April 7, 1964 M. R. RICHMOND 3,128,430

PHASE SHIFTING SYSTEM FOR PHASED ANTENNA ARRAYS

Filed Jan. 9, 1962 2 Sheets-Sheet 1

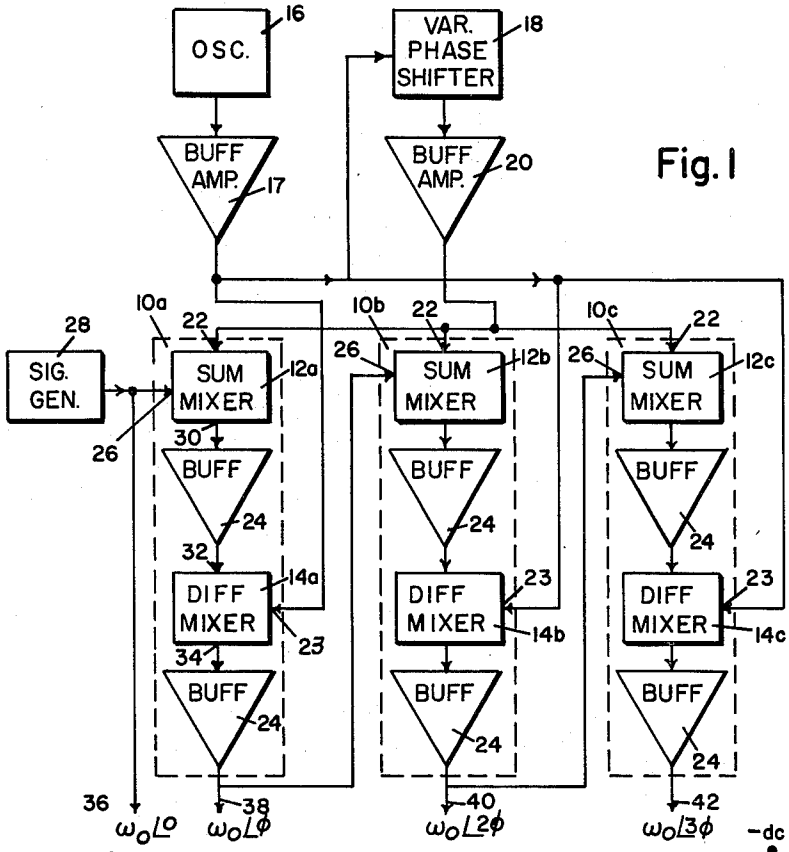


Fig. 1

Fig. 2

Martin R. Richmond

INVENTOR

April 7, 1964 M. R. RICHMOND 3,128,430

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Filed Jan. 9, 1962 2 Sheets-Sheet 2

