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STABILIZATION OF MICROWAVE OSCILLATIONS

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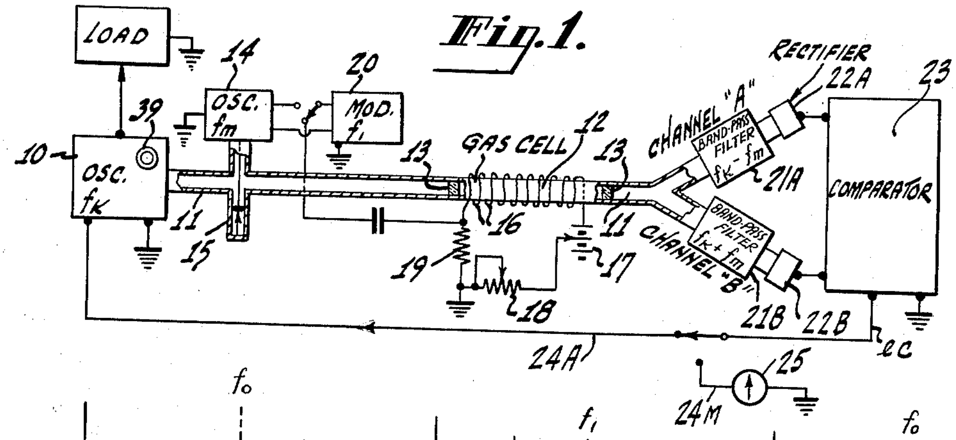


Fig. 1.

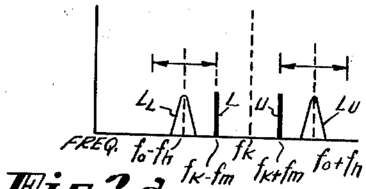


Fig. 2a.

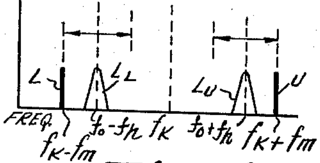


Fig. 2b.

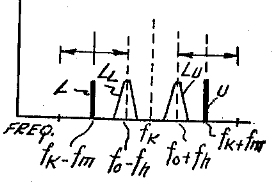
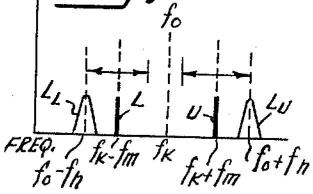


Fig. 3a.

Fig. 3b.



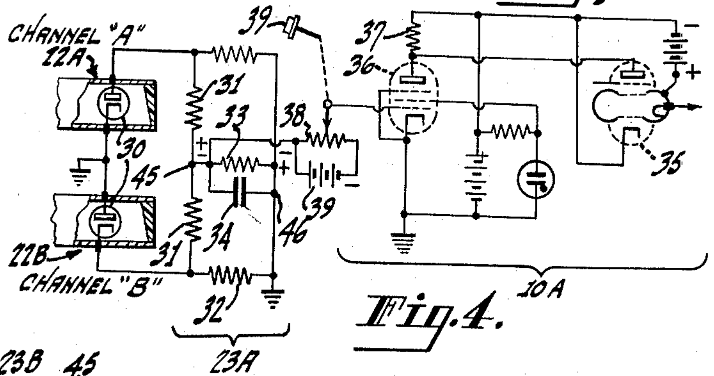


Fig. 4.

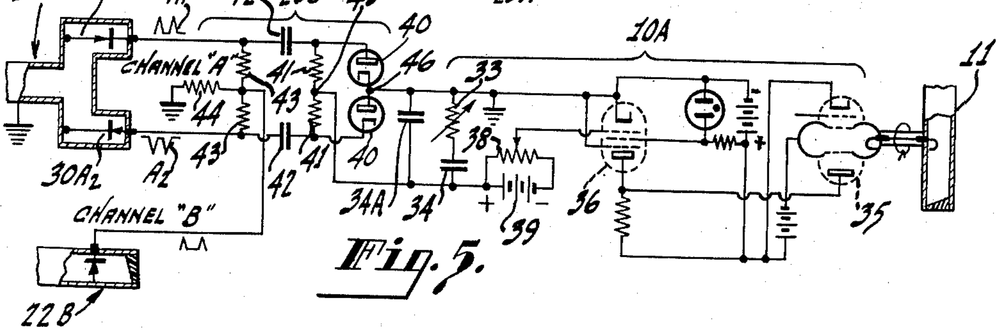


Fig. 5.

