United States Patent

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[54] **ANTENNA ARRAY SYSTEM**
17 Claims, 6 Drawing Figs.

[52] **U.S. Cl.** ..... **343/100 SA,** 343/854
[51] **Int. Cl.** **H01q 3/26**
[50] **Field of Search** 343/100.6, 16.1, 854

[56] **References Cited**

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2,429,726 10/1947 Lewis 343/100

Primary Examiner—T. H. Tubbesing
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CLAIM: 1. In combination:

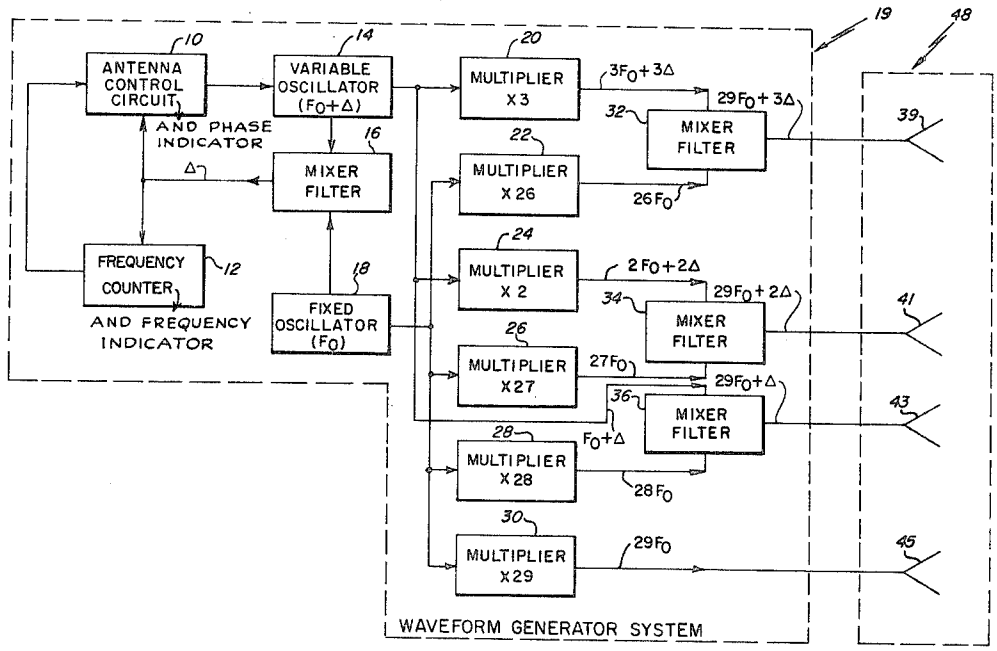
first oscillator means for generating a first signal;

second oscillator means for generating a second signal;

means for obtaining frequency multiples of said first and second signals;

means for mixing predetermined multiples of said first signal with predetermined multiples of said second signal to derive a set of signals differing in frequency by an amount equal to the frequency difference between said first and second signals;

and means for varying the frequency of at least one of said first and second signals.