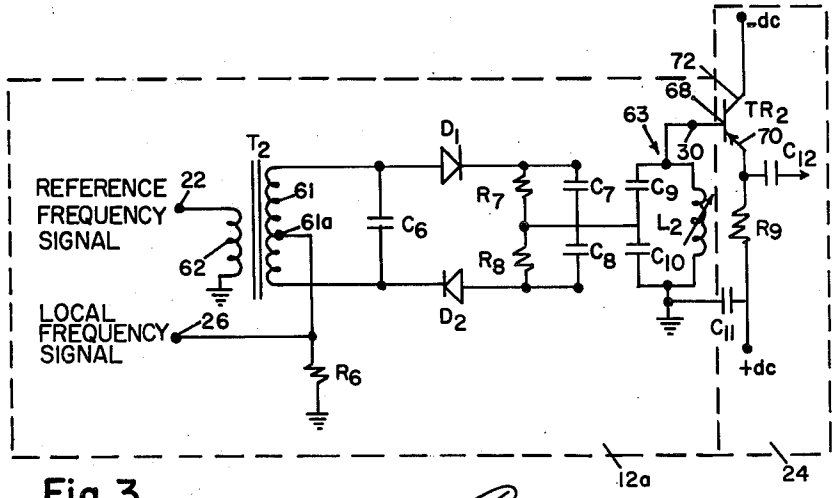


Fig. 3

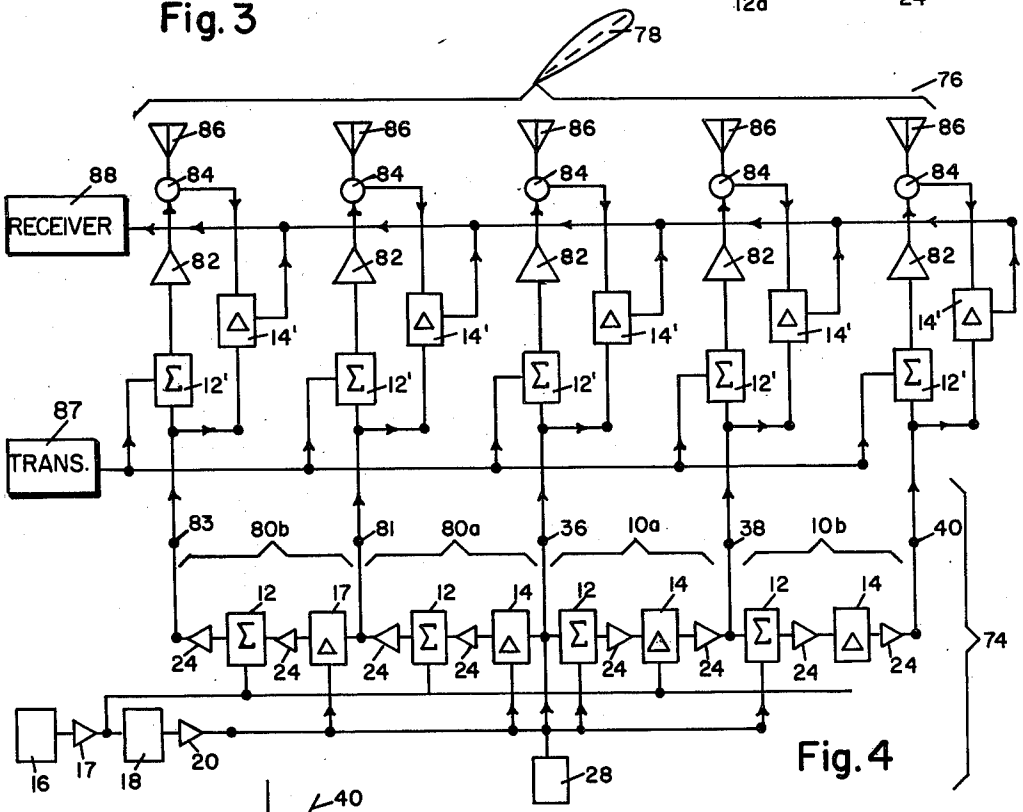


Fig. 4

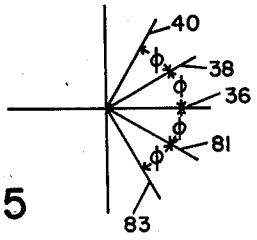


Fig. 5

Martin R. Richmond

INVENTOR

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3,128,430
PHASE SHIFTING SYSTEM FOR PHASED ANTENNA ARRAYS

Martin R. Richmond, Belmont, Mass., assignor to Sanders Associates, Inc., Nashua, N.H., a corporation of Delaware

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This invention relates to an improved system for developing a succession of voltages having selected variable phase increments between them. The phase increments are readily varied in unison and the variation is exactly the same for each increment. The system, which requires only a single phase shifter for a plurality of outputs, is particularly suited for connection with a multi-element antenna array to steer the radiation pattern during both transmission and reception.

In an important application of phasing systems, the beam, or radiation pattern, of a multi-element antenna array is steered in different directions by adjusting the relative phases of the signals delivered to adjacent elements. When the elements are equally spaced apart, the beam can be steered by energizing the elements with signals having a uniform phase gradient between them.

An elementary system well known in the prior art for developing a plurality of signals with a uniform phase gradient between them comprises a delay line, which may be conventional transmission line, having output taps at uniform intervals along it. The phase angle between the signals developed at adjacent taps is proportional to the electrical distance along the delay line between the taps and is readily varied by changing the frequency of the delay line signal.

However, since a finite time is required for signals to propagate from the delay line input to the remote end of the line, there is a significant delay between the time a change in phase increment is initiated and the time it becomes effective at all the output taps. The system thus responds too slowly for many applications. Moreover, since it is inoperative, for all practical purposes, in the interval during which the transmission line attains a uniform condition, its duty cycle is rather short for many purposes.

In another prior system for simultaneously changing the phase increments at a succession of output ports, the ports are fed by variable phase shifters connected intermediate the respective ports and a common source. The phase shifters, which are varied in synchronism, are constructed so that the phase delay relative to the source increases at successive output ports. In an alternate system the phase shifters are connected in tandem and the output ports are tapped from between successive phase shifters.

Disadvantages of this prior phasing system include the requirement for a plurality of highly accurate variable phase shifters and, further, the necessity that the phase shifters track with each other so that changes in phase delay are the same for each shifter. Hence, the system is costly, in addition to requiring complex apparatus to vary the phase shifters in synchronism.

Accordingly, it is a principal object of the present invention to provide an improved phase shifting system for developing a succession of output voltages having selected variable phase gradients between adjacent outputs.

A more specific object of the invention is to provide apparatus of the above description requiring only a single phase-adjusting unit.

A further object of the invention is to provide apparatus requiring only a single phase shifting network to develop a succession of output voltages having selected phase increments between successive outputs and in

which the phase increments can be changed without changing the frequency of the voltages.