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STABILIZATION OF MICROWAVE OSCILLATIONS

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18 Claims. (Cl. 250—36)

This invention relates to methods and systems for stabilizing the frequency of microwave oscillations as generated, for example, by klystrons, magnetrons or other microwave generators.

In accordance with the present invention, a confined body of a gas, such as ammonia, which exhibits sharp molecular absorption at one or more microwave frequencies is subjected to a magnetic field to split an absorption line of the gas into a pair of Zeeman lines somewhat higher and lower than the desired frequency of the microwave oscillations. Before impression upon the gas, the oscillations are modulated to produce upper and lower sidebands which in frequency are normally respectively adjacent the Zeeman absorption lines. The sidebands, with or without the carrier, are impressed upon the gas and modulation applied either to the Zeeman fields or to the sidebands to effect sweeping of frequency ranges respectively above and below the desired carrier frequency. The microwave energies transmitted by the gas in the aforesaid frequency ranges are selectively demodulated to produce pairs of pulses which contain frequency-error information both in their relative amplitude and in their phase relationship.

Preferably, and further in accordance with the invention, the pairs of pulses are impressed upon a detector network which compares their phase or amplitude to produce an error-voltage of sense corresponding with the frequency-deviation of the oscillations and which, for automatic stabilization, may be applied to a frequency-control electrode of the oscillator tube or of a control tube associated therewith.

The invention further resides in methods and systems having the features of novelty and utility hereinafter described and claimed.

For a more detailed understanding of the invention, reference is made to the accompanying drawings, in which:

Fig. 1 schematically illustrates a frequency control system;

Figs. 2*a*, 2*b*, 3*a* and 3*b* are explanatory figures referred to in discussion of other figures including Fig. 1;

Fig. 4 illustrates a modification of Fig. 1 using an amplitude-comparator for automatic stabilization; and

Fig. 5 illustrates another modification of Fig. 1 utilizing a phase-comparator for automatic stabilization.

Referring to Fig. 1, the generator **10** of microwave oscillations may be a klystron, magnetron or other microwave generator, or it may be a lower frequency oscillator followed by a suitable number of harmonic amplifiers. In either event, the microwave energy is transmitted as by a waveguide, concentric line or other suitable transmission line **11** to a chamber **12** containing ammonia or other gas exhibiting sharp molecular absorption at a frequency f_0 corresponding with the desired output frequency of oscillator **10**. By way of example, frequency f_0 may be 23,870.1 megacycles, the frequency of the 3,3 line of ammonia. In copending applications, including Serial No. 1,240, various gases, including ammonia, exhibiting sharp molecular resonance or absorption at many microwave frequencies are identified. The chamber **12**, which may be a length of waveguide, is provided with windows **13**, **13** of quartz, mica, or like material, serving as gas-tight seals which are substantially transparent to the microwaves.

The fine line absorptions of certain materials including ammonia are split when subjected to a properly oriented magnetic field; this splitting is known as the Zeeman effect. In Fig. 1, such splitting of the absorption line at frequency f_0 is produced by the magnetic field of a coil **16** energized from a suitable source of direct current exemplified by battery **17**. In consequence, the original absorption line at frequency f_0 of the gas in cell **12** is split into a pair of lines L_L and L_U at frequencies $(f_0 \pm f_h)$ respectively above and below the original absorption line frequency (Figs. 2*a*, 2*b*, 3*a* and 3*b*). The extent of splitting or the frequency difference between the lines L_L and L_U is determined by the intensity of the magnetic field of coil **16** which can be selected by adjustment of the current from source **17** or the setting of rheostat **18**, or equivalent.

