Dec. 12, 1961 D. D. KING 3,013,224

PHASE SHIFTER CONTROLS

Filed April 27, 1959

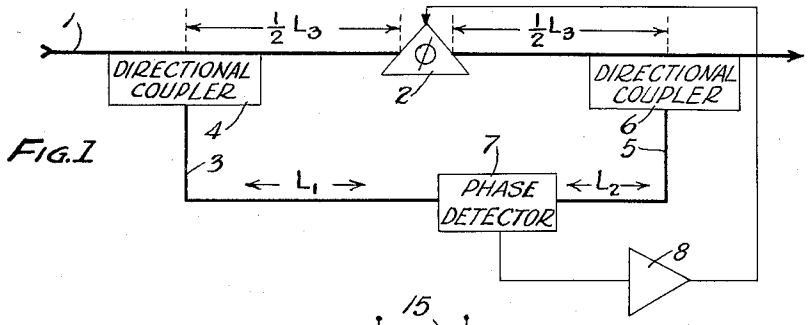


FIG. 1

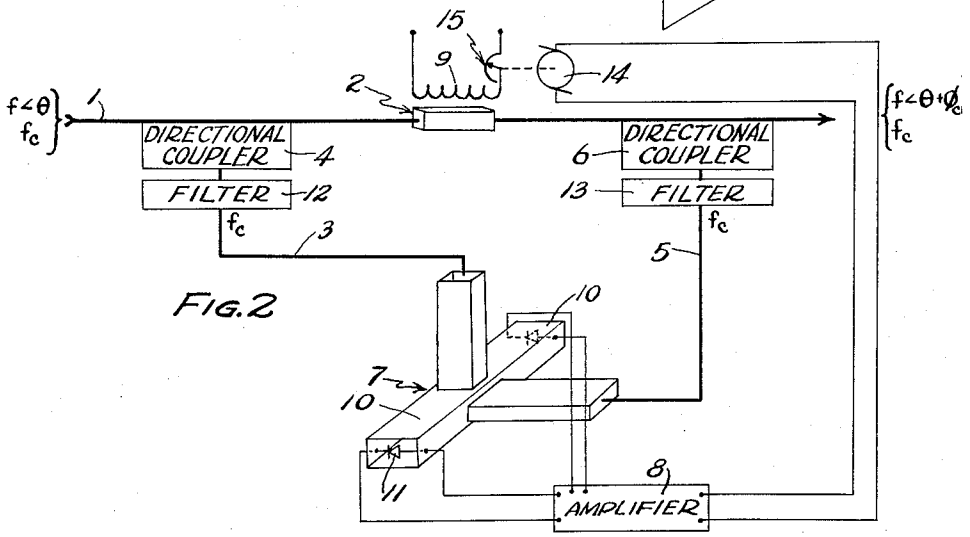


FIG. 2

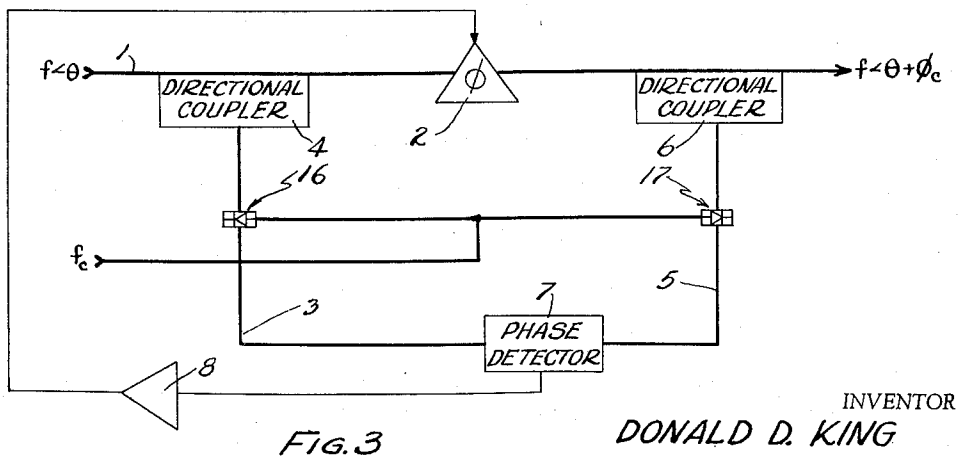


FIG. 3

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PHASE SHIFTER CONTROLS

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4 Claims. (Cl. 333—18)

This invention relates to phase control in electrical transmission lines and more particularly to the control of an electroresponsive phase shifter connected in a transmission line such as a wave guide or a coaxial line.