Another object of the invention is to provide apparatus of the above type in which the phase increments can be varied equally. A more particular object is to provide apparatus of the foregoing description in which the phase increments are equal.

Still another object of the present invention is to provide improved apparatus for electronically steering the beam of a multi-element antenna array.

A further object is to provide apparatus embodying a single phase shifting network to obtain variable equal phase increments between adjacent elements of a uniform multi-element antenna array.

Yet another object of the present invention is to provide apparatus of the above description having a high degree of reliability.

Further objects include the provision of apparatus of the above character that is less complex, less costly and smaller in size than previous apparatus of this type.

The invention accordingly comprises the features of construction, combinations of elements, and arrangement of parts which will be exemplified in the construction hereinafter set forth, and the scope of the invention will be indicated in the claims.

For a fuller understanding of the nature and objects of the invention, reference should be had to the following detailed description taken in connection with the accompanying drawings in which:

FIG. 1 is a schematic block diagram of a phasing system embodying the present invention,

FIG. 2 is a detailed schematic diagram of the phase shifter and buffer amplifier of FIG. 1,

FIG. 3 is a detailed schematic diagram of the sum mixer and buffer circuit used in the system of FIG. 1,

FIG. 4 is a simplified schematic block diagram of a steerable-beam multi-element antenna system incorporating the invention, and

FIG. 5 is a vector diagram showing the relative phases of the voltages developed by the phasing system in FIG. 4.

The present phasing system incorporates a succession of identical stages each comprising a pair of mixer circuits connected in tandem. The first mixer in each stage may, for example, be a sum mixer, tuned to a frequency equal to the sum of the frequencies of the two signals delivered to it. The second mixer is then a difference mixer, tuned to the difference between the frequencies of the signals delivered to it.

A reference voltage is delivered, without delay to a first input of the difference mixer and also, after passing through a variable phase shifter, to a first input of the sum mixer. A second voltage is delivered to a second input of the sum mixer in the first stage and the sum mixer output voltage is delivered to a second input of the difference mixer.

With this system, the output voltage from the difference mixer in the first stage has the frequency of the second voltage and is delayed in phase by the angle, ϕ, imposed on the reference voltage by the variable phase shifter. When the first stage output voltage is delivered to a second stage, identical to the first stage described above, the output from the second stage difference mixer has the frequency of the local voltage and is delayed in phase by another increment, ϕ, for a total of 2ϕ. Thus, by cascading the mixer stages, a succession of voltages is obtained having the same frequency and delayed in phase by 1, 2, 3 . . . n times a selected variable phase angle.

A principal advantage of the phasing system is that the phase shift developed in a single phase shifting network is used to phase each of the output voltages. This results in a uniformly variable phase gradient between successive

output voltages, obtainable with a simple, compact system. A further advantage is that the phase gradient between successive voltages can be continuously varied without changing the frequencies of any of the voltages.

Referring now to FIG. 1, the phasing system comprises a plurality of cascaded stages **10***a*, **10***b* and **10***c*, each incorporating a pair of mixers **12** and **14**. As described below, the output voltages from the successive stages have the same constant frequency but differ in phase by a uniform variable phase angle.

More specifically, a reference voltage from an oscillator **16** is delivered through a first buffer amplifier **17** to a variable phase shifter. After amplification in another buffer amplifier **20**, the phase-delayed reference voltage is delivered to inputs **22** of sum mixers **12***a*, **12***b* and **12***c*.

The undelayed reference voltage from amplifier **17**, is applied to inputs **23** of difference mixers **14***a*, **14***b* and **14***c* connected between the respective sum mixers **12***a*, **12***b* and **12***c*. Isolation between the adjacent mixer circuits is provided by buffer amplifiers **24**.

A signal generator **28** delivers a second voltage to a second input **26** of the first sum mixer **12***a*. The output voltage for the mixer **12***a* is passed through the buffer amplifier **24** to a second input **32** of the difference mixer **14***a*. The connections for the stages **10***b* and **10***c* are similar to those of the stage **10***a*, except that each of the stages **10***a* and **10***b* receives its voltage for input **26** from the output of the difference mixer in the preceding stage (by way of a buffer **24**). The system output voltages are taken from the generator **28** and the buffers **24**.

The operation of the phasing system of FIG. 1 may be explained by assuming an example in which the reference voltage from the oscillator **16** has an angular frequency ω_1, the voltage from generator **28** has a frequency ω_0, ϕ is the phase angle selected with the phase shifter **18**.

The signal developed in the sum mixer **12***a* in response to its two input voltages, $\omega_0 \angle 0$ and $\omega_1 \angle \phi$ includes sum frequency and difference frequency components of the form,

$$A \cos [(\omega_0+\omega_1)t+\phi]+A \cos [(\omega_0-\omega_1)t-\phi] \quad (1)$$

where A is a constant indicating the amplitude of the components.