Prior to its impression upon the gas in cell **12**, the microwave energy is modulated at a lower frequency f_m to produce sidebands L and U (Figs. 2*a*, 2*b*, 3*a*, 3*b*) at frequencies $(f_k \pm f_m)$ which are respectively higher and lower than the carrier frequency of the microwave oscillations and which are respectively adjacent the Zeeman line frequencies $(f_0 \pm f_h)$ when there is null deviation from the desired frequency f_0. In the particular arrangement shown in Fig. 1, the sidebands are produced by impressing upon a mixer **15** the outputs of the microwave oscillator **10** and oscillator **14** generating oscillations at a lower frequency f_m: alternatively the sidebands may be produced by amplitude-modulation of the generated oscillations in manner well known per se. By way of example, frequency f_m may be of the order of 5 megacycles.

Depending upon the chosen intensity of the Zeeman field and the chosen frequency of oscillator **14**, or equivalent amplitude-modulator for oscillator **10**, the sideband frequencies L_L, L_U may be located either between the Zeeman lines (Figs. 2*a* and 3*b*) or beyond them (Figs. 2*b* and 3*a*). As previously above stated, low-frequency modulation may be applied either to the Zeeman fields or to the sidebands to effect sweeping of frequency ranges above and below the desired frequency of the microwave oscillations. Selective absorption of microwave energy by the gas occurs each time either sideband sweeps or is swept by the corresponding Zeeman absorption line. There are thus four specifically different though generically similar methods of operation respectively illustrated by Figs. 2*a*, 2*b*, 3*a* and 3*b* and in turn later discussed.

Reverting to Fig. 1, for discussion of generic aspects of the methods and systems comprehended by the invention: beyond the gas cell **12**, the transmission line **11** is divided into two paths or channels (A, B), respectively including filters **21A**, **21B** each passing the microwave energy in one of the aforesaid swept frequency ranges and excluding the microwave energy within the other swept frequency range. Specifically, the pass characteristics or bandwidth of each filter may be somewhat greater than the width of each Zeeman absorption line and the filters are respectively centered on the frequencies $(f_0 \pm f_h)$ of those lines. The energies so selected are respectively demodulated by demodulators **22A** and **22B**.

The outputs of the demodulators include, for each sweep cycle of repetition frequency f_l, a pair of pulses whose relative amplitude and phase relation each uniquely depend upon the sense of deviation of the frequency f_k of the microwave oscillations from the desired frequency f_0. The pulse output of the demodulators is impressed upon a network **23**, specific forms of which are later herein described, to produce a unidirectional output voltage e_c which is zero for null frequency-deviation of the microwave oscillations and which is of polarity dependent upon the sense of the deviations when existent. This error-voltage e_c may be measured as by a vacuum tube volt meter **25** or equivalent, whereupon an operator may adjust a frequency control **39** of oscillator **10** to correct for the frequency error. Preferably, however, the control voltage e_c is applied automatically to stabilize the frequency of oscillator **10**. It may be applied to a frequency control electrode of the oscillator, as in the case of a klystron or magnetron or it may be applied to a control tube associated with the oscillator.

Assuming the relationships shown in Fig. 2*a*, the intensity of the Zeeman field is periodically varied at frequency f_l so that the Zeeman lines L_L and L_U sweep ranges of frequencies respectively above and below the desired carrier frequency. In the particular arrangement shown in Fig. 1, this variation of the Zeeman field is effected by superimposing an alternating current of frequency f_l from oscillator or modulator **20** upon direct current supplied by source **17** to coil **16**, the particular coupling element shown in Fig. 1 being a resistor **19** although other coupling arrangements may be used. By way of example, rate frequency f_l may be 1000 cycles per second. For pulse-amplitude comparison, the modulation factor is suitably less than unity so that the highest frequency reached by Zeeman L_L is slightly lower than (f_k-f_m) and the lowest frequency reached by Zeeman line L_U is slightly higher than (f_k+f_m). When the microwave oscillations are of the desired frequency, the microwave absorption by the gas will be equal in the two swept frequency ranges and the maxima of the two absorptions will occur at the same time in the sweep cycle. When the frequency of the microwave oscillations is above the desired frequency, there is greater absorption of the upper sideband U, and, conversely, when the frequency of the generated oscillations is below the desired frequency, there is greater absorption of the lower sideband L. In other words, the output pulses of one of the demodulators **22A**, **22B** is greater than the output pulses of the other, depending upon the sense of the frequency-deviation of oscillator **10**. This difference in amplitude of the pulses may be utilized to produce a control voltage e_c of polarity dependent upon the sense of deviations by an amplitude-comparator, one form of which is shown in Fig. 4 and later described.

