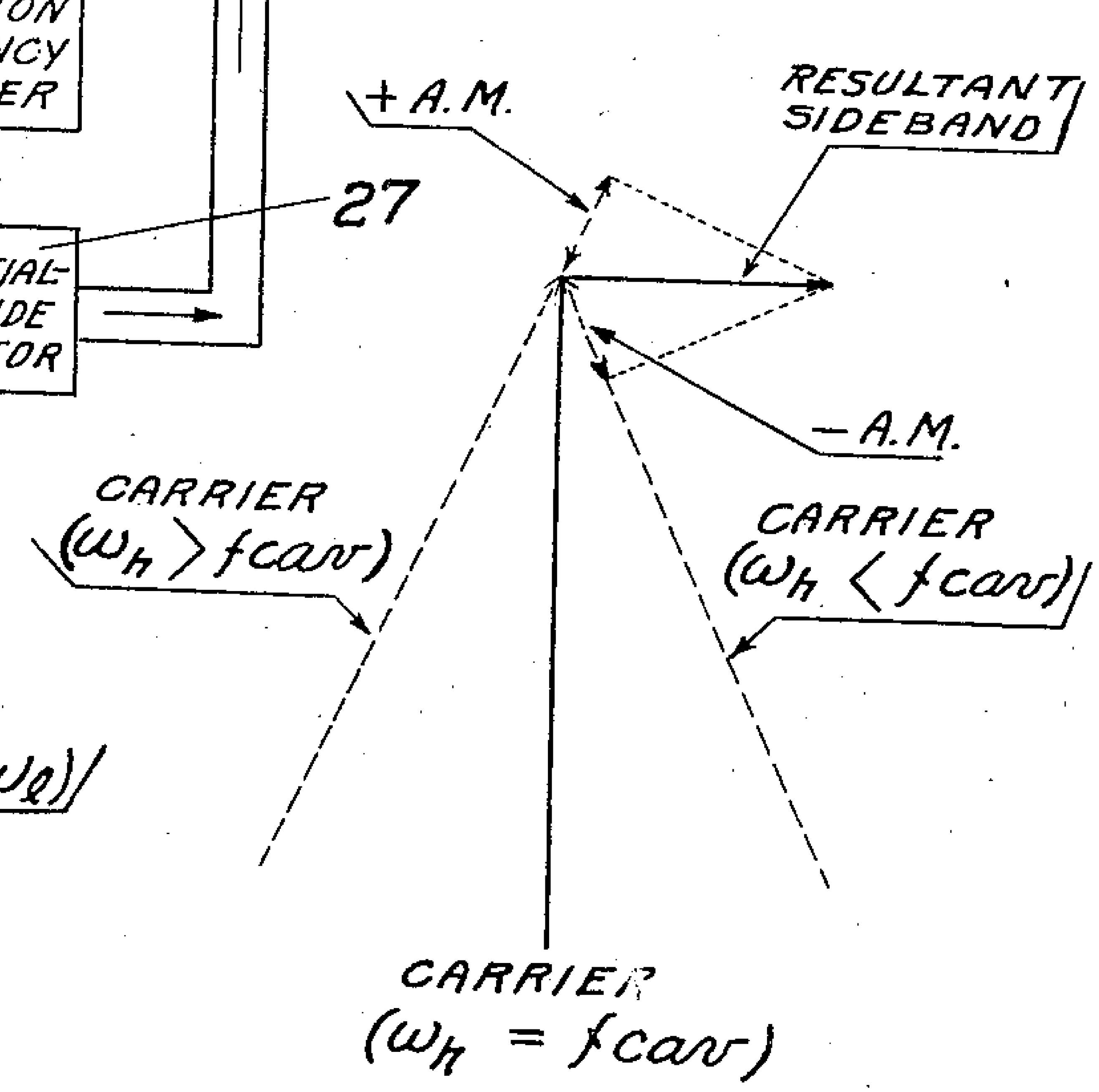

FIG. 2.

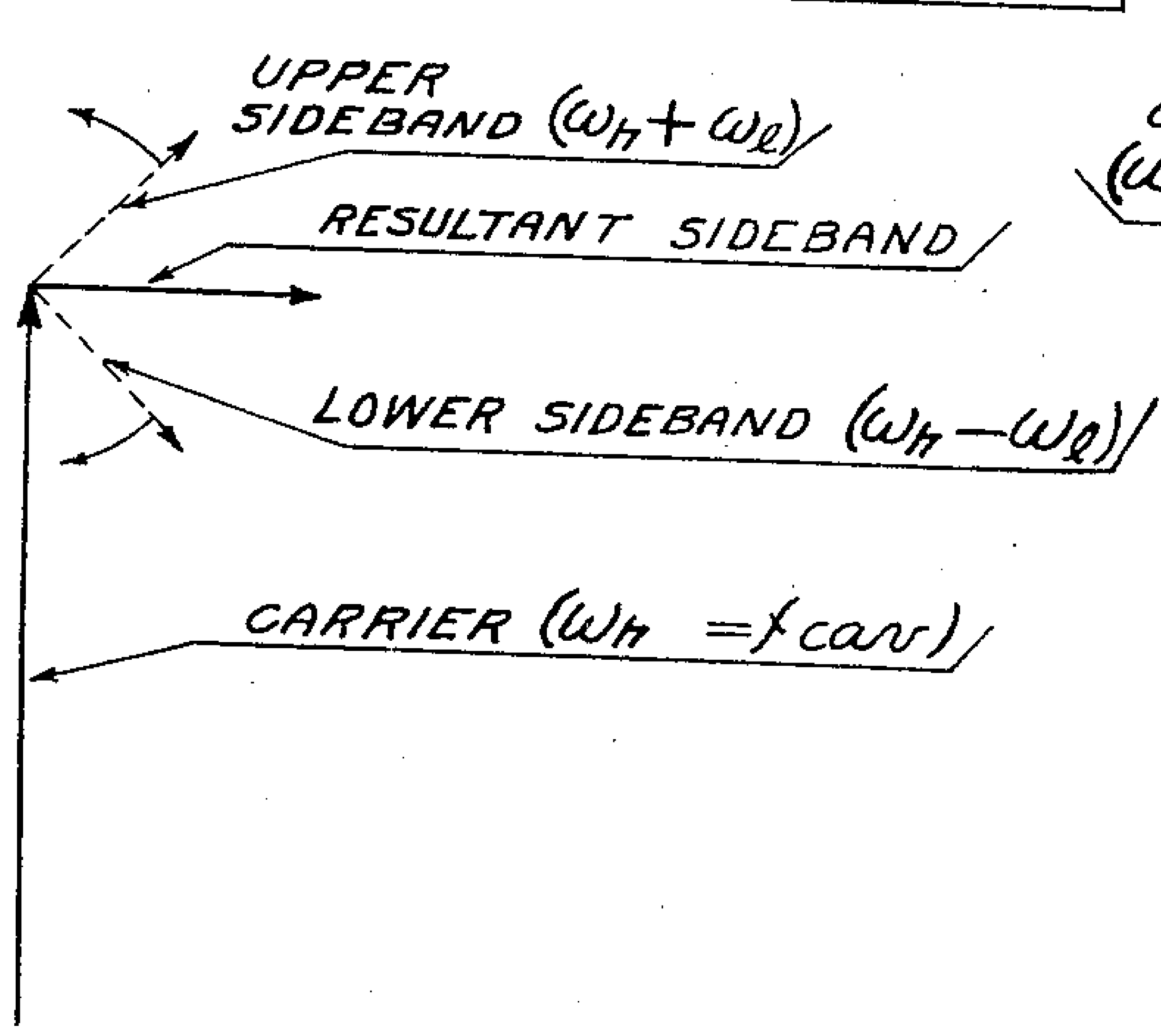

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FIG. 4.