Since the output circuit of the sum mixer **12***a* is tuned to the sum frequency, i.e., $\omega_0+\omega_1$, the output voltage at port **30** of mixer **12***a* is of the form,

$$A' \cos [(\omega_0+\omega_1)t+\phi] \quad (2)$$

The principles of mixers, well-known in the art, are explained in numerous texts, including "Electronic and Radio Engineering," by F. E. Terman, McGraw-Hill Book Company, Inc., 1955 at pages 568–581; and "Vacuum Tube Circuits and Transistors," by L. B. Arguimbau et al., John Wiley and Sons, Inc., 1956, pages 431–435.

Analysis of mixer operation shows that the phases of the input frequencies determine the phases of the output frequencies. In particular, the sum frequency has a phase corresponding to the sum of the individual phases of ω_0 and ω_1, and the difference frequency, $\omega_0-\omega_1$, has a phase corresponding to the difference between the respective phases of the input frequencies.

After amplification by the buffer amplifier **24** to obtain the amplitude at the output of the generator **28**, the signal represented by (2) is delivered to the input **32** of the difference mixer **14***a* for mixing with the output of the amplifier **17**. The sum and difference frequency components developed in the mixer **14***a* are of the form,

$$A \cos [(\omega_0+2\omega_1)t+\phi]+A \cos [(\omega_0+\omega_1)t+\phi-\omega_1 t] \quad (3)$$

Since the difference mixer output circuit is tuned to pass only the frequency equal to the difference between its two input frequencies, i.e., $(\omega_0+\omega_1)-\omega_1=\omega_0$, the signal voltage developed at the output terminal **34** of mixer **14***a* has the form,

$$A' \cos [(\omega_0+\omega_1)t+\phi-\omega_1 t]=A' \cos (\omega_0 t+\phi) \quad (4)$$

The voltage, $\omega_0 \angle 0$, from generator **28** is delivered to an output terminal **36** to provide the first voltage in the desired succession of phased voltages. The voltage of (4), having the same frequency, ω_0, as the terminal **36** voltage but delayed in phase relative to it by the angle ϕ, is the next voltage in the succession and is, accordingly, delivered to an output terminal **38**.

In a similar manner, in the second stage **10***b*, sum mixer **12***b* mixes the voltage of (4) and the delayed reference voltage to develop a sum frequency voltage having the form,

$$A' \cos (\omega_0 t+\phi\omega_1 t+\phi)=A'[\cos (\omega_0+\omega_1)t+2\phi] \quad (5)$$

Difference mixer **14***b* mixes the undelayed reference voltage and the voltage of (5) to develop a difference frequency output voltage represented by,

$$A' \cos [(\omega_0+\omega_1)t+2\phi-\omega_1 t]=A' \cos (\omega_0 t+2\phi) \quad (6)$$

It will now be evident that the output voltage from the third stage **10***c* of the phasing system, comprising sum mixer **12***c* and difference mixer **14***c*, has the form,

$$\cos [\omega_0 t+3\phi] \quad (7)$$

The output voltages represented by (6) and (7), have the frequency ω_0 of the generator **28** and are delayed with respect thereto by 2ϕ and 3ϕ, respectively. These output voltages are present at terminals **40** and **42**.

In the above discussion, the phase delays within the sections **10***a* to **10***c* were neglected, since they do not affect the manner in which the phases at the output terminals of the phasing network vary as the phase shifter **18** is adjusted. In many applications it will be desirable to include a conventional phasing network (not shown) to eliminate phase lags or leads within the sections.

Thus, the novel phasing system of FIG. 1 develops, with a single phase shifter **18**, a sequence of signals uniformly phased apart with a phase angle that is changed readily by varying the phase shifter. The frequency of the phased output signals remains fixed at the frequency of the local generator **28** regardless of the magnitude of the phase increment ϕ.

With further reference to FIG. 1, the oscillator **16** is preferably crystal-controlled so that the phase of the reference voltage remains substantially invariant except for variation by the phase shifter **18**. Also, the frequency is substantially constant, allowing the transmission lines interconnecting the oscillator **16**, the amplifier **17**, phase shifter **18** and the several mixers **12** and **14** to be constructed to provide accurately known phase delays.

In this connection, it will be noted that, when the corresponding transmission paths in different stages have unequal electrical lengths, the phase differences between the voltages developed at the output terminals **36–42** will not be equal. However, the changes in the phase differences, caused by varying the phase shifter **20**, will nevertheless be equal.

The term "mixer," as used in this application, includes conventional "square law" mixers as well as other devices that combine two voltages to develop an output voltage having a sum frequency component and a difference frequency component, with the preservation of relative phases as set forth above. Accordingly, modulators and other frequency converters providing this junction are included within the definition of "mixers" in the description of the present invention.

