June 30, 1964 A. R. SISSON 3,139,592

MAGNETRON STABILIZATION SYSTEM UTILIZING IMPEDANCE MISMATCH

Filed Sept. 26, 1960

3 Sheets-Sheet 1

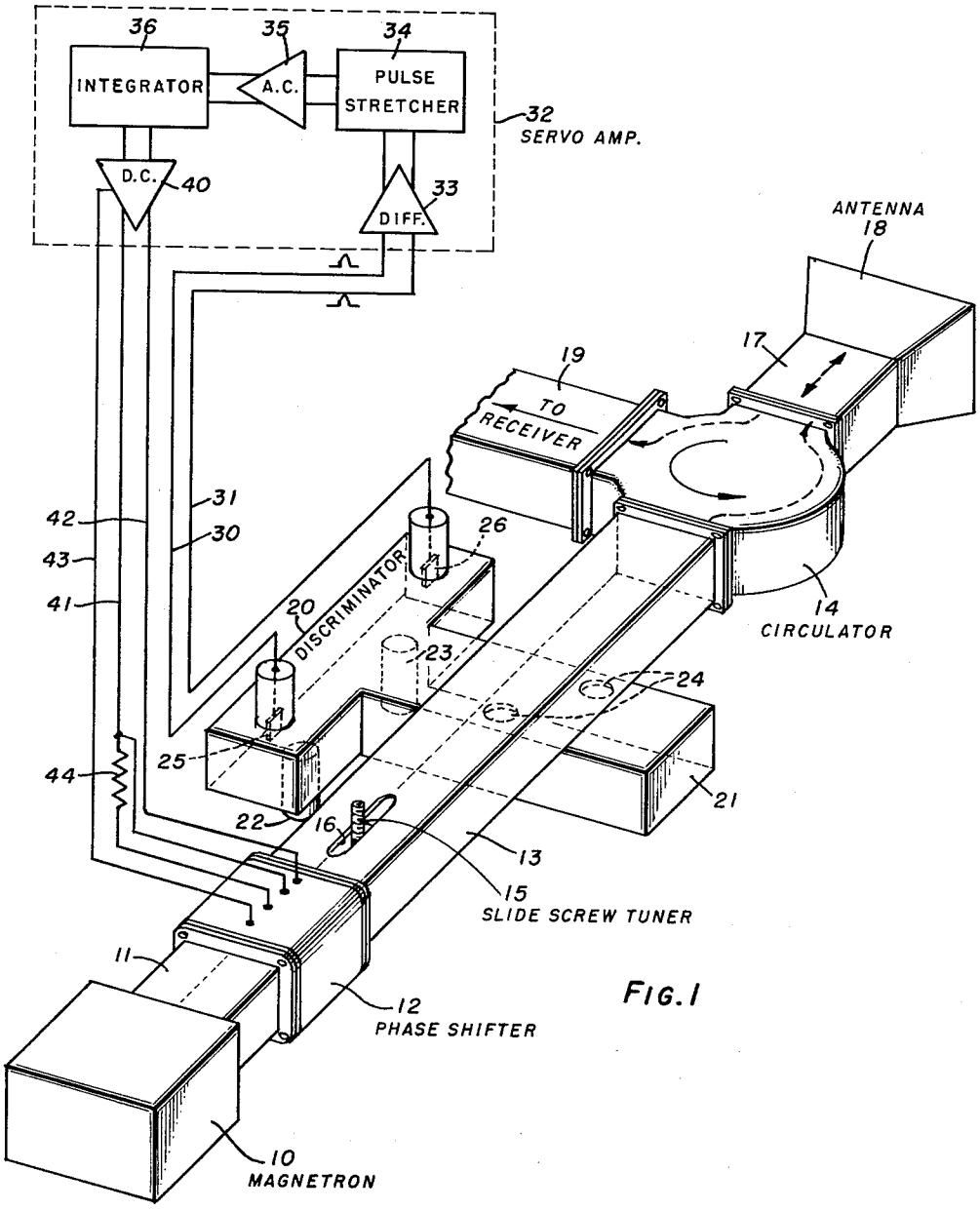


FIG. 1

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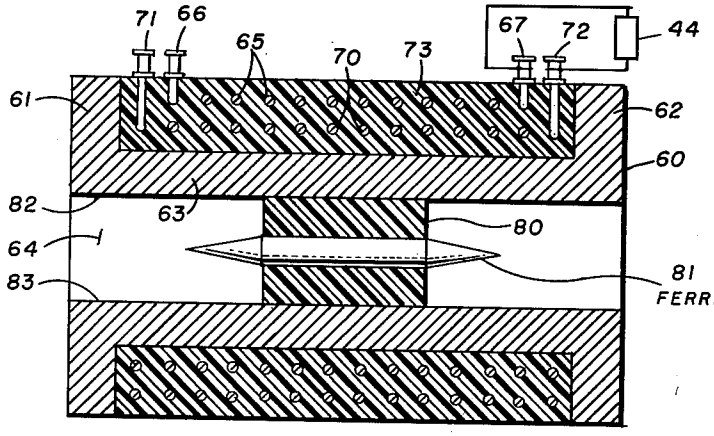