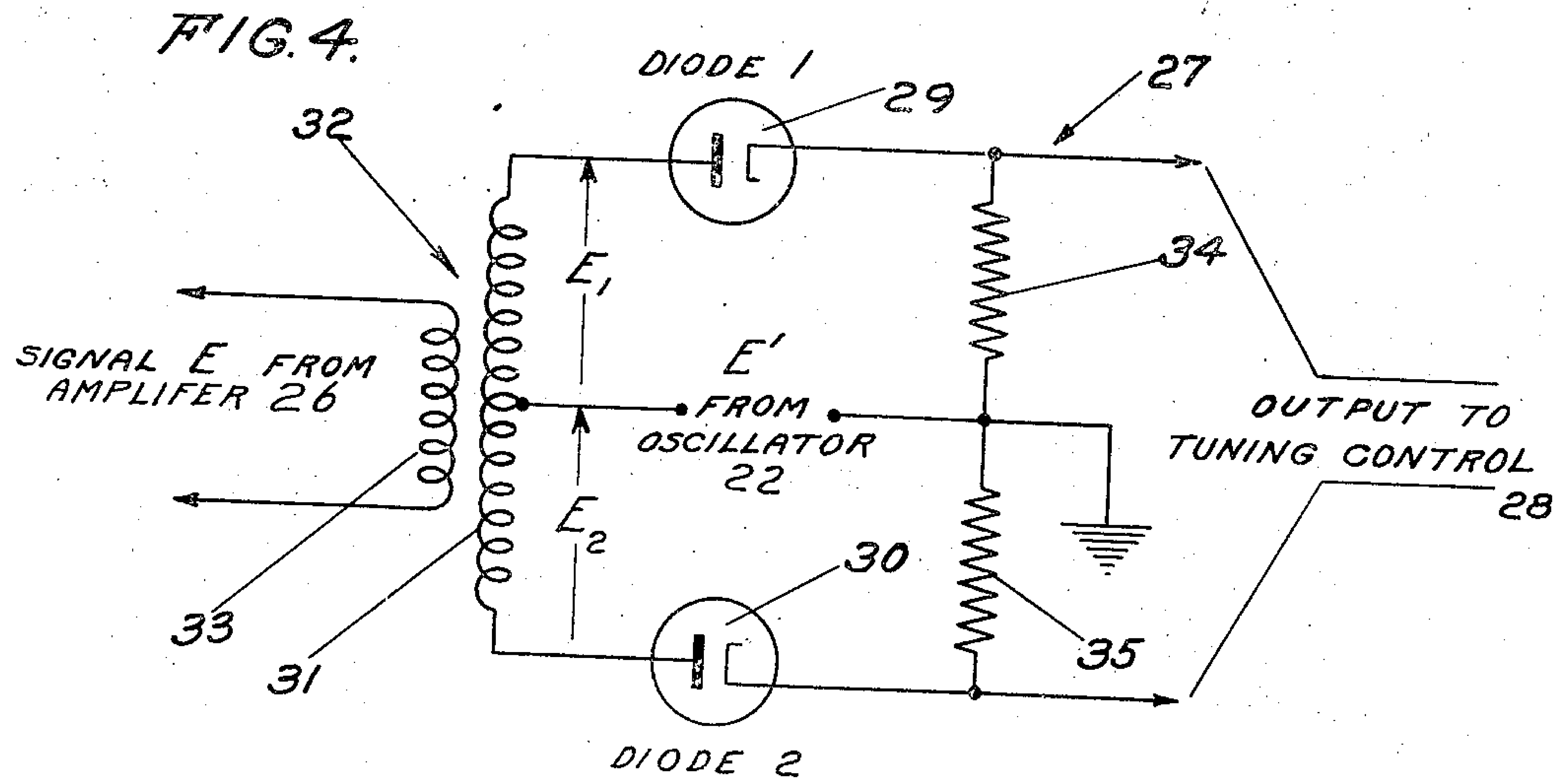


FIG. 5.