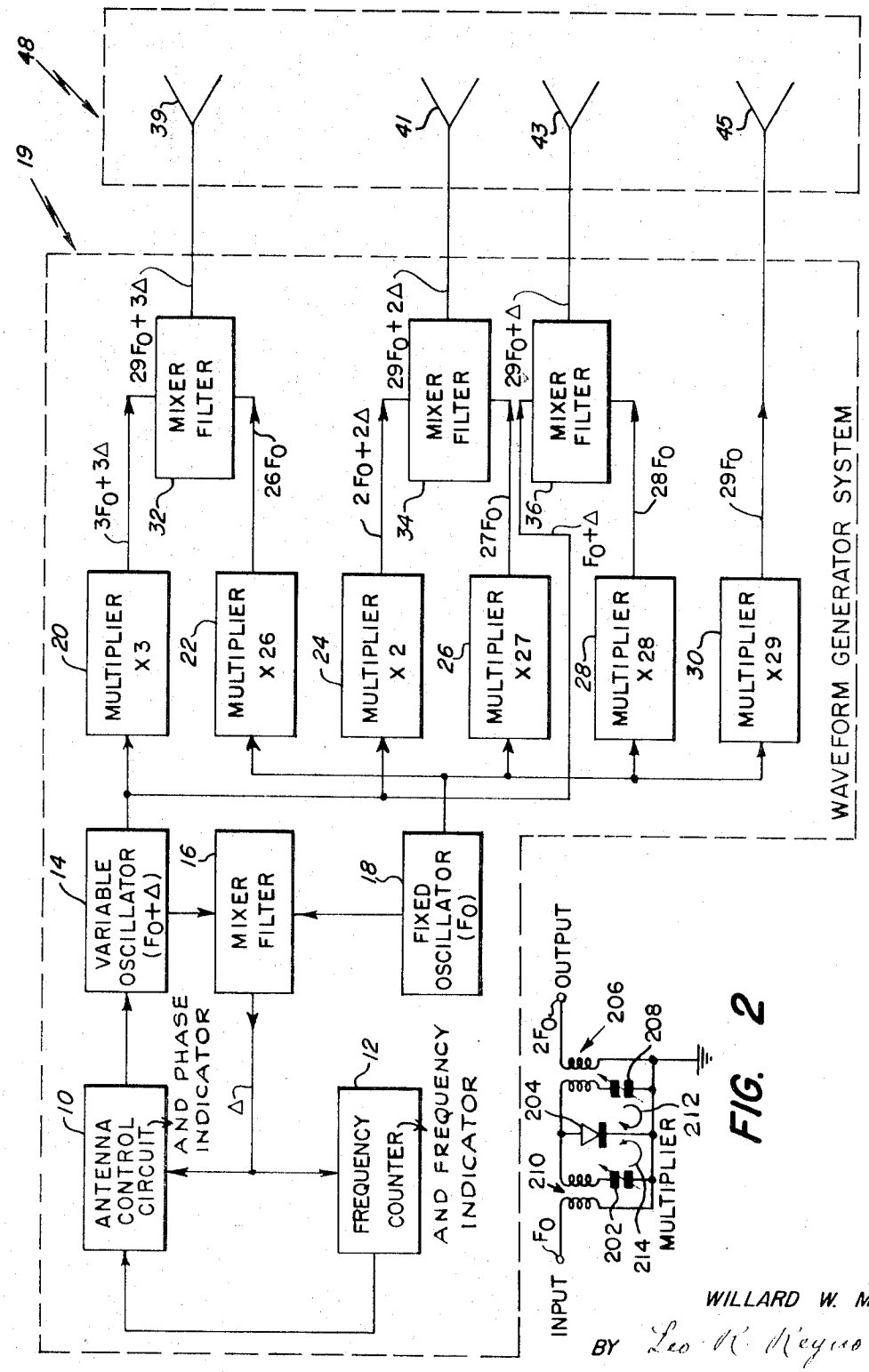


FIG. 1

FIG. 2

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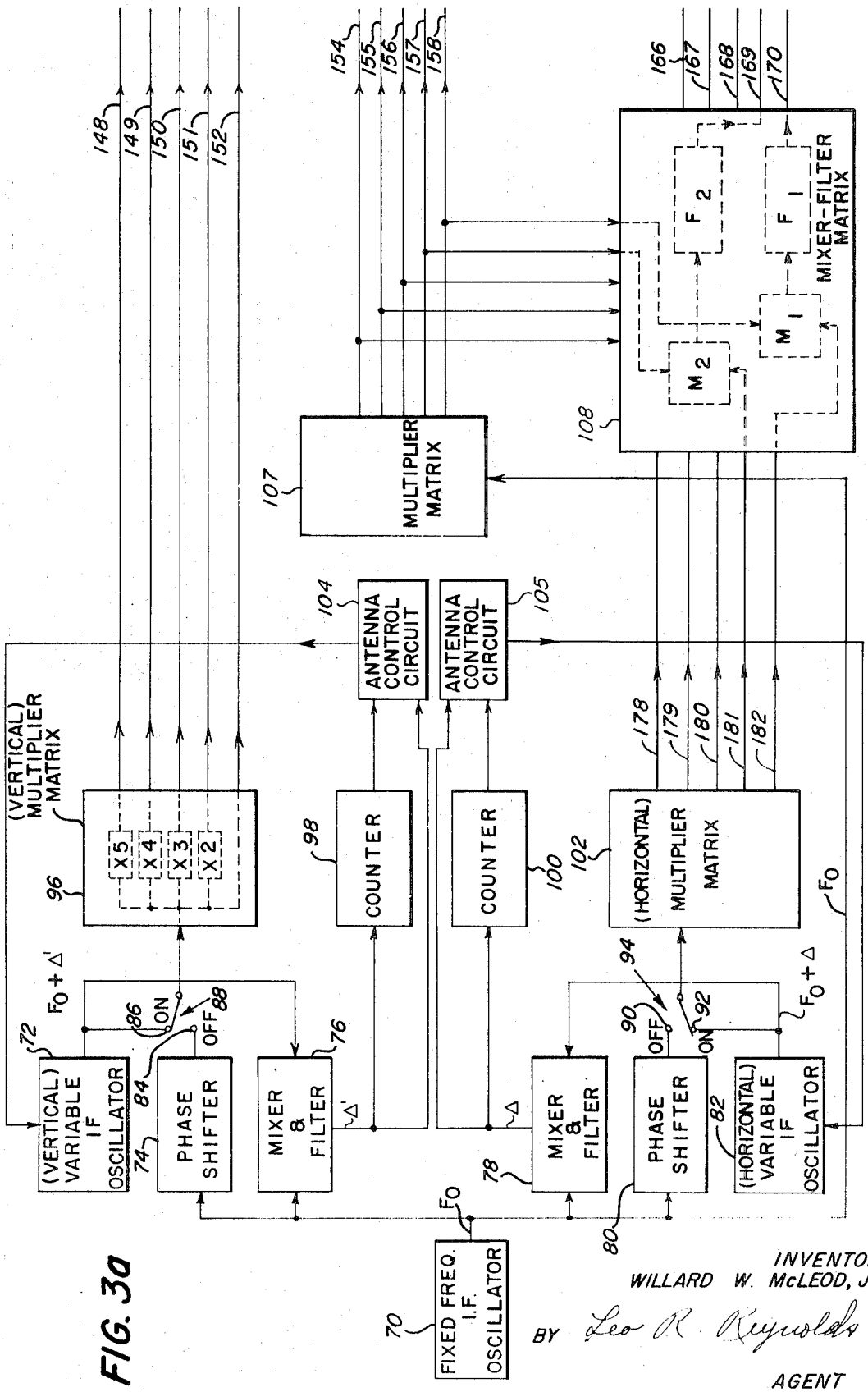