FIG. 2

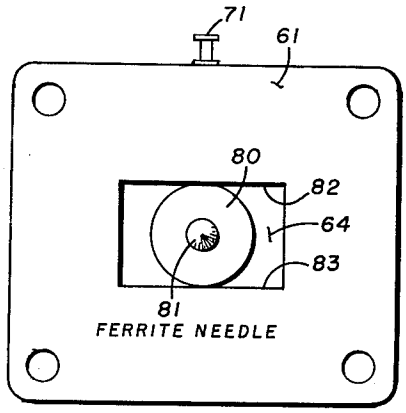


FIG. 3

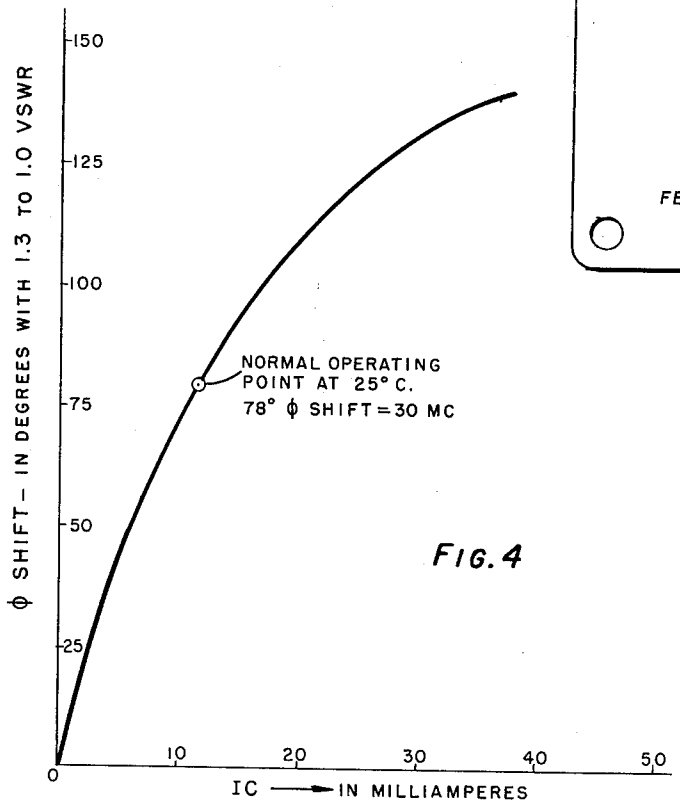


FIG. 4

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MAGNETRON STABILIZATION SYSTEM UTILIZING IMPEDANCE MISMATCH

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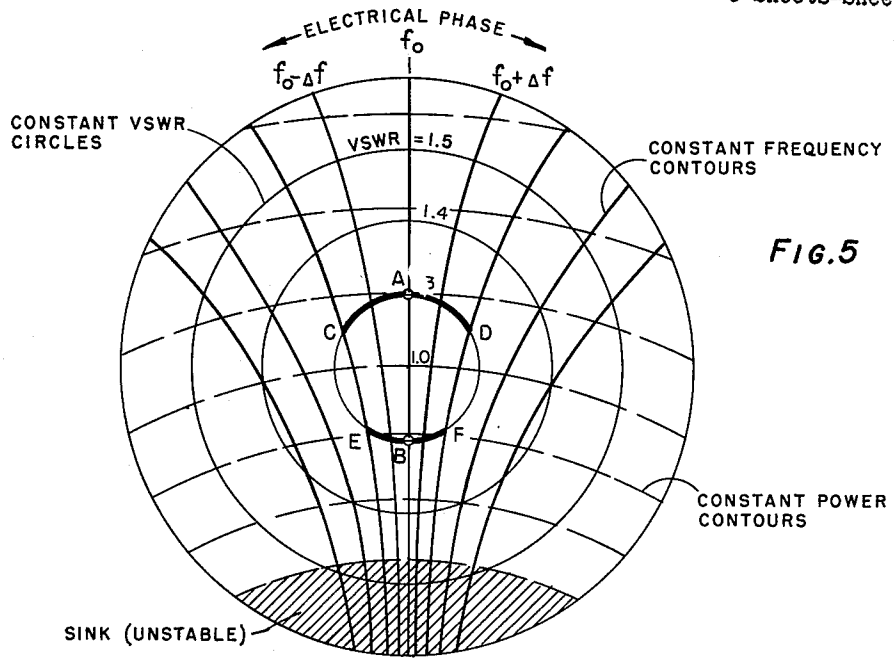


FIG.5

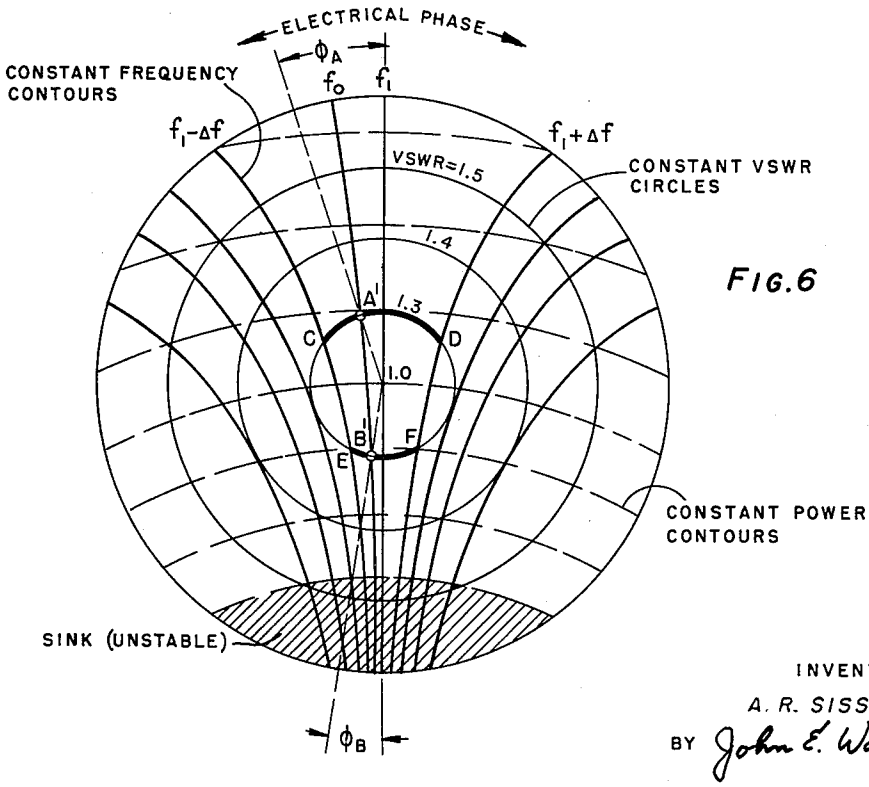


FIG.6

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MAGNETRON STABILIZATION SYSTEM UTILIZING IMPEDANCE MISMATCH

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11 Claims. (Cl. 331—5)

This invention relates to microwave oscillator systems and more particularly to systems for stabilizing the frequency of magnetron oscillators.