Furthermore (reverting to discussion of Fig. 2*a*), one or the other of the pulses occurs earlier in the sweep cycle, depending upon whether the frequency-deviation is positive or negative, that is, above or below the desired frequency, and this phase-difference may be utilized to produce a control voltage e_c of polarity dependent upon frequency-error by a phase-comparator, one form of which is shown in Fig. 5 and later described. When phase-comparison is used, the sweep ranges may be greater than above given for pulse-amplitude comparison.

When, as shown in Fig. 2*b*, the fixed lower and upper sideband frequencies are respectively lower and higher than the lowest and highest Zeeman line frequencies, a deviation from the desired frequency of the microwave oscillations also produces inequality of the pulse amplitudes and reversal of their phase relationship, for opposite senses of their frequency-deviation. However, because of the interchange in frequency location of the sidebands and Zeeman lines, the polarity and phase relation of the output voltage e_c is reversed. Specifically, when the frequency of oscillator **10** is above normal, there is greater absorption of the lower sideband energy; and for subnormal frequency, there is greater absorption of the upper sideband energy. Either of the methods exemplified by Figs. 2*a* and 2*b* may be used for automatic stabilization if the aforesaid relationships are appreciated and the control voltage e_c applied in proper sense to minimize deviation of oscillator **10** from frequency f_0.

To effect sweeping of frequency ranges above and below the desired frequency, the modulation-frequency f_l may be applied to the sidebands (Figs. 3*a*, 3*b*) instead of to the Zeeman lines (Figs. 2*a* and 2*b*). Specifically, as shown in Fig. 1, the low-modulating frequency f_l may be applied (as by shifting the position of a switch) periodically to vary the frequency f_m of the amplitude-modulator or modulating oscillator **14** either abruptly or continuously between two frequencies. The mean frequencies $(f_k \pm f_m)$ of the lower and upper sidebands (L, U) may be respectively lower and higher than the fixed frequencies $(f_0 \pm f_h)$ of the Zeeman lines L_L and L_U (Fig. 3*a*) or may be between those frequencies (Fig. 3*b*): as above stated, either relationship may be chosen by choice of the intensity of the Zeeman field and/or of the modulating frequency f_m.

In either case, the pulse output of the demodulators **22A** and **22B** is zero when the frequency of the microwave oscillations corresponds with the desired frequency; but upon deviation therefrom, the difference between the amplitudes of the pulses and their phase relationship contain frequency-error information convertible to an error-voltage by a pulse-amplitude comparator or a phase-comparator. As evident from Fig. 3*a*, when the carrier frequency of the microwave oscillations shifts upwardly from the desired frequency f_0, there is greater absorption of the lower sideband energy; conversely, upon shift from the desired frequency f_0 to lower frequency, there is greater absorption of the upper sideband energy. Thus, the algebraic sign of the relative amplitude of the pulses reverses with reversal of the sense of the frequency deviation of the microwave oscillations. When the initial conditions are selected as in Fig. 3*b*, the absorption of upper sideband energy increases with increase of frequency above normal and absorption of lower sideband energy increases with decrease of frequency f_k from normal. Again the algebraic sign of the relative amplitude of the pulses reverses with reversal of the sense of the deviation of oscillator frequency f_k from its desired value f_0.