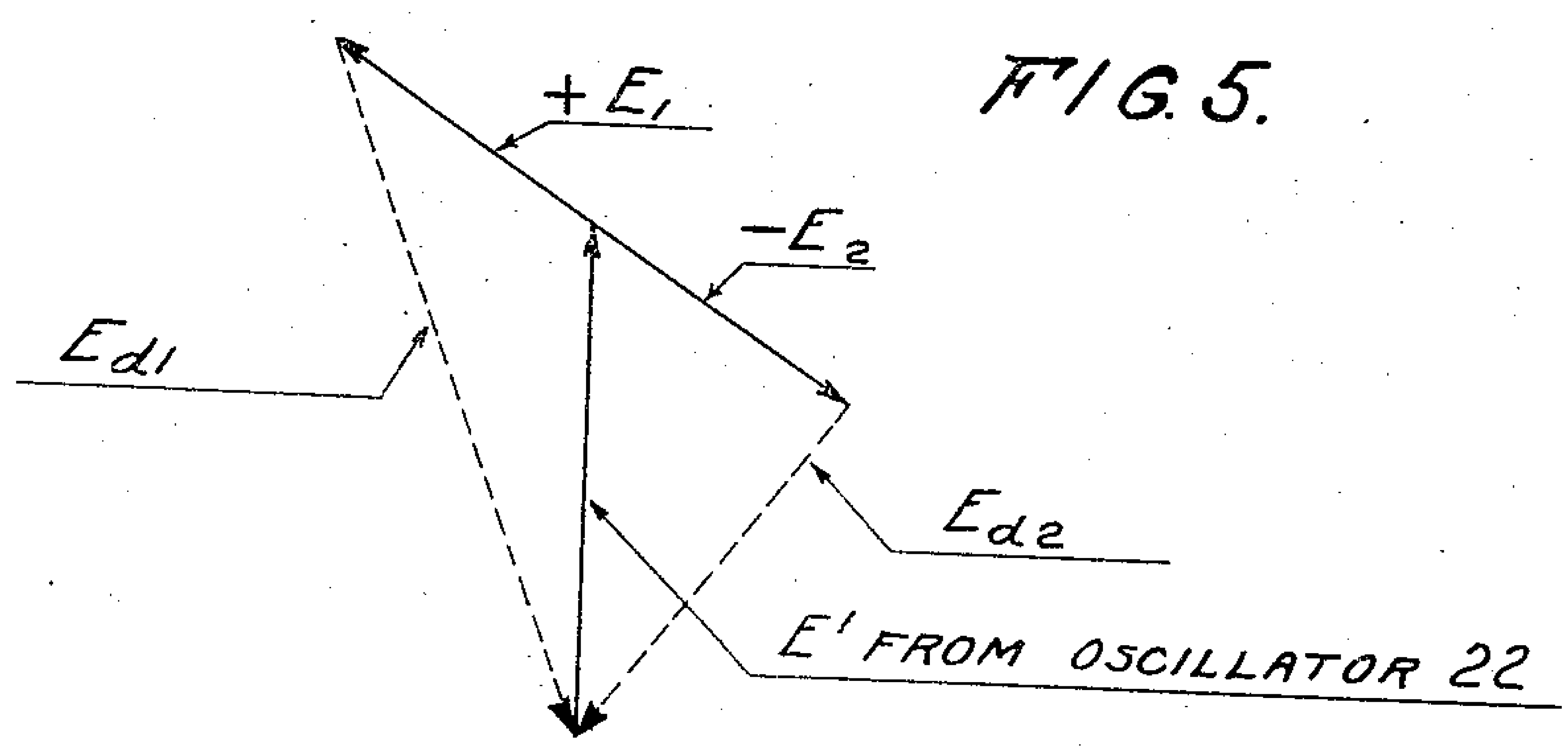
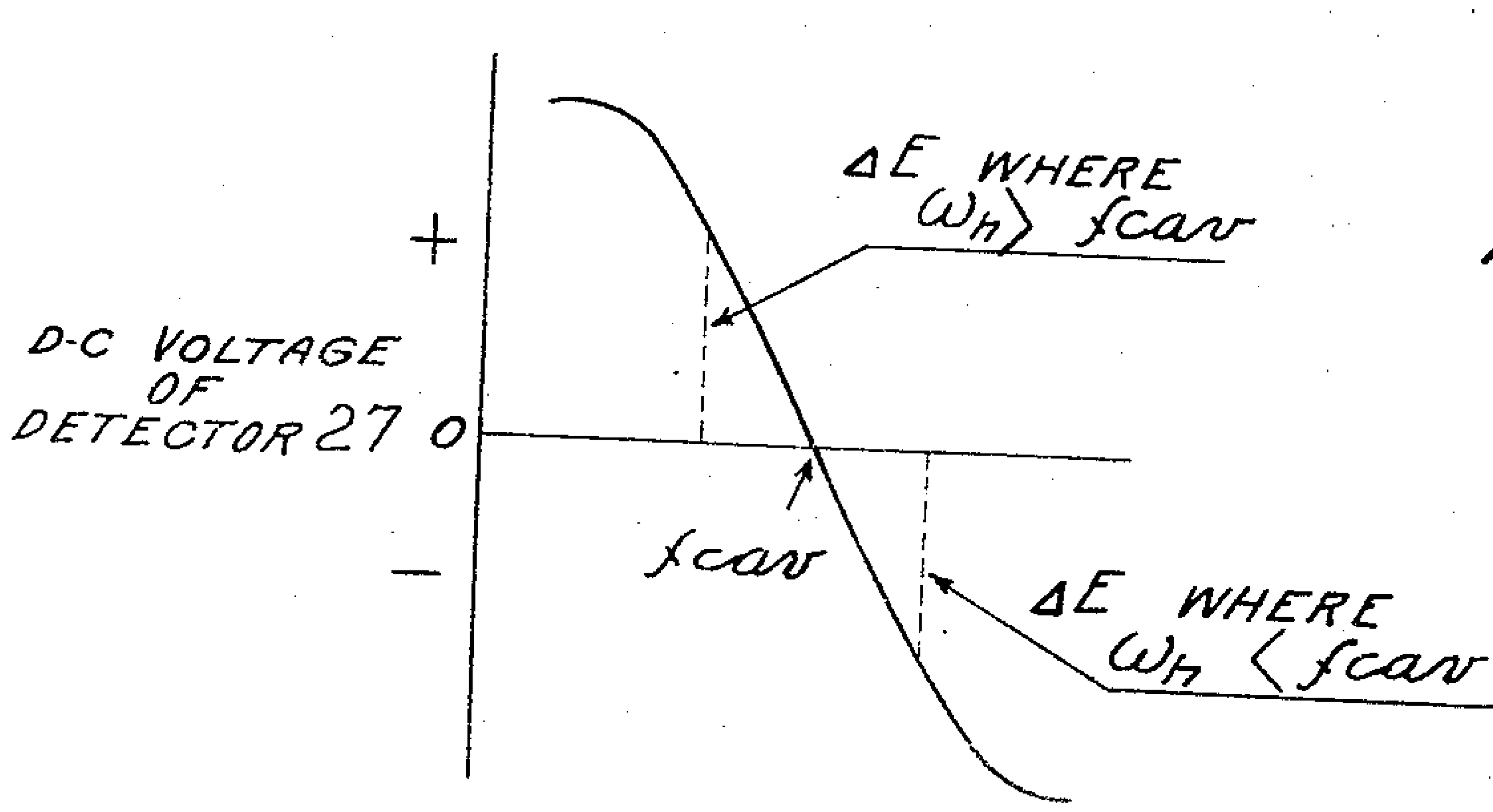


FIG. 6.



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FREQUENCY-STABILIZING SYSTEM

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11 Claims. (Cl. 250—36)

1

This invention relates to automatic frequency-stabilizing systems, and more particularly to apparatus for maintaining a predetermined, fixed relationship between the frequency of a carrier wave, especially, but not necessarily, a carrier wave in the microwave region of the electromagnetic spectrum, and a selected reference frequency.

While not limited thereto, the present invention is admirably adapted to the control of the carrier wave of a communication system comprising, for example, two widely separated terminal stations and a plurality of intermediate relay stations, the system permitting two-way transmission of intelligence between any and all of the stations included therein, with the carrier wave emanating from each relay station under the control of the carrier wave received at each relay station, and all under the master control of the carrier wave originating at one of the terminal stations.

In a system of this general description, it is apparent that the frequency of the carrier wave originating at the master terminal station must be controlled within very close limits, and it is the main object of the present invention to provide apparatus satisfying this requirement.

This, and other objects of the present invention, which will become more apparent as the detailed description thereof progresses, are attained, briefly, in the following manner.

A portion of the carrier wave to be stabilized is applied to an energy-transmission system, for example, a wave guide having a plurality of branches extending from a common junction. One of said branches terminates in a non-linear impedance, such as a crystal, to which modulation is applied whereby a portion of the carrier wave entering said first branch from said common junction is mixed with the modulation in said crystal, and becomes amplitude modulated, the resultant sidebands travelling along said first branch, back toward said common junction.

A second wave-guide branch, along which a portion of the carrier wave likewise travels from said common junction, is terminated in a tuned circuit, such as a cavity, resonator, which is designed to be resonant to a selected reference frequency with respect to which it is desired to maintain the frequency of the carrier wave in a predetermined, fixed relationship.

Preferably, the lengths of said first and second wave-guide branches are such that the difference therebetween is equal to

$$\frac{n\lambda}{8}$$

where n is an odd integer and λ is the wave-guide wavelength corresponding to said selected reference frequency. As a result of such an arrangement, the above referred to amplitude-modulated portion of the carrier wave, and a portion thereof which is reflected from said cavity resonator, meet at said common junction 90° out of phase.

2

A third wave-guide branch is terminated in another non-linear impedance, such as a second crystal, to which is applied said amplitude-modulated and cavity-reflected portions of said carrier wave. The mixing of the amplitude-modulated and cavity-reflected portions of said carrier wave at said last-named crystal produces a substantially constant-amplitude resultant wave provided there has been no deviation from the aforesaid predetermined, fixed relationship between the frequency of said carrier wave and said reference frequency. On the other hand, if there has been a deviation from said fixed relationship, the amplitude-modulated portion of said carrier wave and the portion thereof reflected from said cavity resonator do not arrive at said second crystal in phase quadrature, and, therefore, the in-phase component of the modulated portion causes the cavity-reflected portion to become substantially amplitude modulated.

The modulation envelope of the last-named resultant wave has a phase, relative to the modulation initially applied to the carrier wave, and a magnitude, which depend, respectively, on the sense and magnitude of any deviation from the above-mentioned fixed relationship between the frequency of said carrier wave and said selected reference frequency. Preferably, said modulation envelope is either in phase with said initially applied modulation, or it is in phase opposition thereto.