Microwave oscillators of the magnetron type have several inherent characteristics tending to cause frequency instability. Magnetrons characteristically have relatively massive body structure, including resonant cavities, the dimensions of which and thereby the resonant frequency are subject to change with temperature owing to the thermal expansion of the magnetron body. Also, magnetrons exhibit frequency variations with changes in power supply voltages. Magnetrons often exhibit frequency changes with age, and the oscillators are also subject to shifts in frequency with changes in the load impedance while in operation. This last change is of such importance and magnitude that the amount of frequency shift with changes in load impedance, commonly designated as the pulling figure, is a major figure of merit of the magnetron. Of course, a low pulling figure indicates that the magnetron is relatively insensitive to load impedance changes. Typical pulling figures for present-day magnetrons are of the order of 15 megacycles for a load voltage standing wave ratio of 1.5 to 1.0. A low pulling figure has been considered a necessity in magnetrons intended for radar use in which a scanning or moving antenna is used, because the load impedance normally seen by the magnetron is subject to constant fluctuation.

In the prior art, two general approaches have been taken to the stabilization of magnetron oscillators:

(1) Resonant cavities have been employed either in the output waveguide or coaxial line from the magnetron or in a separate stub line which tends to modify the resonant system of the magnetron to reduce the errors in frequency which arises; and

(2) Automatic frequency control systems have been used in which errors in output frequency are detected and applied in a closed loop system to introduce a correcting quantity into one of the magnetron operating conditions.

In principle, the second method of magnetron stabilization is more desirable than the first, since it in general has the capability of eliminating any frequency error in its entirety, rather than merely reducing it proportionally as is characteristic of the first approach.

Automatic frequency-control systems have introduced the frequency-correcting quantity by either of two types of corrections:

(1) by mechanically tuning the magnetron in manners which are well known in the art, or

(2) by electrically changing operating conditions.

The mechanical tuning of magnetrons, as by adjusting an internal iris with respect to the cavities, has the inherent limitation of slow response speed. In a system operating in the KU band of 16,000 to 17,000 megacycles per second, a typical mechanically tuned frequency-stabilization system will require a period of the order of seconds to correct even a minor frequency deviation. In a close tolerance system, such a frequency correction rate is grossly inadequate.

In electrically compensated systems of the type developed to date, the inherent slow speed of mechanical systems is largely avoided. An example is a system in which the anode voltage applied to the magnetron is

varied in response to the error signal developed by a frequency discriminator. Another such electrically compensated system employs the error signal to vary the magnetic field applied to the magnetron. Both of these systems, although successful in stabilizing the magnetron frequency, vary the power output as well over a wide range and thereby degrade the operation of the microwave system as a whole.

With this state of the prior art in mind, it is a general object of this invention to provide an improved automatic frequency-control system for magnetron oscillators.

A more specific object of this invention is to provide such a system having almost instantaneous response to errors in frequency and which corrects for the frequency deviations without degradation of the power output of the magnetron.

Still another object of this invention is to achieve such a system capable of employing magnetrons without exceptionally low pulling figures as heretofore required.