In FIGS. 2 and 3 we have illustrated examples of circuits suitable for practicing the invention. As shown in FIG. 2, the phase shifter **18** has a transformer T1 with a primary winding **46** across which the reference voltage from the oscillator **16** is applied. The transformer secondary winding **48**, provided with a grounded center tap **48***a*, is connected to apply oppositely phased voltages to a variable capacitor C1 and a resistor R1. A junction **50** is a summing point for the transformer secondary voltages, as modified by the impedances of the capacitor

C1 and resistor R1. As the setting of the capacitor C1 is changed, the phase angle of the voltage at the junction 50 varies.

A blocking capacitor C2 and a resistor R2, serve to couple the phase shifted voltage from the junction 50 to the base 52 of a p-n-p transistor TR1 in the buffer amplifier 20. The transistor TR1 is arranged in a common-emitter circuit including a base return resistor R3, an emitter resistor R4 connected between the emitter 54 and the positive terminal of a power supply (not shown), and an emitter bypass capacitor C3. The collector 56 of the transistor is connected through a tank circuit 58, to the negative terminal of the power supply. The tank circuit 58 comprises a variable inductor L1 connected in parallel with the series combination of capacitors C4 and C5. A shunt resistor R5 is used to reduce the Q, or quality factor, of the tank circuit.

With reference to FIG. 3, the sum mixer 12*a* of FIG. 1 comprises a pair of diodes D1 and D2 connected to opposite ends of the secondary 61 of a transformer T2. The signal from the buffer 20 (FIG. 1) is applied to the transformer primary winding 62 and the voltage at the input terminal 26 is applied across a resistor R6 connected to a center tap 61*a* on the secondary winding 61. Resistors R7 and R8 provide a return path for the direct current developed in the diodes, and capacitors C7 and C8 help to filter out undesired high frequency components. A capacitor C6 resonates with the transformer secondary winding 61 at the frequency of the voltage applied to the primary winding 62.

The junctions of the resistors R7 and R8 and capacitors C7 and C8 are connected to the junction of a pair of capacitors C9 and C10 which resonate with an inductor L2 in a tank circuit 63. The voltage across the tank circuit, which is tuned to the sum frequency, $\omega_0+\omega_1$, is the output voltage of the mixer 12*a*. In the sum mixers, the capacitor C10 has a smaller capacitance than the capacitor C9 to prevent undue shunting of the high, sum frequency components. In the difference mixers 14, on the other hand, the tank circuit 63 is tuned to the frequency ω_0 and shunting of the high frequency components is desirable. This is accomplished giving the capacitor C10 a substantially greater capacitance than that of the capacitor C9.

By way of example, ω_0 may correspond to a frequency of 2 megacycles and ω_1 to 11 megacycles. The output frequencies of the sum and difference mixers are then 13 and 2 megacycles, respectively. The 11 megacycle input to the transformer winding 62 is balanced out at the junction of the capacitors C7 and C8, and the other frequencies in the mixers are sufficiently far apart to permit efficient filtering with a low Q tuned circuit 63.

Low Q is desirable in all the tuned circuits in the system for several reasons. In the first place, the phase delays imposed by these circuits will not change appreciably, even though they drift slightly off tune. Thus, the desired equality of phase delay will not be affected under such conditions. Moreover, the time required to provide a desired change of phase in the voltage across a parallel resonant circuit increases with its Q. Low Q therefore permits more rapid changes in the output of the phasing system in response to changes in the phase of the voltage from phase shifter 18 (FIG. 1).

Again referring to FIG. 3, the buffer circuit 24 incorporates a p-n-p transistor TR2 connected as an emitter-follower. The input signal is applied to the transistor base 68 and the output signal is delivered from the emitter 70 by way of a capacitor C12. The transistor TR2 is powered by the application of a negative voltage to the collector 72 and a positive voltage to the emitter 70. The circuit also includes an emitter resistor R9 and a bypass capacitor C11.

Referring now to FIG. 4, a phasing system 74, similar to the one described above with reference to FIG. 1, is incorporated in the feed system of a stationary multi-element antenna array 76 to steer the beam 78 thereof during both reception and transmission. In the phasing system 74, the oscillator 16, phase shifter 18 and generator 28 are connected with buffer amplifiers 17 and 20 to energize the two mixer stages 10*a* and 10*b* for operation in the manner described above. Thus, at terminals 38 and 40 the system develops successive voltage having the frequency of the generator 28 and delayed by equal phase increments. For ease in identifying them, the sum and difference mixers in FIG. 4 designated with the symbols Σ and Δ, respectively.

In addition, the phasing system 74 includes two sections 80*a* and 80*b* similar to the sections 10*a* and 10*b* but with the sum and difference mixers arranged in reverse order. Accordingly, the output voltages from the sections 80*a* and 80*b*, delivered to output terminals 81 and 83, respectively, have the same frequency as the voltages at terminals 36, 38 and 40 but are advanced in phase, rather than delayed, by increments of the same magnitude as in the sections 10*a* and 10*b*.