Phase shifters, particularly those of the ferrite type, have been developed which are capable of providing phase changes of 360° or more with low loss, especially at the higher microwave frequencies. Such phase shifters find many applications, as in connection with antenna arrays, for example. Accurate calibration of such phase shifters has proved to be difficult, however, and this difficulty gives rise to the need for accurate control of the phase shifter in use. Thus, in the case of a ferrite phase shifter controlled by a magnetic field, hysteresis can cause variations of 30° or more in the phase shift prevailing at a given applied magnetic field. Other factors, particularly including thermal drift, also tend to alter the phase shift obtained.

Accordingly, it is the general object of the present invention to devise a method and system for accomplishing precise control of a phase shifter in a transmission line so as to assure that the phase shifter will provide, within close limits, the particular phase change desired.

A specific object is to provide means for controlling an electroresponsive phase shifter in a transmission independently of such variables as hysteresis and thermal drifts.

Another object is to accomplish precise control of an electroresponsive phase shifter in a transmission line in accordance wthi the frequency of a control signal propagated along the line or otherwise introduced into the system.

A further object is to accomplish such control accurately and continuously in servo fashion.

Yet another object is to devise a system for precise control of a ferrite phase shifter in a transmission line in accordance with the frequency of a control signal, the nature of the system being such that the operating frequency range for the control signal can be predetermined to best suit the dispersive characteristics of the ferrite and the stability of the control signal source.

In order that the manner in which these and other objects are achieved in accordance with the invention can be understood in detail, reference is had to the accompanying drawings, which form a part of the specification, and wherein:

FIG. 1 is a functional schematic diagram of the system of the present invention;

FIG. 2 is a schematic diagram of a system constructed in accordance with one advantageous embodiment of the invention, and

FIG. 3 is a schematic diagram of a system constructed in accordance with a second such embodiment.

Broadly, the invention is based upon the proposition that, in the case of a transmission line having a phase shifter connected therein, if a signal of predetermined frequency is caused to be propagated along the line, the difference in phase of the signal on the input and output sides of the phase shifter will, for a given operative condition of the phase shifter, be directly related to the frequency of the propagated signal. If the operative condition of the phase shifter changes, as by reason of hysteresis or thermal drift, such difference in phase will change and, assuming that the signal frequency and other parameters remain constant, the change in phase difference can be taken as a measure of control of the phase shifter necessary to return the same to its given operative condition. Hence, the signal frequency can be held at a predetermined value corresponding to a desired insertion phase change and, by continuous comparison of the phase of the signal on the input and output sides of the phase shifter, information can be obtained as to the extent of control of the phase shifter necessary to maintain the desired insertion phase change. By changing the frequency of the signal to another predetermined value, representative of a different desired insertion phase change, the phase shifter can be controlled, in the same fashion just described, to maintain such different phase change.

In one form of the invention, a control signal of predetermined frequency corresponding to the desired insertion phase change is caused to be propagated along the transmission line and is tapped off before and after the phase shifter, the two signals so tapped off are supplied to phase comparison means capable of providing a control electrical quantity representative of the phase difference of the compared signals, and this quantity is employed to control the phase shifter, the arrangement being such that, with the frequency of the control signal maintained substantially constant, variation of the control electrical quantity from a definite value is representative primarily of variation of the insertion phase change from the desired value.

In a second form of the invention, the signal tapped off before and after the phase shifter is the work signal for which the transmission line is provided, rather than being a separately provided control signal. The signals so tapped off are then each heterodyned with a control signal of predetermined frequency, and the heterodyned signals supplied to the phase comparison means.