If there has been no deviation from said fixed relationship, and, as a result, a substantially constant-amplitude wave is produced at said second crystal, there is no modulation envelope to recover, but if there has been a deviation, the modulation envelope of the amplitude-modulated resultant wave produced at said second crystal, whether it is in phase with the initially applied modulation, or in opposition thereto, is recovered, the sense and magnitude of the recovered envelope depending, respectively, on the sense and magnitude of said deviation.

The recovered modulation envelope is combined, for example, in a differential-amplitude detector, with a portion of the initially applied modulation to obtain a unidirectional output whose direction and magnitude likewise depend, respectively, on the direction and magnitude of the deviation of the frequency of the carrier wave from its fixed relationship with respect to the selected reference frequency.

Said unidirectional output is applied to any preferred electronic or mechanical tuning control to adjust the source of the carrier wave to compensate for the frequency deviations above referred to.

Now, it is desired to point out that the fixed relationship herein referred to can be either a zero frequency difference, as is preferred, or any predetermined actual difference; and it is further desired to point out that the normal phase relationship between the first above-mentioned amplitude-modulated portion of the carrier wave, and that portion thereof which is reflected from the cavity resonator, need not be 90°. Where said phase relationship is other than 90°, the resultant wave at the second crystal will not be a substantially constant-amplitude wave, but, instead, will have a certain recoverable amplitude characteristic, and upon a frequency deviation occurring, said resultant wave will have a different amplitude characteristic. In this case, the recovered modulation envelope will have an amplitude characteristic which is a function of the difference between the amplitude characteristics of both said last-named resultant waves, and such a difference-characteristics wave may also be used to control the tuning of the source of the carrier wave.

In the accompanying specification there shall be described, and in the annexed drawings shown, an illustrative embodiment of the frequency-stabilizing system of the present invention. It is, however, to be clearly understood that the present invention is not to be limited to the details herein shown and described for purposes of illustration only, inasmuch as changes therein may be made without the exercise of invention, and within the true spirit and scope of the claims hereto appended.

In said drawings,

Fig. 1 is a partial block, partial schematic diagram of a frequency-stabilizing system assembled in accordance with the principles of the present invention;

Figs. 2 and 3 are vector diagrams illustrating phenomena occurring in certain of the components of said system;

Fig. 4 is a schematic diagram of one type of detector which may be utilized in the system; and

Figs. 5 and 6 are vector diagrams explanatory of the operation of said detector.

Referring now more in detail to the aforesaid illustrative embodiment of the present invention, with particular reference to Fig. 1 of the drawings, the numeral **10** designates a carrier-wave generator, for example, a microwave oscillator whose frequency it is desired to control as above indicated, and whose carrier-wave output is applied to an energy-transmission system including, for example, a wave-guide section **11**. The latter communicates with another wave-guide section **12** terminating in oppositely-directed branches **13** and **14**, the junction of said branches being hereinafter considered, for mathematical analysis purposes, as the energy-injection point of the system.

The wave-guide branch **13** may be terminated in any desired matched load, such as an appropriate antenna system for radiating the greater portion of the energy developed by the oscillator **10**, and the wave-guide branch **14**, which is receptive of a small portion of said energy through an iris **15**, may be terminated in a so-called "magic T" **16** comprising three wave-guide branches **17**, **18** and **19** extending from a common junction at right angles to each other.

The branch **17** may be terminated in a crystal mixer **20** to which is applied, in series with a source **21** of direct current, the relatively low-frequency output of an oscillator **22** which is intended to modulate that portion of the carrier wave entering the branch **17** from the above-mentioned common junction, the addition of the direct current assuring the appearance of the full modulation envelope across the crystal.

For the purpose of indicating the relationship which may exist between the carrier-wave output of the oscillator **10** and the modulation output of the oscillator **22**, it is pointed out that the former may have a frequency, for example, of 10,000 megacycles, and the latter may have a frequency, for example, of 50 megacycles.

The wave-guide branch **18** may be terminated, through an iris **23**, in a cavity resonator **24** designed to be resonant at the selected reference frequency with respect to which it is desired to maintain the frequency of the carrier wave in a predetermined, fixed relationship. As stated in earlier portions of this specification, the desired carrier-wave frequency may be the resonant frequency of the cavity resonator, and this relationship is preferred, or there may be an actual predetermined difference between said frequencies.

The lengths of the branches **17** and **18**, or, more accurately, the distance (a) between the center line of the wave-guide section **14** and the crystal **20**, on the one hand, and the distance (b) between the center line of the wave-guide section **14** and the iris **23**, on the other, are such that the difference therebetween $(a-b)$ is, preferably,

$$\frac{n\lambda}{8}$$

where n is an odd integer and λ is the wave-guide wavelength corresponding to the selected reference frequency. By proper choice of the length and cut-off frequency of the branches **17** and **18**, the phase difference can be maintained practically constant over a substantial frequency band. It will be understood by those skilled in the art that, if desired, other relationships may be used, provided appropriate modifications are made in the components to be later described herein.

The wave-guide branch **19** may be terminated in a second crystal **25** which is receptive of the modulated portion of the carrier wave coming from the first crystal **20**, and another portion of said carrier wave reflected from the cavity resonator **24**. As hereinbefore indicated, and as will become more apparent from the mathematical analysis to be hereinafter set forth, the combination of these two waves at the second crystal produces a substantially constant-amplitude or a substantially amplitude-modulated resultant wave, depending upon whether the frequency of the carrier wave has drifted from its fixed relationship with respect to the reference frequency, and if it has drifted, the resultant wave will have a phase, relative to that of the initially applied modulation, and a magnitude, depending, respectively, on the direction and magnitude of said drift.

The output of the crystal **25** is applied to a modulation-frequency amplifier **26** which is tuned to the frequency of the modulation oscillator **22**, and which is capable of passing an appreciable frequency band with a substantially constant phase shift, and the output of said amplifier is applied to a differential-amplitude detector **27**. The latter is also receptive of a portion of the output of the modulation oscillator **22**, and the combination of the modulation-frequency amplifier output and said modulation oscillator output in said detector results in a unidirectional output whose direction and magnitude likewise depend, respectively, on the sense and magnitude of any deviation from the fixed relationship between the frequency of the carrier wave and the selected reference frequency.

The unidirectional output thus obtained is applied to any appropriate tuning control **28**, which may be electronic or electro-mechanical, to tune the carrier-wave oscillator **10**, and compensate for any drift in the frequency thereof.

Except for the details of the differential-amplitude detector **27**, one form of which, shown in Fig. 4 of the drawings, will later be described, this completes the description of the physical aspects of the system of the present invention, and the following is presented as a mathematical analysis of the operation of said system.

It will be assumed that the energy travelling toward the matched load from the energy-injection point is completely absorbed, and any leakage across the "magic T" will be neglected.

At the energy-injection point, the output e_h of the carrier-wave oscillator **10** may be represented by:

$$e_h = E_h \sin(\omega_h t + \theta_1) \qquad (1)$$

where E_h is the peak value of the carrier wave, $\omega_h t$ is the angular velocity thereof, and θ_1 is a reference phase.

Across the crystal **20**, the output e_l of the modulation oscillator **22** may be represented by:

$$e_l = E_l \cos(\omega_l t + \theta_2) \qquad (2)$$

where E_l is the peak value of the modulation wave, ω_l is the angular velocity thereof, and θ_2 is a reference phase.