The relative phases of the voltages developed at the output terminals of the system 74 are illustrated in FIG. 5, with the voltage at each terminal represented by a vector identified with the reference numeral associated with the terminal. It is seen that the voltages at terminals 38 and 74 and at terminals 40 and 76 are phased symmetrically about the voltage at port terminal.

Referring again to FIG. 4, the properly phased voltages at the terminals 83, 81, 36, 38 and 40 are applied to sum mixers 12', which are similar to the mixer illustrated in FIG. 3. The output voltages of these mixers are delivered through power amplifiers 82 and transmit receive devices 84 to radiating elements 86. The output of a transmitter 87 is also applied to each sum mixer 12'. Since the modulation of the transmitter signal is preserved in the mixers 12', the radiating elements 86 are energized with signals that are identical in amplitude and frequency, and are phased according to the phases of the voltages developed at the output terminals of the phasing system 74.

The direction of the beam or radiation pattern 78 of the array 76 depends on the phase gradient between the signals at the elements 86. As the delay of the phase shifter 20 is changed and the phase difference between the voltages at the terminals 76, 74, 36, 38 and 40 varies, the phase difference between the signals delivered to the elements 86 varies correspondingly to change the beam direction. More specifically, with the phase delay increasing as one moves to the right along the output terminals of the phasing system 74, the direction of the beam 78 is to the right. The angle between the beam and the normal to the plane of the elements 86 increases as the magnitude of phase delay increases.

To steer the beam 78 to the left of the normal, the phase delay must increase to the left, i.e., decrease to the right, along the phasing system output terminals. This can easily be accomplished by arranging the phase shifter 18 to provide a phase lead, as well as a phase lag, at its output. With a phase lead, the phases in expressions (2) and (4) above are negative quantities and therefore, there are leads, rather than lags, at successive terminals.

With further reference to FIG. 4, during reception the signals from the radiating elements 86 are coupled by the transmit-receive devices 84 to difference mixers 14' similar to the mixer illustrated in FIG. 3. The phased voltages from the phasing system 74 are also applied to these mixers. The output circuits of the mixers 14' are tuned to the difference between the frequency of the signals intercepted by the elements 86 and the frequency of the local generator 28, i.e., the frequency of the transmitter 87, and the difference frequency signals from the mixers are combined and delivered to a receiver 88. The modulation of the received signals is preserved in the mixers 14' for demodulation by the receiver 88.

More specifically, the signals coupled from the an-

tenna elements 86 to the mixers 14' have substantially the same amplitude but differ in phase depending on the direction from which they arrive. The phase angle of the output from each difference mixer 14' is equal to the difference between the phases of the signal from the element 86 associated therewith and the voltage from the corresponding output terminal of the phasing system 74. Thus, when the phase gradient between the phased voltages from the system 74 equals the phase gradient of the received signals, the signals delivered to the receiver 88 from the difference mixers have the same phase and reinforce each other. Thus, the signal fed to the receiver is the arithmetic sum of the individual signals from the mixers 14'.

However, when the phase gradients of the voltages from the phasing system 74 and the signals from the elements 86 differ, the signal outputs from the mixers 14' are not in phase and thus they interfere with each other. Since the phase gradient between the intercepted signals varies with the direction from which the signal arrives at the array 76, the phasing system 74 provides efficient means for selecting the direction from which signals are to be received.

Still referring to FIG. 4, three port circulators may be used instead of the transmit/receive devices 84 to selectively transfer signals from the mixers 12' to the radiating elements 85 and to couple received signals to the mixers 14'. For wideband reception, tuning means (not shown) may be provided to tune the mixers 14' in synchronism with the tuning of the receiver 88.

In some cases, the phasing systems shown in FIG. 1 and at 74 in FIG. 4, can be simplified, if only transmission of signals is required, by replacing the local generator 28 with the transmitter 87 (FIG. 4) and connecting a power amplifier 82 and radiating element 86 to each output terminal (76, 74 and 36–40) of the phasing system.

In summary, the novel phasing apparatus described herein develops, with a single phase shifter, a succession of voltages having selected phase increments between them. The phase increments are varied readily by equal amounts without changing the frequency of the voltages. Moreover, there is only one source of cumulative phase error. Another feature of the invention is the ease with which the system can be constructed with "building block" techniques to provide any desired number of phased outputs.

It will thus be seen that the objects set forth above, among those made apparent from the preceding description, are efficiently attained and, since certain changes may be made in the above constructions without departing from the scope of the invention, it is intended that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

It is also to be understood that the following claims are intended to cover all of the generic and specific features of the invention which, as a matter of language, might be said to fall therebetween.

