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CIRCULATOR-MODULATOR FREQUENCY CONTROL SYSTEM

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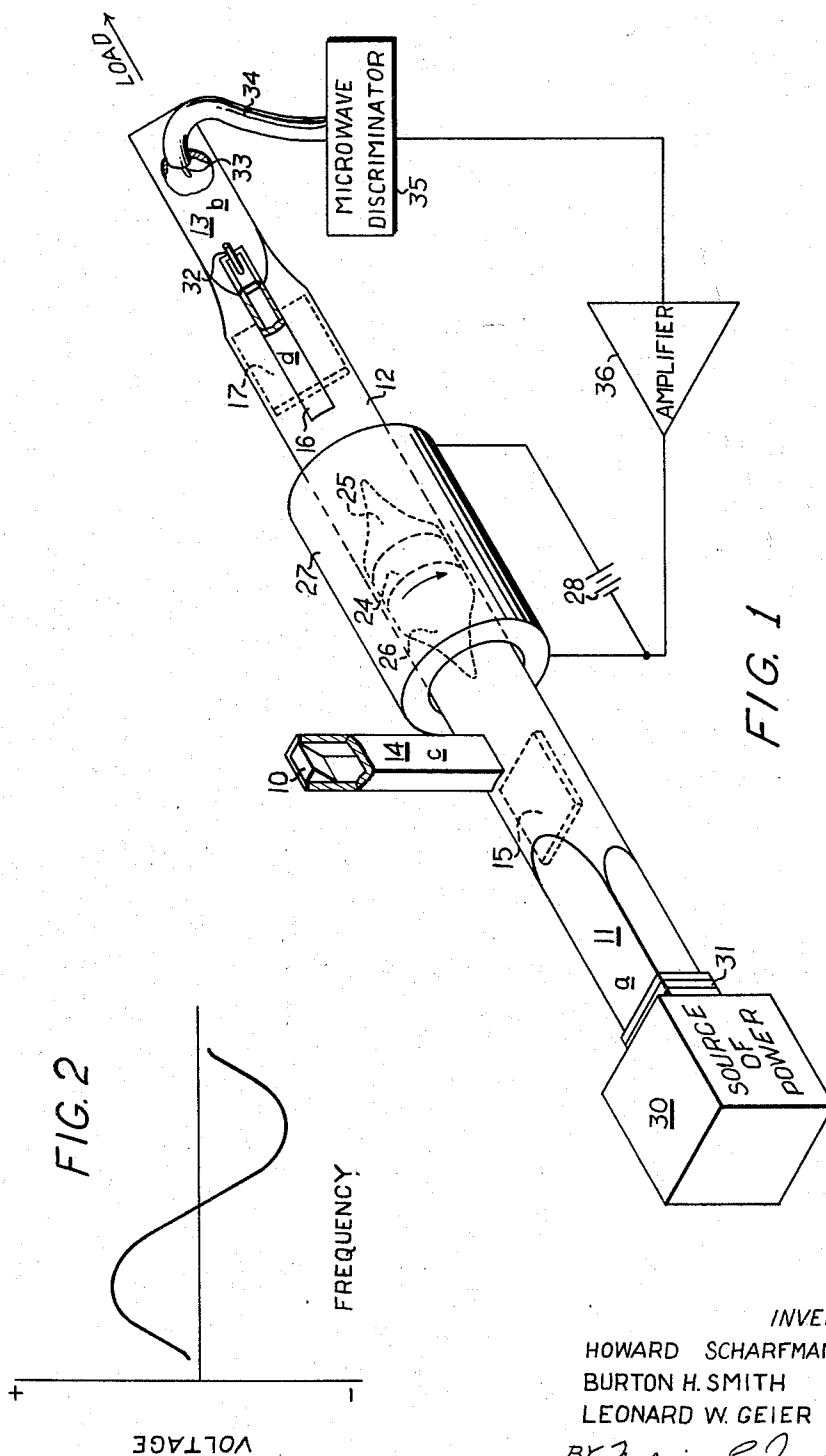


FIG. 1

FIG. 2

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3,178,652 CIRCULATOR-MODULATOR FREQUENCY CONTROL SYSTEM

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Continuation of abandoned application Ser. No. 19,723,
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236,181

6 Claims. (Cl. 331-5)

This is a continuation of our copending application,
Serial No. 19,723, filed April 4, 1960, now abandoned.

This invention relates to frequency control high frequency generators and more particularly to the stabilization of the frequency of magnetron oscillators by utilizing a cavity referenced circulator-modulator loop.