In Fig. 4, there is shown one of various types of detector circuits suitable for comparing the relative amplitudes of the pulses produced by any of the foregoing methods (Figs. 2*a*, 2*b*, 3*a*, 3*b*) for production of an error signal of polarity reversing with change in the sense of deviation of the microwave oscillations and of magnitude corresponding with the magnitude of the deviation. Specifically, the demodulators **22A** and **22B** of comparator **23A** may be pair of diodes **30** connected in series-opposition in a network including load resistors **32**, equal resistors **31**, **31** whose common connection provides output terminal **45** of the network. The differential output of the two diodes or equivalent non-linear resistances is applied to an integrating network comprising resistor **33** and condenser **34** connected between the common terminal **45** of resistors **31**, **31** and the other output terminal **46** of the network. The value of each of resistors **31** is high compared to that of resistor **33** to minimize interaction between the diodes. The voltage drop across the integrating network **33**, **34** is a steady voltage rather than a series of pulses and is of polarity dependent upon whether the output pulses of demodulator **22A** are greater or smaller than those of demodulator **22B**. This error-voltage e_c, in the case of a reflex klystron, may be applied to control the anode potential of the klystron, or preferably and as shown in Fig. 4, it may be applied to the signal grid of a control tube **36**. The resistor **37** is common to the anode circuit of both the control tube and the reflector circuit of the klystron **35** so that the potential of the reflector of the klystron, its frequency-controlling electrode, varies with changes of the output of the amplitude-comparator network **23A** so to effect automatic frequency stabilization of the microwave oscillations. The operating frequency of the klystron may be initially set, or readjusted, by the potentiometer network **38, 39** in the grid circuit of the control tube or may be set, or readjusted, by adjustment of cavity dimensions of the klystron.

A suitable type of phase-comparator network for use in the system of Fig. 1 and for comparison of the phase of pulses produced by any of the methods of Figs. 2*a*, 2*b*, 3*a*, 3*b* is shown in Fig. 5: other suitable phase-comparator arrangements are shown in copending application Serial No. 148,481, filed March 8, 1950. In the particular arrangement shown in Fig. 5, a pair of rectifiers, such as diodes **40, 40**, are connected in series in a direct-current loop including a pair of resistors **41, 41**, the error-voltage being produced between the common terminal **45** of the resistors and the terminal **46** common to the cathode of one of the diodes and the anode of the other. The output pulses of one of the demodulators 22A, 22B are each converted to a pair of pulses A_1, A_2 of opposite polarity which are respectively applied through condensers **42, 42** to the anode of one rectifier and the cathode of the other. This conversion may be effected as shown in Fig. 5 by using two rectifiers **30**A_1, **30**A_2 in the demodulator itself; or as shown in copending application including Serial No. 29,836, now abandoned, a push-pull stage may be interposed between the phase-comparator network and a demodulator having a single rectifier.

The output pulses B of the other demodulator, specifically **22B** of Fig. 5, are applied across resistor **44** connected between the common terminal of resistors **43, 43** and a ground or other return conductor. These pulses are thus applied in push-push to the anode of one rectifier **40** and the cathode of the other. Thus, which of the rectifiers **40, 40** is conducting in a cycle of the sweep or repetition frequency f_1 depends upon the phase relation between the pulses impressed upon the input circuits of the phase-comparator, which in turn as above described, depends upon the sense of the deviation of frequency f_k from the desired frequency f_0.

The output pulses of comparator-network **23B** are impressed upon its integrating circuit **33, 34, 34A** so to produce a steady error-voltage of polarity reversing with reversal of the phase relations between the pulses in the two channels of the control system. This control voltage e_c may be applied, as above described, automatically to stabilize the frequency of the microwave oscillations. Specifically, as shown both in Figs. 4 and 5, the control voltage may be applied to the signal grid of a control tube **36** associated with a klystron oscillator. The input or output connections of the comparator-network **23B** must be reversed, and the same is true of comparator-network **23A**, if there is transition from operation in accordance with Fig. 2*a* (or 3*a*) to operation in accordance with Fig. 3*a* (or 3*b*).

It shall be understood the invention is not limited to the arrangements specifically illustrated and described and that changes and modifications may be made within the scope of the appended claims.