What is claimed is:

1. Apparatus for developing a plurality of voltages having selected phase difference between them, said apparatus comprising, in combination,

(*a*) a first voltage source,

(*b*) a second voltage source,

(*c*) a variable phase shifter connected to receive the output of said first source,

(*d*) a first frequency combiner connected to combine the outputs of said second source and said phase shifter and thereby develop an output voltage having a frequency equal to one of the sum and difference of frequencies of said sources,

(*e*) a second frequency combiner connected to combine said outputs of said first combiner and said first source and thereby develop an output voltage whose frequency is the other of the sum and difference of its input frequencies,

(*f*) whereby when the setting of said phase shifter is changed, the change in phase of said output voltage of said second combiner is equal in magnitude to the change in phase of the output of said phase shifter.

2. The combination defined in claim 1 in which said frequency combiners are so constructed so that said output voltages thereof contain the information present in the voltages from said first and second sources.

3. Apparatus for developing a plurality of alternating voltages having selected phase differences between them, said apparatus comprising, in combination,

(*a*) a first voltage source having a first frequency,

(*b*) a second voltage source having a second frequency,

(*c*) a variable phase shifter connected with said first source to develop a delayed voltage having said first frequency,

(*d*) a first frequency combiner connected with said second source and with said phase shifter to develop a combined output voltage having a third frequency equal to one of the sum and difference of said first and second frequencies,

(*e*) a second frequency combiner connected to receive said combined voltage and the voltage from said first source to develop an output voltage whose frequency is the other of the sum and difference of said first and third frequencies,

(1) each of said first and second combiners being constructed to develop its output voltage at a phase angle corresponding to the relative phase angle between the input voltages thereof,

(*f*) whereby the change in relative phase of said output voltage of said second combiner caused by varying said phase shifter is equal to the change in relative phase of the voltage delivered to said first combiner from said phase shifter,

4. The combination defined in claim 3 in which

(*a*) said first combiner develops a combined voltage at the sum of its input frequencies, and

(*b*) said second combiner develops its output voltage at the difference between its input frequencies.

5. The combination defined in claim 4 further comprising

(*a*) a third frequency combiner connected to said second source and said phase shifter and developing an output voltage having a frequency equal to the difference between the output frequencies of said second source and said phase shifter,

(*b*) a fourth frequency combiner connected to receive said output voltage of said third combiner and the output voltage of said first source and develop an output voltage whose frequency is the sum of the frequencies of said first source and said output voltage of said third combiner,

(1) the frequency of said output voltages of said second and fourth combiners thus being the frequency of said second source,

(*c*) whereby the relative phase angle of said output voltage of said fourth combiner decreases by the same amount that the phase angle of said output voltage of said second combiner increases when the phase delay of said phase shifter is increased.

6. Apparatus for developing a plurality of alternating voltages having selected phase differences between them, said apparatus comprising, in combination,

(*a*) a source of first voltage having a first frequency,

(*b*) a source of second voltage having a second frequency,

(*c*) a variable phase shifter connected to receive said first voltage to develop a delayed voltage having said first frequency,

(*d*) a first frequency combiner connected to receive said second and said delayed voltages and develop a fourth

voltage having a third frequency equal to the difference between said first and second frequencies,

(*e*) a second frequency combiner connected to receive said first and fourth voltages to develop an output voltage whose frequency is the sum of said first and said third frequencies,

(1) said frequency combiners being constructed to develop voltages corresponding to the information in the input voltages thereto, including the phase angles of said input voltages,

(*f*) whereby when the phase delay of said phase shifter is increased, the relative phase angle of said output voltage from said second combiner decreases by an amount equal to the decrease in the phase of said delayed voltage.

7. A voltage phasing system comprising, in combination,

(*a*) a first voltage source providing a first voltage at a first frequency,

(*b*) a second voltage source providing a second voltage at a second frequency,

(*c*) phase shifting means connected to receive said first voltage to develop a delayed voltage at said first frequency,

(*d*) a plurality of stages connected in succession,

(1) each of said stages comprising first and second frequency combiners and means connecting the output voltage from said first combiner to said second combiner,

(2) said first frequency combiner in each said stage being connected to receive said delayed voltage,

(3) said first combiner in a first stage being connected to receive also said second voltage and develop a fourth voltage at a third frequency equal to one of the sum and difference of said first and second frequencies,

(4) said first combiners in successive stages other than said first stage being connected to receive also said output voltage from said second combiner in the preceding stage of said succession and develop fourth voltages at said third frequency,

(5) said second frequency combiner in each stage being connected to receive said first voltage and said fourth voltage in the same stage and develop an output voltage whose frequencies is the other of the sum and difference of said first and third frequencies.

(*e*) whereby when the phase delay of said phase shifting means is changed, the phase angles between said output voltages from said second combiners in successive stages change by the same angle.