Frequency stabilization of high frequency generators for long term drift has been accomplished by several techniques including multi-cavity coupling, Pound stabilization, and other AFC loop-type systems feeding back on the oscillator. The stability of such techniques and systems are generally dependent upon a number of inter-related factors and they require complex, sensitive, and costly components such as crystal control oscillators and complex feedback circuits difficult of adjustment and construction. Such techniques and systems are generally single function arrangements for frequency control and in addition to the above-noted disadvantages do not function to isolate the generator from the load nor may they additionally function as a duplexer if desired. Further, AM and/or FM modulation is not easily obtained, if at all. Generally only one or the other of the above-noted functions are available and inasmuch as stability is not achieved by the direct application of control signals to the generator, high potentials are required. Still further, short time stability is generally not practically obtainable.

On the other hand, ferrite circulators have been used to isolate the generator from the load and to function as duplexers, but so far as is known by the inventors ferrite circulators have not been applied nor successfully utilized for frequency control of the high frequency generator with which it is generally associated.

These and other disadvantages and deficiencies of the prior art are overcome by the present invention which contemplates the provision of a ferrite rotation circulator serially connected in the output line of a high frequency generator wherein the circulator is provided with a feedback loop containing a microwave discriminator for supplying a signal to the solenoid of the rotation circulator in such a manner as to pull the frequency of the generator in the proper direction when it varies from a reference frequency. This is accomplished by providing means for the proper adjustment of the phase of signals reflected back to the high frequency generator through the rotation circulator and superimposing a control signal, obtained by sampling the output signal, on the solenoid of the rotator that is proportional in magnitude and sense to frequency variation. The concept of frequency pulling by means of a single or multicavity referenced rotation circulator is basic to the invention which, although particularly useful with CW oscillators, is also applicable to CW, FM-CW, pulse, and pulse-Doppler systems.

The invention will provide stable operation for what would otherwise be deviations in frequency for large frequency swings of the order of the pulling figure of the sources used, and is limited only by the stability of the cavity system and the attainable loop gain of the system. This results in a system which is independent, at least to the first order, of crystal unbalance and amplifier drift and is also independent of temperature variations when a

high loop gain is used. Further, the generator is simultaneously and substantially isolated from the load, duplexing may be provided if desired, modulation may be easily applied in the feedback loop for AM or FM modulation, frequency stability is provided without additional or complex control elements, and short time stability may be provided by merely extending the loop gain characteristic to high frequencies.

These and other objects and features of the invention, the nature of the present invention and its advantages, will appear more fully upon consideration of the specific illustrative embodiment shown in the accompanying drawing and of the following detailed description of this embodiment.

FIG. 1 is a partly perspective and partly diagrammatic view of a non-reciprocal multi-branch network, in accordance with the present invention; and

FIG. 2 is a graphic representation of the voltage vs. frequency curve of a microwave discriminator suitable for use with the invention.

In more detail, FIG. 1 illustrates a nonreciprocal four branch microwave network constructed in accordance with the present invention. For convenience hereinafter the network will be designated as a "circulator" network. The circulator connecting the terminals *a*, *b*, *c*, and *d* comprises a circular waveguide 12 which tapers smoothly and gradually from its lefthand end into a rectangular waveguide 11 and which is joined near said end by a second rectangular guide 14 in a shunt or H-plane junction. Guide 14 is terminated in a reflectionless and power-absorbing termination 10. The rectangular waveguides 11 and 14 will accept and support only plane waves in which the component of the electric vector, which determines the plane of polarization of the wave, is consistent with the dominant TE₁₀ mode in rectangular waveguide. Likewise, the dimension of guide 12 is preferably chosen so that only the several polarizations of the dominant TE₁₁ mode in it can be propagated. By means of the smooth transition from the rectangular cross-section of guide 11 to the circular cross-section of guide 12, the TE₁₀ mode, that wave energy having a plane of polarization parallel to the narrow dimension of the rectangular cross-section of guide 11, may be coupled to and from the TE₁₁ mode in circular guide 12 which has a similar or parallel polarization. Any other polarization of wave energy in guide 12 will not pass through the polarization-selective terminal comprising guide 11. Guide 14 is physically oriented with respect to guides 11 and 12 so that the TE₁₀ mode in guide 14 is coupled by way of the shunt plane junction between the rectangular cross-section of guide 14 and the circular cross-section of guide 12 into the particular TE₁₁ mode in circular guide 12 which is polarized perpendicular to the TE₁₁ mode introduced by guide 11. Thus, guides 11 and 14 comprise a pair of polarization-selective connecting terminals by which wave energy in two orthogonal TE₁₁ mode polarizations may be coupled to and from one end of guide 12. Furthermore, these guides comprise a pair of conjugately related terminals or branches inasmuch as a wave launched in one will not appear in the other.