The invention can be employed in connection with any electroresponsive phase shifter connected in any electrical transmission line with which the particular phase shifter is suitable for use and from which a signal can be extracted or tapped off, at points on the input and output sides of the phase shifter, for purposes of phase detection. Assuming that the transmission line is a wave guide, the signals for phase comparison can be provided via two wave guide arms of definite, different lengths, each directionally coupled to the transmission line and operatively connected to the phase comparison means, the two arms, the phase shifter and the phase comparison means forming what may be termed a "comparison loop." When the transmission line is a coaxial line, the arms of the comparison loop can be of coaxial transmission line.

Referring now to FIG. 1, it will be seen that the system of the invention here illustrated embodies a transmission line 1 in which is inserted a phase shifter 2. On the input side of the phase shifter, a transmission line arm 3 is operatively connected to the transmission line by means of a directional coupler 4. On the output side of the phase shifter a transmission line arm 5 is operatively connected to the transmission line by means of a directional coupler 6.

Arms 3 and 5, together with the phase shifter and portions of line 1, form a comparison loop in which is conconnected the phase detector 7. The phase detector can comprise a pair of conventional probes, in which case arms 3 and 5 may be provided by one continuous length of transmission line. On the other hand, the phase detector may comprise a hybrid junction, in which case arms 3 and 5 are separate elements connected to the appropriate arms of the junction. The electrical output of the phase detector is connected, via a servo amplifier 8, to control the phase shifter 2.

In operation, a control signal of predetermined constant frequency is caused to be propagated along transmission line 1, in addition to the work signal for which

that transmission line is provided. The control signal is tapped off by the couplers 4 and 6 and supplied to phase detector 7 via arms 3 and 5 in order that the phase of the control signal on the input side of the phase shifter can be compared with that of the control signal on the output side of the phase shifter. A control electrical quantity is derived as a result of such comparison and supplied via the amplifier to control the phase shifter.

It will be noted that the phase detector 7 is disposed at a particular position in the comparison loop, with arm 3 having a predetermined effective length L_1 and arm 5 having a different predetermined effective length L_2. Couplers 4 and 6 are equally spaced from the phase detector 2 by distances indicated as $\frac{1}{2}L_3$. In the detailed explanation of subsequent figures, the same relative line lengths just referred to are to be considered.

A typical embodiment of the invention, illustrated in FIG. 2, will now be described in detail. Here, the phase shifter 2 is of the ferrite type, including a ferrite element inserted in the transmission line, and an electromagnetic winding 9 operatively arranged to influence the ferrite element. In this embodiment, the transmission line is a wave guide of standard construction and the arms 3 and 5 are also wave guides of conventional construction. Directional couplers 4 and 6 are constructed in known fashion and employ a beyond-cutoff section to eliminate coupling to signals of lower frequency than the control signal.

The phase detector in this instance is a hybrid junction having its shunt and series arms connected to arms 3 and 5 of the comparison loop and being provided with the usual side arms 10. As is well known in the art, each side arm 10 is suitably terminated and provided with a crystal 11. The arrangement is thus identical with a standard balanced mixer assembly. Suitable filters 12 and 13 are connected, respectively, in the arms 3 and 5.

The directional couplers are effective to derive from the transmission line 1 signals supplied via arms 3 and 5 for phase comparison at the hybrid junction 7. In terms of the two input signals, the amplitudes at the two crystals 11 are:

$$\sqrt{2}A_1 = ae^{j\theta_E} + be^{j\theta_E} = \left[1+\frac{b}{a}e^{j(\theta_H-\theta_E)}\right][ae^{j\theta_E}] \quad (1a)$$

$$\sqrt{2}A_2 = -ae^{j\theta_E} + be^{j\theta_H} = \left[1+\frac{b}{a}e^{j(\theta_H-\theta_E)}\right][ae^{j\theta_E}] \quad (1b)$$

The output signal difference at the two crystals is

$$|A_1|-|A_2| = \frac{a}{\sqrt{2}}\left\{\left|1+\frac{b}{a}e^{j\Delta\theta}\right| - \left|1-\frac{b}{a}e^{j\Delta\theta}\right|\right\} \quad (2)$$

where $\Delta\theta=\theta_H-\theta_E$.