That portion of the carrier wave travelling along the wave-guide section **14** from the energy-injection point splits at the common junction, part travelling along the wave-guide branch **17** toward the crystal **20**, and part travelling along the wave-guide branch **18** toward the cavity resonator **24**.

At the crystal **20**, there arrives a portion of the carrier wave which may be represented by:

$$e_h = kE_h \sin(\omega_h t + \theta_1 + \phi) \qquad (3)$$

where k is a proportionality constant and ϕ is the phase shift introduced between the energy-injection point and the crystal.

The voltage e_h expressed by Equation 3 and the voltage e_l expressed by Equation 2 are mixed at the crystal **20**, as crystal current, and an amplitude-modulated resultant wave travels back along the wave-guide branch **17** toward the common junction. The carrier portion of the reflected wave is, however, zero if the crystal is properly matched to the wave-guide branch.

Now, the reflection coefficient of the voltage incident upon the crystal **20** is:

$$\text{Reflection coefficient} = \frac{R - Z_g}{R + Z_g} \qquad (4)$$

where R is the effective resistance of the crystal **20** and Zg is the impedance of the wave-guide branch **17**.

Rearranging this formula:

$$\text{Reflection coefficient} = \frac{R/Z_g - 1}{R/Z_g + 1} = \frac{a-1}{a+1} \qquad (5)$$

where $a = R/Z_g$, the relative match between the crystal **20** and the wave-guide branch **17**.

It will be seen that for $a=1$, the carrier is sup-

pressed, and for $a \neq 1$, a carrier component is reflected, with a + phase where $a>1$ and a − phase where $a<1$. Furthermore, any reflected carrier component has an amplitude depending upon the value of a, and has the following form:

$$e_h = k\frac{a-1}{a+1}E_h \sin(\omega_h t + \theta_1 + \phi) \qquad (6)$$

The action at the crystal **20** generates sidebands which are the result of mixing the incident e_h and the injected e_l. Considering only the first order terms, these sidebands have the form:

$$e_h \times e_l = \sin(\omega_h t + \theta_1 + \phi)\cos(\omega_l t + \theta_2) =$$
$$\sin(\omega_h t + \theta_1 + \phi + \omega_l t + \theta_2) + \sin(\omega_h t + \theta_1 + \phi - \omega_l t - \theta_2) \qquad (7)$$

where the first term immediately above is the upper sideband, and the second term immediately above is the lower sideband.

These sidebands, plus reflected carrier, if any, travel back to the common junction, from whence part goes toward the matched load and is absorbed, and part goes toward the crystal **25** which terminates the wave-guide branch **19**.

At this point it is desired to digress momentarily to develop the reflection coefficient of the cavity resonator **24**. Over a narrow frequency band, and where the iris **23** is thin compared to the wavelength of the energy being handled by the system, said iris is equivalent to an ideal transformer between the wave-guide branch **18** and the cavity resonator **24**. The cavity resonator itself may be represented over a narrow frequency band as a parallel resonant circuit having a constant shunt resistance.

The parallel impedance of the uncoupled resonator is:

$$Z_p = \frac{Z_0}{1+jS} \qquad (8)$$

where Z_0 is the parallel impedance of the uncoupled cavity resonator, at resonance, $=r$, and

$$S = Q_d \frac{2\Delta f}{f_{cav}}$$

in which latter expression Q_d is the dissipative Q of the cavity resonator, Δf is the difference between the frequency of the injected carrier wave and the resonant frequency of said cavity resonator, and f_{cav} is the resonant frequency of said cavity resonator.

Now, considering the iris coupling between the wave guide and the cavity resonator, the parallel impedance of the coupled cavity resonator at the wave-guide side of the iris becomes:

$$Z'_p = \frac{n^2 Z_0}{1+jS} \qquad (9)$$

where n is the ratio of an ideal transformer.

The reflection coefficient for the wave-guide, terminating in the impedance Z'_p represented by Equation 9, is:

$$\text{Reflection coefficient} = \frac{Z'_p - Z'_g}{Z'_p + Z'_g} \qquad (10)$$

$$= \frac{\frac{n^2 Z_0}{1+jS} - Z'_g}{\frac{n^2 Z_0}{1+jS} + Z'_g} = \frac{\frac{n^2 Z_0}{Z'_g} - (1+jS)}{\frac{n^2 Z_0}{Z'_g} + (1+jS)} \qquad (11)$$

where Z'_g is the impedance of the wave-guide branch **18**.

Substituting a_1 for

$$\frac{n^2 Z_0}{Z'_g}$$

the relative match between the cavity resonator **24** and the wave-guide branch **18**:

$$\text{Reflection coefficient}=\frac{a_1-(1+jS)}{a_1+(1+jS)} \qquad (12)$$

$$=\frac{(a_1-1)-jS}{(a_1+1)+jS}\cdot\frac{(a_1+1)-jS}{(a_1+1)-jS}$$

$$=\frac{a_1^2-1-S^2-2j\,a_1S}{(a_1+1)^2+S^2} \qquad (13)$$

For the special case where the cavity resonator and the wave-guide branch are matched at resonance, i. e., $a_1=1$, the reflection coefficient reduces to:

$$\text{Reflection coefficient}=\frac{-S^2-2jS}{4+S^2} \qquad (14)$$

Returning now to the analysis of the system as a whole, there arrives at the cavity resonator **24**, from the common junction, a portion of the carrier wave which may be represented by:

$$e_h=k_1E_h\sin\ (\omega_ht+\theta_1+\phi') \qquad (15)$$

where k_1 is a proportionality constant and ϕ' is the phase shift introduced from the energy-injection point to the cavity resonator.

With a reflection coefficient as expressed in Equation 13, $a_1\neq 1$, and for small S, so that said reflection coefficient is nearly constant in magnitude and the angle thereof is nearly proportional to S, the voltage reflected from the cavity resonator **24** has an angle which is nearly proportional to S, and has the form:

$$e_h=k_1\frac{a_1^2-1-S^2-2ja_1S}{(a_1+1)^2+S^2}E_h\sin\ (\omega_ht+\theta_1+\phi') \qquad (16)$$

which is, for small S:

$$e_h-k_1\frac{a_1^2-1-S^2}{(a_1+1)^2+S^2}E_h\sin\ (\omega_ht+\theta_1+\phi'\pm\Delta\alpha) \qquad (17)$$

where

$$\Delta\alpha=-\frac{2ja_1S}{a_1^2-1-S^2}\text{radians}$$

Practically, therefore:

$$\Delta\alpha=k_2\Delta f \qquad (18)$$

where k_2 is a proportionality constant and, as above stated, Δf is the difference between the frequency of the injected carrier wave and the selected reference frequency, which is the resonant frequency of the cavity resonator.

The carrier wave reflected from the cavity resonator **24** travels back to the common junction of the "magic T," from whence part goes toward the matched load and is absorbed, and part goes toward the crystal **25**, said cavity-reflected wave having the form:

$$e_h=\sin\ (\omega_ht+\theta_1+\phi'+\Delta\alpha) \qquad (19)$$

Thus, there arrives at the crystal **25**, from the crystal **20**, upper and lower sidebands and, possibly, a carrier-wave component depending in amplitude on the relative match of the crystal **20** with the wave-guide branch **17**, and reversing in phase as said crystal and guide go through match. Also arriving at the crystal **25**, from the cavity resonator **24**, is a carrier wave which is nearly constant in amplitude but has a phase angle depending on the deviation of its frequency from the predetermined, fixed relationship thereof with respect to the selected reference frequency of the cavity resonator **24**.