A highly conductive reflecting vane 15, which may be in the order of one-half wavelength in length, may be diametrically disposed in circular guide 12 opposite the junction aperture of guide 14 to assist in reflecting into guide 14 those waves having their plane of polarization coincident with the plane of vane 15.

At the other end of guide 12 is a similar pair of polarization-selective conjugate terminals comprising rectangular guides 13 and 16 coupled to orthogonally related waves in guide 12 which waves are polarized in planes 45 degrees

inclined to the planes of the corresponding waves, respectively, to which guides 11 and 14 are coupled. Thus, guide 12 tapers into a rectangular guide 13 which supports a wave polarized in a plane inclined 45 degrees with respect to the polarization of the wave in guide 11. Guide 12 is joined in a shunt plane junction by a second rectangular guide 16 which is perpendicular to both guides 12 and 13 and which will accept waves from guide 12 having a plane of polarization inclined at 45 degrees to the polarization of those waves accepted by guide 14. A highly conductive reflecting vane 17 may be positioned with respect to the aperture of guide 16 and bears the same relation thereto as vane 15 bears to the aperture of guide 14. It is obvious to one skilled in the art that any of a number of other well-known coupling means may be employed in lieu of one or more of the waveguides 11, 13, 14, and 16 to couple to and from the proper polarizations of waves in guide 12.

Interposed and carried between the first pair of conjugate terminals comprising guides 11 and 14 and the second pair of conjugate terminals comprising guides 13 and 16 in the path of wave energy passing therebetween in guide 12 is suitable means of the type which produces an antireciprocal rotation of the plane of polarization of these electromagnetic waves. For example, a Faraday-effect element having such properties functions such that an incident wave impressed upon a first side of the element emerges on the second side polarized at a different angle from the original wave and an incident wave impressed upon the second side emerges upon the first side with an additional rotation of the same angle. Thus, the polarization of a wave passing through the element first in one direction and then in the other undergoes two successive space rotations or space phase shifts in the same sense, thereby doubling the rotation undergone in a single passage. As illustrated by way of example in the drawing, this means comprises a Faraday-effect element 24 with accompanying conical transition members 25 and 26 which may be of polystyrene and are provided to cut down reflections from the faces of element 24, mounted inside guide 12 approximately midway between the conjugate pairs.

As a specific embodiment, element 24 may be a block of magnetic material, such as, for example, nickel-zinc ferrite having a thickness of the order of magnitude of a wavelength. This material has been found to operate satisfactorily as a directionally selective Faraday-effect rotator for polarized electromagnetic waves to an extent up to 90 degrees or more when placed in the presence of a longitudinal magnetizing field of strength which is readily produced in practice and in such thickness is capable of transmitting electromagnetic waves, for example, in the centimeter range, with substantially negligible attenuation. Suitable means for producing the necessary longitudinal magnetic field surrounds element 24 which means may be, for the purpose of illustration, a solenoid 27 mounted upon the outside of guide 12 and supplied by a source 28 of energizing current. It should be noted, however, that element 24 may be permanently magnetized or element 27 can be a permanently magnetized structure. The angle of rotation of polarized electromagnetic waves in such magnetic material is approximately directly proportional to the thickness of the material traversed by the waves and to the intensity of the magnetization to which the material is subjected, whereby it is possible to adjust the amount of rotation by varying or properly choosing the thickness of the material comprising element 24 and the intensity of magnetization supplied by solenoid 27.

In the simplified view of the phenomenon involved, a plane-polarized wave incident upon the magnetic material in the presence of the magnetic field produces two sets of secondary waves in the material, each set of secondary waves being circularly polarized. The two sets of secondary waves are circularly polarized in opposite senses and they travel through the medium at unequal speeds.

Upon emergence from the material the secondary waves in combination set up a plane-polarized wave, which is in general polarized at a different angle from the original wave. It should be noted that the Faraday rotation depends for its direction upon the direction of the magnetic field. Thus, if the direction of the magnetic field is reversed, the direction of the Faraday rotation is also reversed in space while retaining its original relationship to the direction of the field.