These objects are accomplished in accordance with this invention, one embodiment of which comprises a magnetron oscillator having a relatively high pulling figure. An output circuit couples the magnetron to a load which may match the normal output impedance of the magnetron or which may vary, as in typical radar installations. The output circuit includes a tuning element positioned between the magnetron and the load for introducing a controlled amount of mismatch between the magnetron output impedance and the load impedance. The output circuit also includes a frequency discriminator for detecting variations from the normal output frequency, and positioned between the magnetron and the tuning element is an electromagnetically-controlled phase-shifting element. The phase-shifting element is electrically connected to the frequency discriminator through a servo amplifier which produces a unidirectional current of amplitude varying with the extent of frequency deviation detected by the discriminator.

One feature of this invention is the combination of a magnetron having a substantial pulling figure with a mismatched impedance load having a phase shift which is controlled by the amount of frequency deviation from normal detected in the magnetron output circuit.

Another feature of this invention involves the combination of a magnetron having a relatively high pulling figure and an electromagnetically-controlled phase shifter which changes the impedance seen by the magnetron responsive to current changes through the phase shifter.

A complete understanding of this invention may be had from the following detailed description and the drawing, in which:

FIG. 1 is a simplified isomatic view of the frequency-stabilization system of the invention;

FIG. 2 is a vertical section through the phase shifter of FIG. 1;

FIG. 3 is an end view of the phase shifter of FIG. 2;

FIG. 4 is a graphical representation of the coil current-phase shift characteristic of the phase shifter of FIG. 3; and

FIGS. 5 and 6 are Rieke diagrams illustrating the operating characteristics of a magnetron oscillator incorporating this invention.

Referring now to FIG. 1, a typical X-band or KU-band frequency-stabilized radar beacon system includes a magnetron, shown for simplicity's sake as a box **10**, having a waveguide section **11** coupled thereto as the energy output conductor. Coupled to the waveguide section **11** is a phase shifter **12**, the details of which appear in FIGS. 3 and 4. In tandem with the phase shifter **12** is another waveguide section **13** which is coupled ultimately to a load. In a typical installation, the load is an antenna or may be an antenna coupled to the waveguide section

13 through a duplexer or circulator 14 which isolates the load impedance from the magnetron 10 and thereby minimizes the normal variation in load impedance which otherwise would be seen by the magnetron.

The circulator 14 of well known design includes one waveguide connection 17 to an antenna 18 and another waveguide connection 19 to a receiver, unshown in this drawing. The circulator 14 allows the passage of microwave energy in the direction of the central arrow; i.e., counter-clockwise in the drawing. Therefore, energy from the magnetron 10 reaching the circulator 14 from waveguide section 13 follows the dashed arrow to the waveguide section 17 and antenna 18. Energy picked up by antenna 18 from the surrounding medium passes through waveguide section 17, then into the circulator 14 in the direction of the dash-dot arrow to waveguide section 19, and thence to a receiver. The circulator 14, as is well known in the art, isolates the transmitted from the received signals in such a system. It also isolates the antenna impedance changes from the magnetron 10 source to a degree. Therefore, the input impedance to the circulator is substantially a constant load which may be matched to the magnetron 10 output impedance for maximum energy transfer.

The waveguide section 13 includes a slide screw tuning element in the form of a screw 15 positioned within a slot 16. The screw 15 is adjustable in and out of the waveguide and carries a capacitative member to adjust the quantity of loading introduced into the waveguide system, and the screw is adjustable longitudinally in the waveguide 13 to establish a standing wave pattern within the waveguide system, and to produce an impedance mismatch in the order of 1.3 to 1 between the load impedance seen by the magnetron 10 and its output impedance. The tuning screw 15 insures that at all times in operation there is an impedance mismatch sufficient for the successful operation of the invention, yet slight enough to limit the loss of power transmitted to the antenna 18. Microwave energy generated by the magnetron 10 and transmitted through waveguide 11, phase shifter 12 and waveguide 13 to the load 14 is partially reflected so that the magnetron sees an unmatched impedance of variable phase. The waveguide 13 also includes a discriminator section for detecting the frequency of energy within the waveguide.