When $\Delta\theta=\pi/2$, the difference output is zero, corresponding to a bridge balance. For smaller values of $\Delta\theta$, the difference is positive; for larger values it is negative. Adequate sense information is therefore provided for maintaining a balance condition at $\Delta\theta=\pi/2$. Controlling the phase shifter via servo amplifier 8, it is thus possible to position the standing wave pattern by controlling the phase θ_H of the output wave. The position of the standing wave pattern is also a function of relative line lengths and of the frequency. The relationship between these quantities is now examined quantitatively.

From FIG. 1, the condition for balance (zero difference output) at the hybrid junction 7 can be written in terms of individual phase delays. Thus,

$$\phi+\frac{2\pi}{\lambda}(L_3+L_2) = \frac{2\pi}{\lambda}L_1 \pm (2n+1)\frac{\pi}{2} \quad (3)$$

Equation 3 is periodic with interval π. However, the slope of the error signal versus angular deviation curve given by Equation 2 alternates in sign from one balance point to another. Once negative feedback has been established for a particular control amplifier, the system is then stable only at alternate balance points having the proper slope. Therefore, the effective balance equation is periodic with an interval 2π:

$$\phi+\frac{2\pi}{\lambda}(L_3+L_2) = \frac{2\pi}{\lambda}L_1 \pm (4n+1)\frac{\pi}{2} \quad (4)$$

In terms of the path difference,

$$L = L_1-(L_2+L_3) \quad (5)$$

The normalized phase shift introduced by the phase shifter being controlled becomes

$$\frac{\phi}{2\pi} = \frac{L}{\lambda} \pm \frac{4n+1}{4} \quad (6)$$

The phase excursion is assumed to run from $\phi_1=0$ to $\phi_2=m\pi$ radians. The balance Equation 6 then takes on the following values

$$\frac{L}{\lambda_1} = \frac{4n_1+1}{4} (\phi_1=0) \quad (7)$$

$$\frac{L}{\lambda_2} = \frac{4n_2+2m+1}{4} (\phi_2=m\pi) \quad (8)$$

The difference in wave numbers between the two expressions is

$$\frac{1}{\lambda_1}-\frac{1}{\lambda_2} = \frac{1}{L}\left(n_1-n_2-\frac{m}{2}\right) \quad (9)$$

For $m\leq 2$, corresponding to the gamut of useful excursions $0<\phi<2\pi$, the difference in wavenumbers can be kept to one or less. This eliminates the possibility of ambiguities from $n_1\neq n_2$, i.e., from harmonic operation.

The minimum path difference L for a 360° phase shift occurs for $n=0$. Then Equations 7 and 8 yield,

$$L = \frac{\lambda_1}{4} = \frac{5\lambda_2}{4} : \frac{\lambda_1}{\lambda_2} = 5 \quad (10)$$

To achieve a small ratio of wave lengths, higher values of n may be chosen. For example, for $n=5$

$$L = \frac{21}{4}\lambda_1 = \frac{25}{4}\lambda_2 : \frac{\lambda_1}{\lambda_2} = \frac{25}{21} \quad (10a)$$

By suitable choice of the path difference L, all control frequencies f_c necessary to produce phase shifts in the interval $0<\phi<2\pi$ can be located in a narrow interval $f_1\leq f_c\leq f_2$. This interval is chosen to lie close to the signal frequency f. The phase shift at the signal frequency then differs by a negligible amount from its precisely determined value at the control frequency.

Amplifier 8 is of conventional construction and embodies input circuit means of the usual design for algebraic addition of the signals from crystals 10 and 11. To complete the servo system, the output of the amplifier is connected to the means for actuating the active element of the phase shifter. In this case, such means has been illustrated as a motor 14 arranged to drive the movable contact of a potentiometer 15 connected to vary the amount of current supplied through coil 9 of the phase shifter. All mechanical motion is eliminated by replacing the motor and potentiometer with a direct coupled amplifier. The current delivered to the coil by the amplifier power stages is controlled by varying the gain. This gain variation is in turn actuated by the output of amplifier 8. The control voltage provided by amplifier 8 corresponds to the error signal derived from the hybrid junction 7. The functional relationship between error signal magnitude and phase error can be derived as follows.