A high frequency generator 30, such as a magnetron, the Rieke diagram of which is known is connected to terminal *a*. Removable shims 31 may be provided between the reference surface of the magnetron used in determining the Rieke diagram to secure the proper phase adjustment for waves, hereinafter described in detail, reflected back to the magnetron. Alternately, and preferably, means for providing the desired phase adjustment as described hereinafter in detail is provided at guide 16 and comprises an adjustable shorting element 32 forming a termination for guide 16 which functions to vary the phase of waves received from the magnetron and reflected back toward the magnetron.

The output wave in guide 13 is sampled by a probe 33, which preferably projects only slightly into guide 13 so as to disturb transmission therein only slightly and functions to pick up a monitoring potential from the wave in guide 13. The probe 33 may be connected as through a coaxial transmission line 34 to a conventional microwave discriminator 35, the output of which may be connected to an amplifier 36 which in some cases may be desirable to increase the output of the discriminator 35 to a more suitable value. The output of the amplifier 36 is connected to the solenoid 27 whereby the aforementioned output is superimposed on the current supplied by source 28. It is obvious to those skilled in the art that well-known directional coupling means other than a probe as described herein may be used and that if desired a separate solenoid may be provided in conjunction with solenoid 27 to receive the output signal of the discriminator 35. Further, any suitable microwave discriminator may be used having a voltage vs. frequency curve different from that shown in FIG. 2 to provide a control signal having the desired magnitude and sense variation for frequency variation from a fixed reference. However, in such a case, additional biasing potentials and the like will be necessary to provide a reference potential indicative of the reference frequency.

The mode of operation of the invention is as follows. A vertically polarized wave introduced at terminal *a* from a high frequency generator 30 such as, for example, a magnetron which has a pulling characteristic and acts as a source of wave energy into guide 11, travels past the aperture of guide 14 and its associated vane 15 unaffected thereby inasmuch as the effective polarization of these components is perpendicular to the polarization of the wave, and past transition member 26, to element 24. The thickness of element 24 and the potential from source 28 are adjusted, as pointed out thereinbefore, to give a 45 degree rotation of the plane of polarization in the same direction as the angle existing between the first pair of terminals comprising guides 11 and 14 and the second pair of terminals comprising guides 13 and 16. Thus, as shown in FIG. 1, the polarization of the wave is rotated 45 degrees in a clockwise direction, as indicated by the arrow on element 24 in the drawing, thereby bringing the plane of polarization of the wave into the preferred direction for transmission unaffected past guide 16 and into the preferred polarization of passage through guide 13 to terminal *b* and a suitable load connected thereto. Substantially free transmission is therefore afforded from terminal *a* to terminal *b*.

For a specific adjustment of the length of guide 16 when the magnetron is oscillating at the desired frequency, when a wave having the same polarity as the wave heretofore described as leaving terminal *b* by guide 13 is ap-

plied from means acting as a source to guide 13 or is a wave reflected back through guide 13 as the case may be, it will be transmitted unaffected past the conjugate guide 16 to element 24. This wave will be rotated 45 degrees by element 24 bringing the wave into a horizontal polarization at the aperture of guide 14 into which it will be reflected by vane 15 for absorption in termination 10. However, it is important to note that if the amount of rotation varies from 45 degrees a portion of this signal will be coupled to guide 11. Similarly, a wave leaving guide 16 and having the same polarization as a wave entering guide 16 will be launched in guide 12 in a polarization conjugate to guide 13 and will travel to element 24 where it receives a further 45 degree rotation bringing its plane of polarization into the preferred direction for transmission through guide 11 to terminal *a* and magnetron 30 acting now as a utilizing means. The microwave discriminator 35, having a voltage vs. frequency curve such as for example, as shown in FIG. 2, is adjusted so that its zero (or reference) voltage condition corresponds to the desired magnetron output frequency. Obviously, for the zero voltage condition no feedback signal will be supplied to solenoid 27 and the operation of the system will remain unchanged. However, for the proper adjustment of the length of guide 16 as determined, for example, by use of the Rieke diagram for the magnetron 30 and the selected parameters of the network, or by experimentation, the magnitude and phase of the signal propagated toward the magnetron 30 from guide 16 will be changed from that as received by guide 16 when the magnetron drifts off frequency.