The discriminator section includes a cross-guide T coupler 20 having a terminating section 21 on one side of waveguide section 13 and a pair of resonant cavities 22 and 23 in the arms of the T. The coupler 20 includes a pair of openings 24 communicating with the interior of the waveguide 13, allowing the sampling of energy within the waveguide 13. Positioned beyond the respective cavities 22 and 23 are crystal detectors 25 and 26 which are connected to respective input leads 30 and 31 of a servo amplifier 32. The cavity 22 is tuned to a frequency slightly below, e.g., 15 megacycles, the magnetron normal operating frequency, while the cavity 23 is tuned to a similar frequency above that of the magnetron 10.

The servo amplifier 32 includes an input stage connected to leads 30 and 31 comprising a differential amplifier 33 made up, for example, of a dual triode which produces an output pulse of either positive or negative polarity depending upon the relative magnitudes of the input signals on input leads 30 and 31. The pulse output from the triode is amplified and is introduced to a pulse stretcher 34 and thence via further A.C. amplification stage 35 to an integrating network 36 which produces a direct current varying in magnitude with the difference between the relative levels of the input signals on leads 30 and 31. The output of integrator 36 is amplified by a D.C. amplifier 40 and the current from amplifier 40 introduced into the phase shifter 12 over conductors 41 and 42. A constant current bias for an auxiliary winding of the phase shifter is also derived from the D.C. amplifier 40 over lead 43 to provide for temperature compensation of the phase shifter itself. A current limiting resistor 44 is connected in series with lead 41 of the phase shifter 12 in order that the current variation applied to the phase shifter 12 covers a selected range and does not exceed the value for the maximum desired phase shift to be introduced into the system.

The structure of the phase shifter 12 appears in FIG. 3 as including a bobbin 60 having end flanges 61 and 62 which mate with adjoining sections of waveguide 11 and 13. The central body portion 63 of the bobbin 60 includes a rectangular waveguide opening 64 of the same dimension as the waveguide sections 11 and 13. The region between the flanges 60 and 61 includes a winding 65 having terminals 66 and 67 and a winding 70 with terminals 71 and 72, all encapsulated in an insulating material 73.

Within the waveguide opening 64 of the phase shifter 12 is a dielectric member 80 in the form of either an elongated tube or a finlike structure extending between the upper and lower walls 82 and 83, respectively, of the waveguide opening 64. Positioned within a central opening in the dielectric member 80 is a ferrite rod or needle 81 axially aligned within the waveguide.

The relative position of the ferrite needle 81 and its supporting member 80 within the waveguide opening 64 may all be seen in FIG. 3. In the configuration shown in FIGS. 2 and 3, the characteristics of the ferrite needle 81 are such that the phase shift between flanges 61 and 62 is essentially a linear function of the D.C. current amplitude in windings 65 and/or 70.

The ferrite phase shifter of FIGS. 2 and 3 has the typical operating characteristic shown in FIG. 4. With no current flowing through winding 65 and a current of 20 milliamperes flowing through the bias winding 70, a reference phase is established. With increases in the current flowing between terminals 66 and 67, the phase shifter 12 presents an impedance to the magnetron which varies linearly in phase shift while maintaining a constant voltage standing wave ratio over a range of 0° to 100° when the voltage standing wave ratio, as determined by the adjustment of slide screw tuner 15 has a value of 1.3 to 1 which is a typical impedance mismatch employed. This coil current-phase shift characteristic allows the control accurately and almost instantaneously of the load impedance seen by the magnetron under varying operating conditions. The output characteristic of the servo amplifier 32 is designed to produce a current with varying frequency from the center frequency sufficient to provide the necessary phase shift in the phase shifter to pull the magnetron back onto frequency, as may be seen in conjunction with the description below of FIG. 5.