Equation 2 is the starting point for the calculation:

$$|A_1|-|A_2| = \frac{a}{\sqrt{2}}\left\{\left(\frac{b}{a}\cos\Delta\theta+1\right)^2+\left(\frac{b}{a}\sin\Delta\theta\right)^2\right\}^{1/2} - \frac{a}{\sqrt{2}}\left\{\left(\frac{b}{a}\cos\Delta\theta-1\right)^2+\left(\frac{b}{a}\sin\Delta\theta\right)^2\right\}^{1/2} \quad (11)$$

The difference vanishes for

$$\Delta\theta=(2n+1)\frac{\pi}{2}$$

as noted in connection with Equation 3 previously. Representing this explicitly:

$$\Delta\theta=(2n+1)\frac{\pi}{2}+\epsilon \tag{12}$$

where ϵ is the phase deviation from the balance condition. Inserting (12) into (11), and assuming an identical detection efficiency β for each crystal, the following exact relation between difference output Δe and the phase error ϵ is obtained:

$$\frac{\Delta e}{a}=\frac{\beta}{\sqrt{2}}\left\{\left(\frac{b}{a}\right)^2+1-\frac{2b}{a}(-1)^n\sin\epsilon\right\}^{1/2}-\frac{\beta}{\sqrt{2}}\left\{\left(\frac{b}{a}\right)^2+1+\frac{2b}{a}(-1)^n\sin\epsilon\right\}^{1/2} \tag{13}$$

For operation near the balance point, only small errors apply, and Equation 13 can be expanded

$$\frac{\Delta e}{a}=\beta\epsilon\left\{\frac{\sqrt{2}(-1)^n}{\left[1+\left(\frac{a}{b}\right)^2\right]^{1/2}}\right\} \tag{14}$$

The ratio of input amplitudes evidently has only a second order effect on the sensitivity. By keeping $b>a$, the maximum phase sensitivity is achieved. Per unit amplitude in the E arm, Equation 14 can then be written as

$$\Delta e\sim\sqrt{2}\beta\epsilon(-1)^n \tag{15}$$

The factor $(-1)^n$ shows that the control loop feedback is either positive or negative, depending on the interval of π occupied by the phase shift. Choosing the sign of feedback therefore determines whether n is even or odd for stable balance. This effectively makes the system periodic in 2π, as indicated previously.

For unit rectification efficiency, Equation 15 yields a sensitivity

$$\Delta e\approx 25 \text{ millivolts/degree phase error} \tag{16}$$

Referring now to FIG. 3, there is illustrated here an embodiment of the invention in which the signals supplied for phase comparison are derived by tapping off, by couplers 4 and 6 and lines 3 and 5, the work signal carried by transmission line 1, no control signal being present in line 1. Conventional mixers, indicated generally at 16 and 17, are connected respectively in transmission line arms 3 and 5. The control signal, at a predetermined higher frequency than the signal propagated along transmission line 1, is supplied to mixers 16, 17 and mixed with the signals in transmission line arms 3 and 5.

Since the mixing operation is linear, phases are preserved. With equiphase injection of the control or local oscillator signal, the relative phases of the signals in the lower part of the control loop remain the same, but are referred to the sum or difference frequency $f'=f\pm f_c$. For sum frequency operation Equation 5 need only be scaled to the different wave lengths in the upper and lower portions of the control loop.

$$\frac{L}{\lambda'}=\frac{L_2}{\lambda'}-\left(\frac{L_2}{\lambda'}+\frac{L_3}{\lambda}\right) \tag{10b}$$

or

$$L=L_1-L_2-L_3\left(\frac{\lambda'}{\lambda}\right) \tag{10c}$$

The average wave length in the loop is now shorter; hence, a more compact structure is possible. Operation at the difference frequency with low-frequency discriminators is also feasible.