The nature of the phase shifting operation accomplished by guide 16 is such that by reason of the signal superimposed on solenoid 27, which varies the amount of rotation affected, the polarization of the reflected wave is varied in the proper direction such that at least a portion thereof is received by guide 11 and varies the pulling characteristic of the magnetron in such a direction as to pull the frequency of the magnetron back toward the desired frequency. As is well known, pulling results from load susceptance and is generally avoided and considered to be undesirable. Briefly, by way of explanation in a quantitative manner, a lagging wave incident on the magnetron, such as, for example, that reflected from a capacitive load, always adds susceptance to the resonant system and reduces the magnetron frequencies. Similarly, a leading wave incident on the magnetron and reflected from an inductive load always adds negative susceptance to the resonant system and increases the magnetron frequencies. As may now be readily evident the preferred embodiment of the present invention results in frequency pulling in the proper direction by reason of the provision and adjustment of the proper phase of a wave reflected back to the magnetron by guide 16 in combination with variation of the direction and amount of rotation from 45 degrees effected by the circulator. This variation from the normal or steady state rotation of 45 degrees is controlled by the output signal of the discriminator the variations of which output signal are proportional and due to frequency deviations of the magnetron and are related in sense to the proper phase adjustment provided, for example, by guide 16.

An alternative but less flexible arrangement comprises elimination of the function of guide 16 as a shorting stub to vary the phase of and reflect a wave back to the magnetron and variation of the phase of signals incident on the magnetron by adjustment of the number of shims 31. In this case guide 16 may be eliminated altogether or it may function as an output part to receive, for example, a wave coupled to guide 14 from a directional coupler adapted to permit signals to travel toward guide 12 through guide 14 and the absorption of signals traveling from guide 12 through guide 14. In this case the reflected signal incident on the magnetron is derived from reflected signals due

to mismatch and the like between the circulator and the load, either inherent in the system or planned.

It may now be obvious that when the sense of rotation provided by the discriminator for frequency variations of the magnetron is correlated with the proper phase adjustment for signals incident on the magnetron, as the magnetron tends to increase in frequency susceptance is added to pull the frequency back toward the reference frequency to which the discriminator is turned and when the magnetron tends to decrease in frequency susceptance is subtracted to again pull the frequency back toward the reference frequency.

Having thus analyzed the structure and characteristics of the invention, it will be readily apparent to those skilled in the art that many modifications may be made without deviating from the spirit and scope of the invention. For example, modulation of the magnetron output signal may be easily provided by inserting means in conventional manner in the discriminator feedback loop for amplitude or frequency modulation or modulation may be provided by other well-known means. The circulator may be used as a duplexer for CW systems, and in conjunction with a fast ferrite switch in the receiver arm, it may be used for duplexing in pulsed systems as well. Of course, in any case the magnetron is always isolated from the load.

In all cases, it is to be understood that the above-described arrangements are simply illustrative of a small number of many possible specific embodiments which can represent applications of the principles of the invention. Numerous and varied other arrangements can readily be devised in accordance with said principles by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. In a frequency stabilizing system the combination comprising:
 - a section of waveguide adapted to support electromagnetic wave energy in a plurality of linear polarizations;
 - a first polarization-selective connection at a first location along said waveguide coupled to a given one of said polarizations at said first location;
 - a source of linearly polarized wave energy connected to said first connection;
 - a second polarization-selective connection at a second location along said waveguide coupled to a polarization of linearly polarized wave energy therein related by a first angle to the polarization of said first connection;
 - coupling means for sampling a portion of wave energy in said second connection;
 - ferromagnetic means carried by said waveguide between said first and second locations for rotating the plane of polarization of incident electromagnetic wave energy through a second angle substantially equal to said first angle;
 - frequency discriminator means connected between said coupling means and said ferromagnetic means for varying said second angle of rotation in accordance with frequency variations of energy in said coupling means;
 - and means connected to said waveguide disposed between said source and said second connection for selectively adjusting the phase of energy propagated toward and incident on said source.
2. In a frequency stabilizing system the combination comprising:
 - a section of waveguide adapted to support electromagnetic wave energy in a plurality of linear polarizations;
 - a first polarization-selective connection at a first location along said waveguide coupled to a given one of said polarizations at said first location;

a source of linearly polarized wave energy connected to said first connection;

a second polarization-selective connection at a second location along said waveguide coupled to a polarization of linearly polarized wave energy therein related by a first angle to the polarization of said first connection;

a load circuit connected to said second connection for receiving wave energy and reflecting a portion of said received wave energy;

coupling means for sampling a portion of wave energy in said second connection;

ferromagnetic means carried by said waveguide between said first and second locations for rotating the plane of polarization of incident electromagnetic wave energy through a second angle substantially equal to said first angle;

frequency discriminator means connected between said coupling means and said ferromagnetic means for varying said second angle of rotation in accordance with frequency variations of energy in said coupling means;

and means connected to said waveguide disposed between said source and said first connection for selectively adjusting the phase of energy propagated toward and reaching said source.