The phase shifter is not, in itself, insensitive to temperature changes, so the additional winding 70 is employed to temperature compensate the phase shifter. This may be accomplished by employing a thermistor network in the bias circuit to vary the bias current through bias winding 70 as a function of temperature. The permeability of the ferrite needle 81 increases with an increase in temperature, and with a constant current in the coils 65 and 70 an increase in phase shift between the flanges 61 and 62 results. The thermistor network decreases the current through the bias winding 70 to maintain the phase shift between flanges 61 and 62 substantially independent of temperature.

It is further desirable in the operation of the phase shifter that the load phase be shifted over controlled range, but that phase not exceed selected values as will be clearly understood upon examination of the Rieke diagram of FIG. 5. Therefore a current-limiting resistor 44 is connected in series with lead 41 to limit the amount of current which passes through the winding 65.

FIGS. 5 and 6 are typical Rieke diagrams of a magnetron. Initially, the frequency-stabilization system is adjusted to a selected frequency f_0 by means of tuning screw

15, bias resistor 44 in series with lead 41, and by mechanically tuning the magnetron 10 so that the magnetron operates at either point A or point B on FIG. 5. Now, if during the course of operation in a typical radar system any, or a combination of any, of the parameters described above cause the magnetron frequency to deviate from the selected frequency f_o, the constant frequency contours on the Rieke diagram rotate clockwise or counterclockwise as the frequency increases or decreases. FIG. 6 demonstrates the conditions under which the constant frequency contours have rotated counterclockwise. A signal voltage is then developed in the output leads 30 and 31 of the discriminator section of waveguide 13 and applied to the servo amplifier 32. The sense of said signal is such as to cause the D.C. current in the output leads 41 and 42 of D.C. amplifier 40 to vary in the proper direction and amount, which in turn causes the phase shifter to vary the phase in the proper direction by an amount ϕ_A or ϕ_B as shown on FIG. 6, depending on whether the frequency stabilization system was initially adjusted to operate at point A or point B of FIG. 5. This action is accomplished almost instantaneously. The new phase value ϕ_A or ϕ_B corresponds to the selected frequency f_o. When the frequency corresponds to the selected frequency f_o, the signal voltage in the discriminator leads 30 and 31 described above reduces to zero, and the phase value ϕ_A or ϕ_B is maintained constant unless there are further changes in parameters which tend to change the frequency. During the course of operation the loci of operating point A forms the arc of the 1.3 VSWR circle from C to D or the loci of point B the arc from E to F, depending on initial adjustment as described above.

During the frequency deviation from point A or B of FIG. 5 to the point A′ or B′ of FIG. 6 and the compensating action of this invention to return the operating point to point A or B, the power output of the magnetron remains substantially constant. This can be observed in FIGS. 5 and 6 by noting the relatively close registration between the operating curves C–D and EF and the constant power contours. The overall effect on the system is that frequency deviations by the magnetron are almost instantaneously corrected by correcting changes in the phase of the load seen by the magnetron without degradation of the power output of the system.

Although for the purpose of explaining the invention a particular embodiment thereof has been shown and described, obvious modifications will occur to a person skilled in the art, and I do not desire to be limited to the exact details shown and described.

I claim:

1. A microwave oscillator system comprising:
a microwave oscillator;
an output circuit coupled to said oscillator adapted to to be connected to a load;
means in said output circuit for adjusting the impedance of said output circuit to provide mismatch between the output impedance of said oscillator and input impedance of said output circuit;
phase-shifting means in said output circuit between said oscillator and said impedance-adjusting means; and
means responsive to variations in output frequency from said selected frequency for adjusting said phase shifting means to vary the impedance of said output circuit as seen by the oscillator.

2. A microwave oscillator system comprising:
a microwave oscillator having the property of substantial change in frequency with change in load impedance;
an output circuit adapted to couple said oscillator to a load;
means in said output circuit for adjusting the impedance to provide a mismatch between the oscillartor output and load impedance;
means in said output circuit between said oscillator and said impedance-adjusting means for adjusting the phase of energy in said output circuit reflected toward said oscillator;
means for detecting variations in the output frequency of said oscillator from a selected value; and
means responsive to frequency variations detected by said last means for adjusting said phase-shifting means to shift the phase angle of the load impedance seen by said oscillator in amount and direction sufficient to cause said oscillator to change to substantially said selected frequency.