8. The combination defined in claim 7 in which

(*a*) said frequency combiners are mixers,

(*b*) said third frequency is the sum of said first and second frequencies, and

(*c*) the frequency of said output voltage is the difference between said first and third frequencies and is equal to said second frequency.

9. The phasing system defined in claim 7 in which said frequency combiners are constructed to develop said fourth and output voltages, respectively, at phase angles corresponding to the relative phase angles between the input voltages thereto.

10. Apparatus for developing a succession of voltages having selected phase differences between them, said apparatus comprising, in combination,

(*a*) a first source of voltage having a first frequency,

(*b*) a variable phase shifter,

(*c*) a first isolation circuit connecting said first source with said phase shifter whereby said phase shifter develops a delayed voltage having said first frequency,

(*d*) a second source of voltage having a second frequency,

(*e*) a plurality of sum mixers, each of which has first and second input terminals and an output terminal,

(*f*) a plurality of difference mixers, each of which has third and fourth input terminals and an output terminal,

(*g*) transmission means connecting said second source to said first terminal of a first sum mixer,

(*h*) second isolation circuits interconnecting said sum and difference mixers in an alternate succession to deliver to each of said third input terminals the voltage developed at the output terminal of the preceding sum mixer and to deliver to each of said first terminals of the sum mixers other than said first mixer the voltage developed at the output terminal of the preceding difference mixer,

(*i*) whereby a change in the phase angle between the input voltages of said first sum mixer causes the phase of the output voltages from said difference mixers to change by the same angle.

11. The combination defined in claim 10 in which

(*a*) each of said sum mixers is connected to develop an output signal having a third frequency equal to the sum of said first and second frequencies and

(*b*) each of said difference mixers is connected to develop an output voltage having a frequency equal to the difference between said first and third frequencies.

12. A steerable beam multi-element antenna array comprising, in combination,

(*a*) a first voltage source having a first frequency,

(*b*) a second voltage source having a second frequency,

(*c*) a variable phase shifter connected to said first source to develop a delayed voltage at said first frequency,

(*d*) a first frequency combiner connected to said second source and with said phase shifter to develop a combined voltage having a third frequency equal to one of the sum and difference of said first and second frequencies,

(*e*) a second frequency combiner connected to receive said combined voltage and said first source and develop an output voltage whose frequency is the other of the sum and difference of said first and third frequencies and thus equal to said second frequency,

(*f*) a plurality of radiating elements,

(*g*) transmission means connected between said elements and said second combiner and second source to deliver said output voltage and delayed voltage to said elements,

(*h*) whereby the radiation pattern of said array is directed in different directions when the phase delay imparted by said phase shifter is changed.

13. A communication system comprising, in combination,

(*a*) a first voltage source having a first frequency,

(*b*) a second voltage source having a second frequency,

(*c*) a variable phase shifter connected to said first source to develop a delayed voltage at said first frequency,

(*d*) a first frequency combiner connected to said second source and said phase shifter to develop a combined voltage having a third frequency equal to the sum of said first and second frequencies,

(*e*) a second frequency combiner connected to receive said combined voltage and the voltage from said first source and develop an output voltage whose frequency is the difference between said first and third frequencies and thus equal to said second frequency,

(*f*) a third frequency combiner connected to said sec-

ond source and said phase shifter to develop a second combined voltage having a fourth frequency equal to the difference between said first and second frequencies,

(*g*) a fourth frequency combiner connected to receive said second combined voltage and the voltage from said first source and develop a second output voltage whose frequency is the sum of said first and fourth frequencies and thus equal to said second frequency,

(*h*) a transmitter,

(*i*) fifth frequency combiners each connected to said transmitter and one of said output voltages and voltage from said second source to develop a transmission signal whose frequency is the sum of said second and transmitter frequencies, and

(*j*) a plurality of radiating elements each connected to receive said transmit signal from a corresponding fifth frequency combiner.

14. The combination defined in claim 13 in which

(*a*) said first, fourth and fifth frequency combiners are sum mixers, and

(*b*) said second and third frequency combiners are difference mixers.

15. The combination defined in claim 13 further comprising,

(*a*) a receiver,

(*b*) a plurality of transmit/receive devices each interconnecting one of said elements and the corresponding fifth frequency combiner to deliver said transmit signals to said radiating elements,

(*c*) a plurality of sixth frequency combiners each connected to a transmit/receive device to receive signals intercepted by the radiating elements connected thereto and further connected to receive the same output or second source voltage that is delivered to the fifth combiner connected with said transmit/receive device,

(1) each of said sixth combiners developing a difference signal having a frequency equal to the difference between the frequency of the signal being received and said second frequency,

(*d*) means combining said difference signals and delivering them to said receiver,

(*e*) whereby the direction from which signals are received is changed by changing the phase delay of said phase shifter.

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