3. In a frequency stabilizing system the combination comprising:

a section of waveguide adapted to support electromagnetic wave energy in a plurality of linear polarizations;

a pair of polarization-selective connections at a first location along said waveguide each coupled to an orthogonal polarization of linearly polarized wave energy at said first location;

a source of linearly polarized wave energy connected to one of said connections;

a polarization-selective connection at a second location along said waveguide coupled to a polarization of linearly polarized wave energy therein related by a first angle to the polarization of said one connection at said first location;

coupling means for sampling a portion of wave energy in said connection at said second location;

ferromagnetic means carried by said waveguide between said first and second locations for rotating the plane of polarization of incident electromagnetic wave energy through a second angle substantially equal to said first angle;

frequency discriminator means connected between said coupling means and said ferromagnetic means for varying said second angle of rotation in accordance with frequency variations of energy in said coupling means;

and means connected to said waveguide disposed between said source and said connection at said second location for selectively adjusting the phase of energy propagated toward and reaching said source.

4. In a frequency stabilizing system the combination comprising:

a section of waveguide adapted to support electromagnetic wave energy in a plurality of linear polarizations;

a first polarization-selective connection at a first location along said waveguide coupled to a given one of said polarizations in said waveguide;

a source of linearly polarized wave energy connected to said first connection;

second and third polarization-selective connections at a second location along said waveguide each coupled to an orthogonal polarization of linearly polarized wave energy at said second location and related by a first angle to the polarization of said first connection, said second connection being terminated by an adjustable short;

coupling means for sampling a portion of wave energy in said third connection;

ferromagnetic means carried by said waveguide between said first and second locations for rotating the plane of polarization of incident electromagnetic wave energy through a second angle substantially equal to said first angle for coupling energy in said first connection to said third connection;

and frequency discriminator means connected between said coupling means and said ferromagnetic means for varying said second angle of rotation in accordance with frequency variations of energy in said coupling means.

5. In a frequency stabilizing system the combination comprising:

a section of waveguide adapted to support electromagnetic wave energy in a plurality of linear polarizations; first and second polarization-selective connections at a first location along said waveguide each coupled to an orthogonal polarization of linearly polarized wave energy at said first location;

a source of linearly polarized wave energy connected to said first connection;

means connected to said second connection for preventing energy received by said second connection from said waveguide from returning thereto;

third and fourth polarization-selective connections at a second location along said waveguide each coupled to an orthogonal polarization of linearly polarized wave energy at said second location and related by a first angle to the polarization of said first connection, said fourth connection being terminated by an adjustable short;

coupling means for sampling a portion of wave energy in said third connection;

ferromagnetic means carried by said waveguide between said first and second locations for rotating the plane of polarization of incident electromagnetic wave energy through a second angle substantially equal to said first angle for coupling energy in said first connection to said third connection;

and frequency discriminator means connected between said coupling means and said ferromagnetic means for varying said second angle of rotation in accordance with frequency variations of energy in said coupling means.

6. In a frequency stabilizing system the combination comprising:

a section of waveguide adapted to support electromagnetic wave energy in a plurality of linear polarizations;

first and second polarization-selective connections at a first location along said waveguide each coupled to an orthogonal polarization of linearly polarized wave energy at said first location;

a source of linearly polarized wave energy connected to said first connection;

means connected to said second connection for preventing energy received by said second connection from said waveguide from returning thereto;

third and fourth polarization-selective connections at a second location along said waveguide each coupled to an orthogonal polarization of linearly polarized wave energy at said second location and related by a first angle to the polarization of said first connection;

a load circuit connected to said third connection receiving wave energy and reflecting a portion of said received wave energy;

coupling means for sampling a portion of wave energy in said third connection;

ferromagnetic means carried by said waveguide between said first and second locations for rotating the plane of polarization of incident electromagnetic wave energy through a second angle substantially equal to

said first angle for coupling energy in said first connection to said third connection;
frequency discriminator means connected between said coupling means and said ferromagnetic means for varying said second angle of rotation in accordance with frequency variations of energy in said coupling means;
and means connected to said waveguide disposed between said source and said first connection for select-

ably adjusting the phase of energy propagated toward and reaching said source.

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JOHN KOMINSKI, *Acting Primary Examiner.*