The various voltages arriving at the crystal **25** have the following forms:

Carrier from crystal 20— $\sin\ (\omega_ht+\theta_1+\phi+\phi'')$ (20)

Upper sideband— $\sin\ (\omega_ht+\theta_1+\phi+\omega_lt+\theta_2+\phi'')$ (21)

Lower sideband— $\sin\ (\omega_ht+\theta_1+\phi-\omega_lt-\theta_2+\phi'')$ (22)

where ϕ'' is the phase shift introduced between the crystals **20** and **25**.

Carrier from cavity resonator 24—

$$\sin\ (\omega_ht+\theta_1+\phi'\pm\Delta\alpha+\phi''') \qquad (23)$$

where ϕ''' is the phase shift introduced between the cavity resonator **24** and the crystal **25**.

Now, any carrier component from the crystal **20** combines with the carrier wave from the cavity resonator **24** vectorially, and so, at the crystal **25**, only one carrier input need be considered.

The combination, at said crystal **25**, of the upper sideband, as represented by the Expression 21, and the carrier wave, as represented by the Expression 23, is as follows:

$$\sin\ (\omega_ht+\theta_1+\phi+\omega_lt+\theta_2+\phi'')\ \sin\ (\omega_ht+\theta_1+\phi'\pm\Delta\alpha+\phi''')=$$
$$\cos\ (\omega_ht+\theta_1+\phi+\omega_lt+\theta_2+\phi''-\omega_ht-\theta_1-\phi'\mp\Delta\alpha-\phi''') \qquad (24)$$
$$-\cos\ (\omega_ht+\theta_1+\phi+\omega_lt+\theta_2+\phi''+\omega_ht+\theta_1+\phi'\pm\Delta\alpha+\phi''')$$

in which the low-frequency or modulation envelope term is:

$$\cos\ (\omega_lt+\theta_2+\phi+\phi''-\phi'-\phi'''\mp\Delta\alpha) \qquad (25)$$

The combination, at the crystal **25**, of the lower sideband, as represented by the Expression 22, and the carrier wave, as represented by the expression 23, is as follows:

$$\sin\ (\omega_ht+\theta_1+\phi-\omega_lt-\theta_2+\phi'')\ \sin\ (\omega_ht+\theta_1+\phi'\pm\Delta\alpha+\phi''')=$$
$$\cos\ (\omega_ht+\theta_1+\phi-\omega_lt-\theta_2+\phi''-\omega_ht-\theta_1-\phi'\mp\Delta\alpha-\phi''') \qquad (26)$$
$$-\cos\ (\omega_ht+\theta_1+\phi-\omega_lt-\theta_2+\phi''+\omega_ht+\theta_1+\phi'\pm\Delta\alpha+\phi''')$$

in which the low-frequency or modulation envelope term is:

$$\cos\ (-\omega_lt-\theta_2+\phi+\phi''-\phi'-\phi'''\mp\Delta\alpha) \qquad (27)$$

Letting $\phi+\phi''-\phi'-\phi'''=B$, the two low-frequency terms (25) and (27) may be rewritten as follows:

$$\cos\ (\omega_lt+\theta_2+B\mp\Delta\alpha) \qquad (28)$$

and

$$\cos\ (-\omega_lt-\theta_2+B\mp\Delta\alpha)=\cos-(\omega_lt+\theta_2-B\pm\Delta\alpha)$$
$$=\cos\ (\omega_lt+\theta_2-B\pm\Delta\alpha) \qquad (29)$$

The sum of the Expressions 28 and 29 gives the resultant low-frequency output from the crystal **25**.

Now, as previously indicated, the difference between the lengths of the wave-guide branches **17** and **18** is, preferably,

$$\frac{n\lambda}{8}$$

and since $\phi+\phi''-\phi'-\phi'''=B$, B must equal 90°.

Hence, where $\Delta\alpha$ is zero, corresponding to no deviation from the fixed relationship between the frequency of the carrier wave and the selected reference frequency, the low-frequency output from the crystal **25** is zero. In this case, the only output from said crystal **25** is direct current and even harmonics, or a substantially constant-amplitude output resulting from rectification of the carrier-wave input.

This has been illustrated vectorially in Fig. 2 of the drawings. The upper sideband may be considered as a vector rotating in a counter-clockwise direction at the frequency of the carrier wave plus that of the modulation wave, and the lower sideband may be considered as a vector rotating in the same direction at a frequency of the carrier wave minus that of the modulation wave. These two vectors periodically become in phase and so, they may also be considered as oppositely-rotating vectors combining to produce a non-rotating vector, which is the resultant sideband. The latter, actually, is the carrier wave varying in amplitude at the modulation frequency, and when combined with the cavity-reflected portion of the carrier wave, with which it is 90° out of phase, said cavity-reflected portion of the carrier wave remains substantially unaffected. Therefore, no modulation envelope is recovered at the crystal **25**.

Where, however, $\Delta\alpha$ is not zero, in other words, the frequency of the carrier wave has drifted from its fixed relationship with respect to the reference frequency, a recoverable output does appear across the crystal **25**, the phase of said output depending on the sign of $\Delta\alpha$, i. e., the direction of the frequency drift, and the amplitude of said output depends on the magnitude of $\Delta\alpha$, i. e., the extent of the frequency drift.

This, too, has been illustrated vectorially, in Fig. 3 of the drawings, from which it can be seen that where the carrier frequency drifts above the resonant frequency of the cavity resonator **24**, as indicated by the dashed vector to the left of the full line labelled "Carrier ($\omega_h = f_{cav}$)," the carrier wave from said cavity resonator acquires, at the crystal **25**, "+ amplitude modulation," and, where the carrier frequency drifts below the resonant frequency of the cavity resonator, as indicated by the dashed vector to the right of said full line, said carrier wave acquires "− amplitude modulation," said + and − modulation referring, of course, to the phase of the modulation envelope. The modulation thus produced results from the effect of an in-phase portion of the resultant sideband acting upon the carrier wave whose frequency has been altered by $\Delta\alpha$.

In any event, the output of the crystal **25**, after passing through the modulation-frequency amplifier **26**, is applied to the detector **27** to extract the sense thereof, depending on whether $\Delta\alpha$ is + or −, and obtain a unidirectional output of the proper sense and magnitude to operate the tuning control **28**.

Referring to Fig. 4 of the drawings, it will be seen that the detector **27** may comprise a pair of diode vacuum tubes **29** and **30** the anodes of which are connected to the opposite ends of the secondary winding **31** of the transformer **32**, the primary winding **33** of said transformer having applied thereto a signal E, the output of the modulation-frequency amplifier **26**. The cathodes of the tubes **29** and **30** are connected to ground, respectively, through resistors **34** and **35**, and the secondary winding **31** of the transformer **32** is center-tapped, whereby a portion of the output E' of the modulation oscillator **22** may be applied between said center-tap and ground. The output of the detector is taken from across the cathode ends of the resistors **34** and **35**.

The input signal E appears across the secondary winding **31** of the transformer **32** as the sum of the voltages E_1 and E_2. Assuming that $\Delta\alpha$ is +, the input to the tube **29**, diode **1**, is the vector sum of $E'+E_1$, producing the output E_{d1} shown in Fig. 5 of the drawings. At the same time, the input to the tube **30**, diode **2**, is the vector sum of $E'-E_2$, producing the output E_{d2} shown in the same figure.

The voltages E_{d1} and E_{d2} appear across the resistors **34** and **35** in opposition to each other, and the algebraic difference therebetween, ΔE, constitutes the final output of the differential-amplitude detector, as shown in Fig. 6 of the drawings.