What is claimed is:

1. A system of producing an error-signal corresponding in sense with deviations of the carrier frequency of microwave oscillations which comprises means for modulating the oscillations to produce a pair of sidebands at frequencies respectively lower and higher than the carrier frequency, means for impressing the modulated oscillations upon gas having a sharp molecular absorption line, means for producing a Zeeman field in said gas to split said absorption line into a pair of absorption lines at frequencies respectively adjacent the sideband frequencies and respectively above and below the desired carrier frequency, means for cyclically sweeping one pair of said pairs over ranges of frequency including the frequencies of the other pair, means for selectively demodulating the microwave energy transmitted by the gas in said ranges of frequency to produce a pair of pulses for each sweep cycle, and means for combining said pulses to produce a frequency-error signal of reversible polarity dependent upon the sense of deviation of said carrier frequency.

2. A system as in claim 1 in which the Zeeman field is modulated at low frequency to effect cyclic sweeping of fixed frequency sidebands by the pair of varying frequency absorption lines.

3. A system as in claim 1 in which the sidebands are modulated at low frequency to effect cyclic sweeping of a pair of absorption lines of fixed frequencies by varying frequency sidebands.

4. A system as in claim 1 in which the polarity of the error-signal is dependent upon the relative amplitude of the paired pulses.

5. A system as in claim 1 in which the polarity of the error-signal is dependent upon the time relation of the paired pulses in the sweep cycle.

6. A system as in claim 1 in which the error signal is applied to vary the potential of a frequency-control electrode of a tube for stabilization of the carrier frequency of the microwave oscillations.

7. A system as in claim 1 in which the ranges of frequency are respectively higher and lower than the desired carrier frequency and exclusive of it.

8. A system as in claim 2 in which the frequency of the lower sideband is higher than the mean frequency of the adjacent sweeping absorption line and the frequency of the upper sideband is lower than the mean frequency of the adjacent sweeping absorption line.

9. A system as in claim 2 in which the frequency of the lower sideband is lower than the mean frequency of the adjacent sweeping absorption line and the frequency of the upper sideband is higher than the mean frequency of the adjacent sweeping absorption line.

10. A system as in claim 9 in which the frequency ranges of the sweeping absorption lines are mutually exclusive and exclusive of the desired carrier frequency.

11. A system as in claim 3 in which the mean frequency of the lower sweeping sideband is lower than the fixed frequency of the Zeeman absorption line adjacent thereto and the mean frequency of the upper sweeping sideband is higher than the fixed frequency of the Zeeman absorption line adjacent thereto.

12. A system as in claim 3 in which the mean frequency of the lower sweeping sideband is higher than the fixed frequency of the Zeeman absorption line adjacent thereto and the mean frequency of the upper sweeping sideband is lower than the fixed frequency of the Zeeman absorption line adjacent thereto.

13. A system as in claim 12 in which the frequency ranges of the sweeping sidebands are mutually exclusive.

14. A system for producing an error-signal corresponding in sense with deviations of the carrier frequency of microwave oscillations which comprises means for modulating the microwave oscillations to produce sidebands at frequencies respectively higher and lower than said carrier frequency, an enclosed body of gas upon which the modulated oscillations are impressed and which has a sharp molecular absorption line, magnetic means for producing in said gas a Zeeman field splitting said line into a pair of absorption lines respectively adjacent said sideband frequencies and above and below the desired carrier frequency, sweep-frequency modulating means for effecting relative sweeping of the paired sidebands and the paired absorption lines in frequency ranges respectively above and below the desired frequency of said oscillations, means for selectively demodulating the microwave energy transmitted by said gas in said ranges of frequency to produce paired pulses during successive cycles of said sweep-frequency, and a detector network upon which said paired pulses are impressed to produce an error signal.

15. A system as in claim 14 in which the sweep-frequency modulating means varies the intensity of the Zeeman field cyclically to vary the frequencies of the

paired absorption lines over said frequency ranges.

16. A system as in claim 14 in which the sweep-frequency modulating means cyclically varies the upper and lower sidebands over said frequency ranges.

17. A system as in claim 14 in which the detector network is of amplitude-comparator type to produce a unidirectional output voltage of polarity and magnitude dependent upon the relative amplitude of the paired pulses.

18. A system as in claim 14 in which the detector network is of phase-comparator type to produce a unidirectional output voltage of polarity and magnitude dependent upon the time relation of the paired pulses in the sweep cycle.

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