3. A magnetron oscillator frequency-stabilizing circuit comprising:
a magnetron oscillator;
an output circuit for said magnetron adapted to be connected to a load;
means in said output circuit for establishing a mismatch between the output impedance of said magnetron and the input impedance of the load;
a phase shifter in said output circuit between said oscillator and said last means;
means for detecting variations in the output frequency of said oscillator from a selected value; and
means responsive to frequency variations detected by said last means for varying the phase shift of said phase shifter in amount and direction sufficient to change the impedance seen by said oscillator whereby said oscillator is pulled back to said selected frequency.

4. A magnetron oscillator frequency-stabilizing circuit comprising:
a magnetron oscillator having a pulling figure of at least several megacycles;
a waveguide output circuit adapted to couple said oscillator to a load;
tuning means in said waveguide for adjusting the impedance looking toward the load to a mismatch with the output impedance of said oscillator;
a ferrite element positioned longitudinally within said waveguide between said oscillator and said tuning means; a winding coupled to said ferrite element;
means for detecting variations in the output frequency of said oscillator from a selected value; and
means responsive to the variation in output frequency detected for passing current through said winding to vary the phase of the impedance of the output circuit an amount and direction sufficient to cause said magnetron oscillator to pull substantially to said selected frequency.

5. A magnetron oscillator system comprising:
a magnetron oscillator exhibiting the property of a substantial change in operating frequency with change in load impedance;
an output circuit for said magnetron;
a load connected to said output circuit, said load having an input impedance differing in magnitude from the output impedance of said magnetron;
means in said output circuit for varying the phase of energy from said magnetron reflected back by the impedance mismatch between said magnetron and said load;
means for detecting variations in the operating frequency of said magnetron from a selected frequency; and
means responsive to said detecting means for controlling said phase varying means whereby the energy reflected back from said load is of such phase as to pull said magnetron to said selected frequency.

6. The combination in accordance with claim 5 wherein said detecting means comprises a frequency discriminator including a first frequency sensitive element tuned to a frequency below said selected frequency, and a second frequency sensitive element tuned to a frequency above said selected frequency and means responsive to the difference in level of energy detected by said first and sec-

ond frequency sensitive elements for generating a substantially linearly varying unidirectional current.

7. The combination in accordance with claim 6 wherein said phase varying means comprises a current responsive ferromagnetic loading element in said output circuit.

8. A magnetron oscillator frequency-stabilizing circuit comprising:

a magnetron oscillator exhibiting a significant change in output frequency with changes in load impedance;

an output circuit adapted to couple said oscillator to a load;

impedance-adjusting means in said output circuit for establishing an impedance mismatch between the output impedance of said oscillator and the input impedance to the load;

frequency-discriminating means coupled to said output circuit to detect variations in the output frequency of the oscillator from a selected value;

means for producing a unidirectional current having a magnitude varying directly with frequency in the range of said selected frequency;

current-responsive phase-shifting means coupled to said waveguide between said magnetron oscillator and said impedance-tuning element; and

means for introducing the unidirectional current into said phase-shifting means to vary the phase of the load seen by the magnetron oscillator.

9. The combination in accordance with claim 8 wherein said phase-shifting means responds to said current source to change the phase of the load impedance seen by the said oscillator an amount and in a direction sufficient to pull said oscillator back to said selected frequency.

10. The combination in accordance with claim 9 wherein said phase-shifting means comprises

a ferro magnetic element positioned within said output circuit and a winding inductively coupled to said ferro-magnetic element.

11. The combination in accordance with claim 10 wherein said output circuit comprises a waveguide section and said ferromagnetic element comprises a bar of ferrite positioned longitudinally within said waveguide section and spaced from the walls thereof.

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