This final output, a unidirectional voltage whose direction and magnitude depend, respectively, on the direction and magnitude of the deviation of the carrier frequency from the frequency desired thereof, is applied to the tuning control **28**, which, in turn, acts upon the carrier wave oscillator **10** to compensate for any such deviation.

While the detector **27** has been shown to include diode vacuum tubes, triodes may be used, in which case the center-tap of the secondary **31** may be omitted, and the output from the oscillator **22** may be applied to the grids of the triodes in parallel.

This completes the description of the aforesaid illustrative embodiment of the frequency-stabilizing system of the present invention. It will be noted from all of the foregoing that the present invention enables the maintenance, within close limits, of a predetermined fixed relationship between the frequency of a carrier wave and a selected reference frequency.

Other objects and advantages of the present invention will readily occur to those skilled in the art to which the same relates.

What is claimed is:

1. Apparatus for stabilizing the frequency of a carrier wave comprising: means for amplitude modulating a portion of said carrier wave; means for shifting the phase of another portion of said carrier wave through such an angle that, upon combination of said amplitude-modulated and phase-shifted portions thereof, a wave having a selected amplitude characteristic results; means, responsive to any drift in the frequency of said carrier wave, for altering the phase of said phase-shifted portion thereof; means for combining said amplitude-modulated and phase-shifted portions of said carrier wave whereby, in the event no frequency drift has occurred, the resultant wave has the aforesaid selected amplitude characteristic, and, in the event a frequency drift has occurred, the resultant wave has a substantially different amplitude characteristic; means for deriving from said last-named resultant wave a wave having an amplitude characteristic which is a function of the difference between the amplitude-characteristics of both said resultant waves; and means, receptive of said difference-characteristics wave, for so tuning the source of said carrier wave as to compensate for said frequency drift.

2. Apparatus for stabilizing the frequency of a carrier wave comprising: means for amplitude modulating a portion of said carrier wave; means for shifting the phase of another portion of said carrier wave through such an angle that, upon combination of said amplitude-modulated and phase-shifted portions thereof, a wave having a selected amplitude characteristic results; means, responsive to any drift in the frequency of said carrier wave, for altering the phase of said phase-shifted portion thereof, the sense and magnitude

of said phase-shift alteration depending, respectively, on the sense and magnitude of any such frequency drift; means for combining the amplitude-modulated and phase-shifted portions of said carrier wave whereby, in the event no frequency drift has occurred, the resultant wave has the aforesaid selected amplitude characteristic, and, in the event a frequency drift has occurred, the resultant wave has a substantially different amplitude characteristic; means for deriving from said last-named resultant wave a wave having an amplitude characteristic which is a function of the difference between the amplitude characteristics of both said resultant waves, the phase of the amplitude characteristic of said difference-characteristics wave, relative to the modulation initially applied to said carrier wave, and the magnitude thereof, depending, respectively, on the sense and magnitude of said frequency drift; means for combining said difference-characteristics wave with a portion of said initially applied modulation to obtain a unidirectional output whose sense and magnitude likewise depend, respectively, on the sense and magnitude of said frequency drift; and means, receptive of said unidirectional wave, for so tuning the source of said carrier wave as to compensate for said frequency drift.

3. Apparatus for stabilizing the frequency of a carrier wave comprising: means for amplitude modulating a portion of said carrier wave; means for shifting the phase of another portion of said carrier wave through an angle of 90°; means, responsive to any drift in the frequency of said carrier wave, for altering the phase of said phase-shifted portion thereof; means for combining the amplitude-modulated and phase-shifted portions of said carrier wave whereby, in the event no frequency drift has occurred, the resultant wave is a substantially constant-amplitude wave, and, in the event a frequency drift has occurred, the resultant wave is a substantially amplitude-modulated wave; means for recovering the modulation envelope of said last-named resultant wave; and means, receptive of said modulation envelope, for so tuning the source of said carrier wave as to compensate for said frequency drift.

4. Apparatus for stabilizing the frequency of a carrier wave comprising: means for amplitude modulating a portion of said carrier wave; means for shifting the phase of another portion of said carrier wave through an angle of 90°; means, responsive to any drift in the frequency of said carrier wave, for altering the phase of said phase-shifted portion thereof, the sense and magnitude of said phase-shift alteration depending, respectively, on the sense and magnitude of any such frequency drift; means for combining the amplitude-modulated and phase-shifted portions of said carrier wave whereby, in the event no frequency drift has occurred, the resultant wave is a substantially constant-amplitude wave, and, in the event a frequency drift has occurred, the resultant wave is a substantially amplitude-modulated wave, the phase of the modulation envelope of said last-named resultant wave, relative to the modulation initially applied to said carrier wave, and the magnitude thereof, depending, respectively, on the sense and magnitude of said frequency drift; means for recovering said modulation envelope; means for combining said modulation envelope with a portion of said initially applied modulation to obtain a unidirectional output whose sense and magnitude likewise depend, respectively, on the sense and magnitude of said frequency drift; and means, receptive of said unidirectional wave, for so tuning the source of said carrier wave as to compensate for said frequency drift.

5. Apparatus for maintaining a fixed relationship between the frequency of a carrier wave and a selected reference frequency comprising: an energy-transmission system, receptive of said carrier wave, and having a plurality of branches extending from a common junction; means, terminating a first of said branches, for amplitude modulating that portion of said carrier wave entering the same; a tuned circuit, resonant to said selected reference frequency, terminating a second of said branches; said first and second branches being of such lengths that the difference therebetween is equal to

$$\frac{n\lambda}{8}$$

where n is an odd integer and λ is the wave-guide wavelength corresponding to said selected reference frequency, whereby, at said common junction, said amplitude-modulated portion of said carrier wave and that portion of said carrier wave reflected from said tuned circuit are 90° out of phase; means, terminating a third of said branches, for combining said amplitude-modulated and reflected portions of said carrier wave whereby, in the event the aforesaid fixed relationship between the frequency of said carrier wave and said selected reference frequency has been maintained, the resultant wave is a substantially constant-amplitude wave, and, in the event said fixed relationship has been altered, the resultant wave is a substantially amplitude-modulated wave; means for recovering the modulation envelope of said last-named resultant wave; and means receptive of said modulation envelope, for so tuning the source of said carrier wave as to reestablish said fixed relationship between the frequency of said carrier wave and said selected reference frequency.

6. Apparatus for maintaining a fixed relationship between the frequency of a carrier wave and a selected reference frequency comprising: a wave guide, receptive of said carrier wave, and having a plurality of branches extending from a common junction; means, terminating a first of said branches and including a source of modulation and a mixer adapted to be energized thereby, for amplitude modulating that portion of said carrier wave entering the same; a cavity resonator, resonant to said selected reference frequency, terminating a second of said branches; said first and second branches being of such lengths that the difference therebetween is equal to

$$\frac{n\lambda}{8}$$

where n is an odd integer and λ is the wave-guide wavelength corresponding to said selected reference frequency, whereby, at said common junction, said amplitude-modulated portion of said carrier wave and that portion of said carrier wave reflected from said cavity resonator are 90° out of phase; means, terminating a third of said branches and including a second mixer, for combining said amplitude-modulated and reflected portions of said carrier wave whereby, in the event the aforesaid fixed relationship between the frequency of said carrier wave and said selected reference frequency has been maintained, the resultant wave is a substantially constant-amplitude wave, and, in the event said fixed relationship has been altered, the resultant wave is a substantially amplitude-modulated wave; means for recovering the modulation envelope of said last-named resultant wave; and means, receptive of said modulation envelope, for so tuning the source of said carrier wave as to reestablish said fixed relationship between the frequency of said carrier wave and said selected reference frequency.