In this embodiment of the invention, the actual signal

phase shift is controlled in the heterodyne stage, rather than controlling the phase shift at a nearby frequency. This mode of operation eliminates the need for filters 12 and 13, FIG. 2, and provides substantially complete accuracy of control. However, to use the system of FIG. 3, it is necessary that the modulation characteristics of the work signal to be carried by transmission line 1 be such as to permit the servo system to operate. In general, the system of FIG. 3 is not suitable for use when the work signal has a very short duty cycle and/or a rapid frequency modulation, the embodiment of FIG. 2, for example, being free from limitations in this regard.

The control signal required for the operation of the device, either in the direct mode shown in FIG. 2, or in the heterodyne mode shown in FIG. 3, can be supplied at low level. Any signal source providing power at milliwatt levels, such as a klystron oscillator or a triode oscillator, suffices. However, since the phase shift depends directly on frequency, the source must be capable of a stable and adjustable frequency output.

What is claimed is:

1. In a system for precise control of an electroresponsive phase shifter in a transmission line in accordance with the frequency of a control signal propagated along the transmission line, the combination of a hybrid junction having a shunt arm, a series arm and a pair of side arms, each of said side arms being operatively provided with a transducer; first wave guide means connected to said shunt arm and coupled to said transmission line at a point on one side of said phase shifter; second wave guide means connected to said series arm and coupled to said transmission line at a point on the other side of said phase shifter, said first and second wave guide means having predetermined, unequal, effective lengths; circuit means operatively connected to said transducers to supply a control electrical quantity representative of the phase difference between the signals supplied to said junction by said first and second wave guide means, and circuit means connected to apply such control electrical quantity to control said phase shifter.

2. A system in accordance with claim 1 and wherein said phase shifter comprises a ferrite element and an operating electromagnetic winding operatively arranged with respect to said ferrite element and said last-mentioned circuit means is connected to control said winding.

3. In a system for precise control of an electroresponsive phase shifter in a transmission line, the combination of two transmission line arms operatively coupled to said transmission line, one of said arms being coupled to said transmission line at a point on the input side of said phase shifter and the other being coupled to said transmission line at a point on the output side of said phase shifter, said arms having predetermined unequal lengths; a pair of mixers each connected in a different one of said arms, each of said mixers being operative to effect equiphase mixing of a control signal supplied thereto with the signal supplied from the transmission line via the arm in which such mixer is connected; phase comparison means operatively connected between said arms, said phase comparison means being operative to provide a control electrical quantity representative of the phase difference between the two signals supplied from said mixers, and control circuit means connected to said phase comparison means and said phase shifter to control said phase shifter in accordance with said control electrical quantity.

4. A system in accordance with claim 3 and wherein said phase shifter is a ferrite phase shifter comprising an operating winding and said control circuit means is connected to control said operating winding.

References Cited in the file of this patent

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UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Patent No. 3,013,224 December 12, 1961

Donald D. King

It is hereby certified that error appears in the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

Column 1, line 37, for "wthi" read -- with --; column 3, line 44, equation (1a), for the expression "$be^{j\theta E}$" read -- $be^{j\theta H}$ --; line 46, for that portion of equation (1b) reading

$$[1+\frac{b}{a}e^{j(\theta_H-\theta_E)}] \quad \text{read} \quad [1-\frac{b}{a}e^{j(\theta_H-\theta_E)}]$$

column 3, line 59, after "phase shifter" insert -- 2 --; column 4, line 19, the expression "($\phi_1=0$)" should be spaced from the remaining portion of equation (7); line 21, the expression "($\phi_2=m\pi$)" should be spaced from the remaining portion of equation (8); column 5, lines 15 to 20, lower left-hand portion of the equation (13), for

$$-\frac{\beta}{2} \quad \text{read} \quad -\frac{\beta}{\sqrt{2}}$$

Signed and sealed this 31st day of July 1962.

(SEAL)

Attest:

ERNEST W. SWIDER
Attesting Officer

DAVID L. LADD
Commissioner of Patents