7. Apparatus for maintaining a fixed relationship between the frequency of a carrier wave and a selected reference frequency comprising: an energy-transmission system, receptive of said carrier wave, and having a plurality of branches extending from a common junction; means, terminating a first of said branches, for amplitude modulating that portion of said carrier wave entering the same; a tuned circuit, resonant to said selected reference frequency, terminating a second of said branches; said first and second branches being of such lengths that the difference therebetween is equal to

$$\frac{n\lambda}{8}$$

where n is an odd integer and λ is the wave-guide wavelength corresponding to said selected reference frequency, whereby, at said common junction, said amplitude-modulated portion of said carrier wave and that portion of said carrier wave reflected from said tuned circuit are 90° out of phase if the aforesaid fixed relationship between the frequency of said carrier wave and said selected reference frequency has been maintained, and a different amount if said fixed relationship has been altered, the sense and magnitude of the latter amount depending, respectively, on the sense and magnitude of the deviation from said fixed relationship; means, terminating a third of said branches, for combining said amplitude-modulated and reflected portions of said carrier wave whereby, in the event said fixed relationship has been maintained, the resultant wave is a substantially constant-amplitude wave, and, in the event said fixed relationship has been altered, the resultant wave is a substantially amplitude-modulated wave, the phase of the modulation envelope of said last-named resultant wave, relative to the modulation initially applied to said carrier wave, and the magnitude thereof, depending, respectively, on the sense and magnitude of said deviation from said fixed relationship; means for recovering said modulation envelope; means for combining said modulation envelope with a portion of said initially applied modulation to obtain a unidirectional output whose sense and magnitude likewise depend, respectively, on the sense and magnitude of said deviation from said fixed relationship; and means, receptive of said unidirectional output, for so tuning the source of said carrier wave as to reestablish said fixed relationship between the frequency of said carrier wave and said selected reference frequency.

8. Apparatus for maintaining a fixed relationship between the frequency of a carrier wave and a selected reference frequency comprising: a wave guide, receptive of said carrier wave, and having a plurality of branches extending from a common junction; means, terminating a first of said branches and including a source of modulation and a mixer adapted to be energized thereby, for amplitude modulating that portion of said carrier wave entering the same; a cavity resonator, resonant to said selected reference frequency, terminating a second of said branches; said first and second branches being of such lengths that the difference therebetween is equal to

$$\frac{n\lambda}{8}$$

where n is an odd integer and λ is the wave-guide wavelength corresponding to said selected reference frequency, whereby, at said common junction, said amplitude-modulated portion of said carrier wave and that portion of said carrier wave reflected from said cavity resonator are 90° out of phase if the aforesaid fixed relationship between the frequency of said carrier wave and said selected reference frequency has been maintained, and a different amount if said fixed relationship has been altered, the sense and magnitude of the latter amount depending, respectively, on the sense and magnitude of the deviation from said fixed relationship; means, terminating a third of said branches and including a second mixer, for combining said amplitude-modulated and reflected portions of said carrier wave whereby, in the event said fixed relationship has been maintained, the resultant wave is a substantially constant-amplitude wave, and, in the event said fixed relationship has been altered, the resultant wave is a substantially amplitude-modulated wave, the phase of the modulation envelope of said last-named resultant wave, relative to the modulation initially applied to said carrier wave, and the magnitude thereof, depending, respectively, on the sense and magnitude of said deviation from said fixed relationship; means for recovering said modulation envelope; means for combining said modulation envelope with a portion of said initially applied modulation to obtain a unidirectional output whose sense and magnitude likewise depend, respectively, on the sense and magnitude of said deviation from said fixed relationship; and means, receptive of said unidirectional output, for so tuning the source of said carrier wave as to reestablish said fixed relationship between the frequency of said carrier wave and said selected reference frequency.

9. Apparatus for stabilizing the frequency of a carrier wave comprising: means for amplitude modulating a portion of said carrier wave, a tuned circuit having a resonant frequency with respect to which it is desired to maintain the frequency of said carrier wave in a fixed relationship, said tuned circuit being receptive of another portion of said carrier wave to produce a reflected wave whose phase and magnitude are functions, respectively, of the direction and magnitude of any deviation of the frequency thereof from that desired of said carrier wave; means, receptive of said amplitude modulated portion of said carrier wave and said reflected wave, for detecting the phase of said reflected wave and deriving a unidirectional control voltage whose direction and magnitude are, likewise, functions of said frequency deviation; and means, receptive of said control voltage for tuning the source of said carrier wave to compensate for any such frequency deviation.

10. Apparatus for stabilizing the frequency of a carrier wave comprising: means for amplitude modulating a portion of said carrier wave, a cavity resonator having a resonant frequency with respect to which it is desired to maintain

the frequency of said carrier wave in a fixed relationship, said cavity resonator being receptive of another portion of said carrier wave to produce a reflected wave whose phase and magnitude are functions, respectively, of the direction and magnitude of any deviation of the frequency thereof from that desired of said carrier wave; means, receptive of said amplitude modulated portion of said carrier wave and said reflected wave, for detecting the phase of said reflected wave and deriving a unidirectional control voltage whose direction and magnitude are, likewise, functions of said frequency deviation; and means, receptive of said control voltage for tuning the source of said carrier wave to compensate for any such frequency deviation.

11. Frequency-stabilizing apparatus comprising: a source of relatively high-frequency oscillations; a source of relatively low-frequency oscillations; a circuit, receptive of said relatively high and low-frequency oscillations, and including a cavity resonator having a resonant frequency with respect to which it is desired to maintain the frequency of said high-frequency oscillations in a fixed relationship, for modulating said high-frequency oscillations with said low-frequency oscillations to produce a modulated wave the phase and magnitude of whose

modulation envelope are functions, respectively, of the direction and magnitude of any deviation of the frequency of said high-frequency oscillations from that desired thereof; means, receptive of said modulated wave, for recovering said modulation envelope; means, receptive of said modulation envelope and a portion of the output of said source of relatively low-frequency oscillations, for comparing the phases thereof and deriving therefrom a unidirectional control voltage whose direction and magnitude are, likewise, functions of said frequency deviation; and means, receptive of said control voltage and coupled to said source of relatively high-frequency oscillations, for tuning said source of relatively high-frequency oscillations to compensate for any such frequency deviation.

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REFERENCES CITED

The following references are of record in the file of this patent:

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Certificate of Correction

Patent No. 2,486,001

October 25, 1949

GEORGE G. BRUCK ET AL.

It is hereby certified that errors appear in the printed specification of the above numbered patent requiring correction as follows:

Column 1, line 47, after the word "cavity" strike out the comma; column 6, lines 67 and 68, for that portion of the equation reading

$$\text{“}\frac{n^2Z_0}{Z'_s}+\text{”} \quad \text{read} \quad \frac{n^2Z_0}{Z'_s}+$$

column 7, line 38, for "$e_h - k_1$" read $e_h = k_1$; line 59, for "$\phi' + \Delta\alpha$" read $\phi' \pm \Delta\alpha$; and that the said Letters Patent should be read with these corrections therein that the same may conform to the record of the case in the Patent Office.

Signed and sealed this 21st day of February, A. D. 1950.

[SEAL]

THOMAS F. MURPHY,
Assistant Commissioner of Patents.