FIG. 3a

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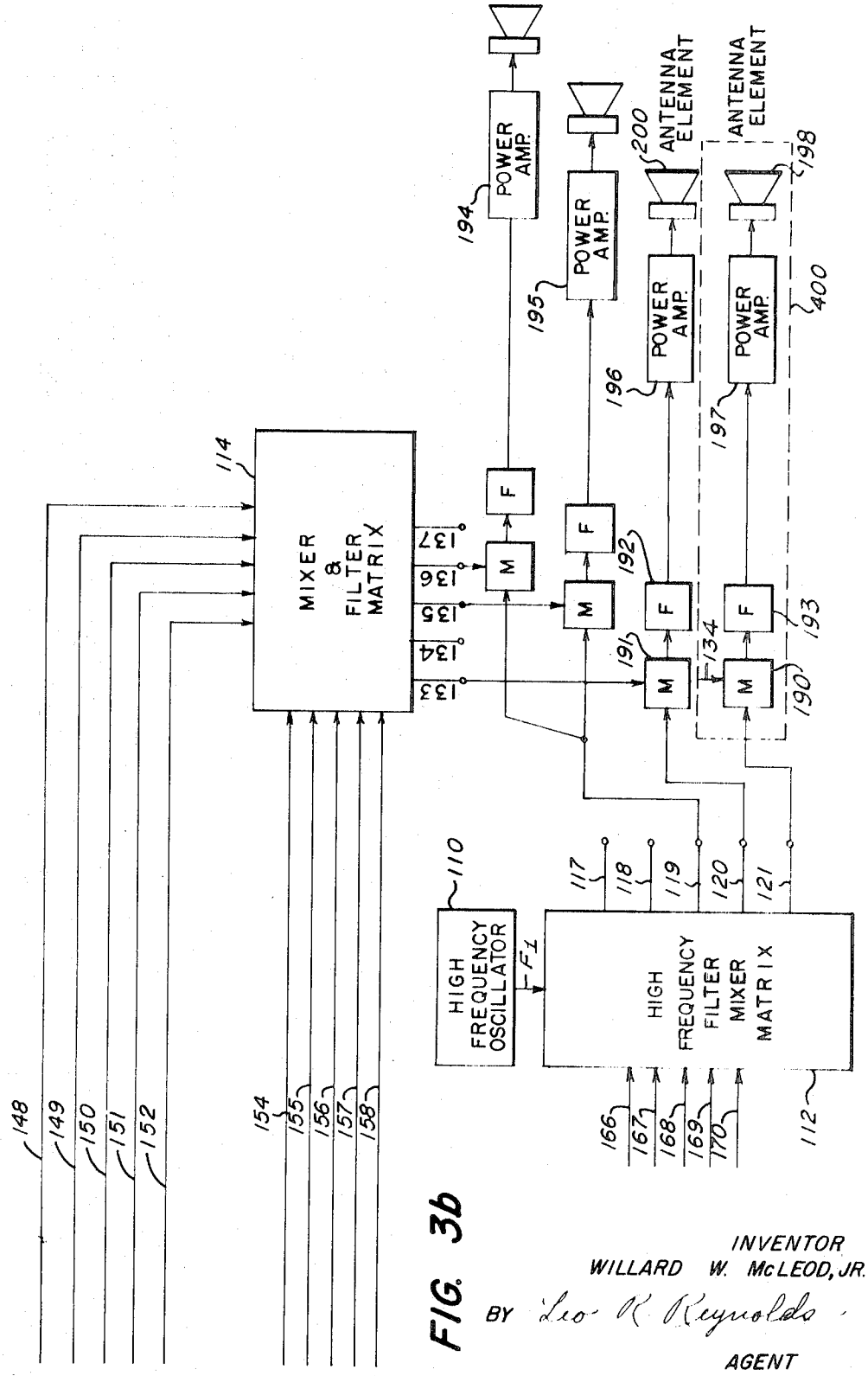


FIG. 3b

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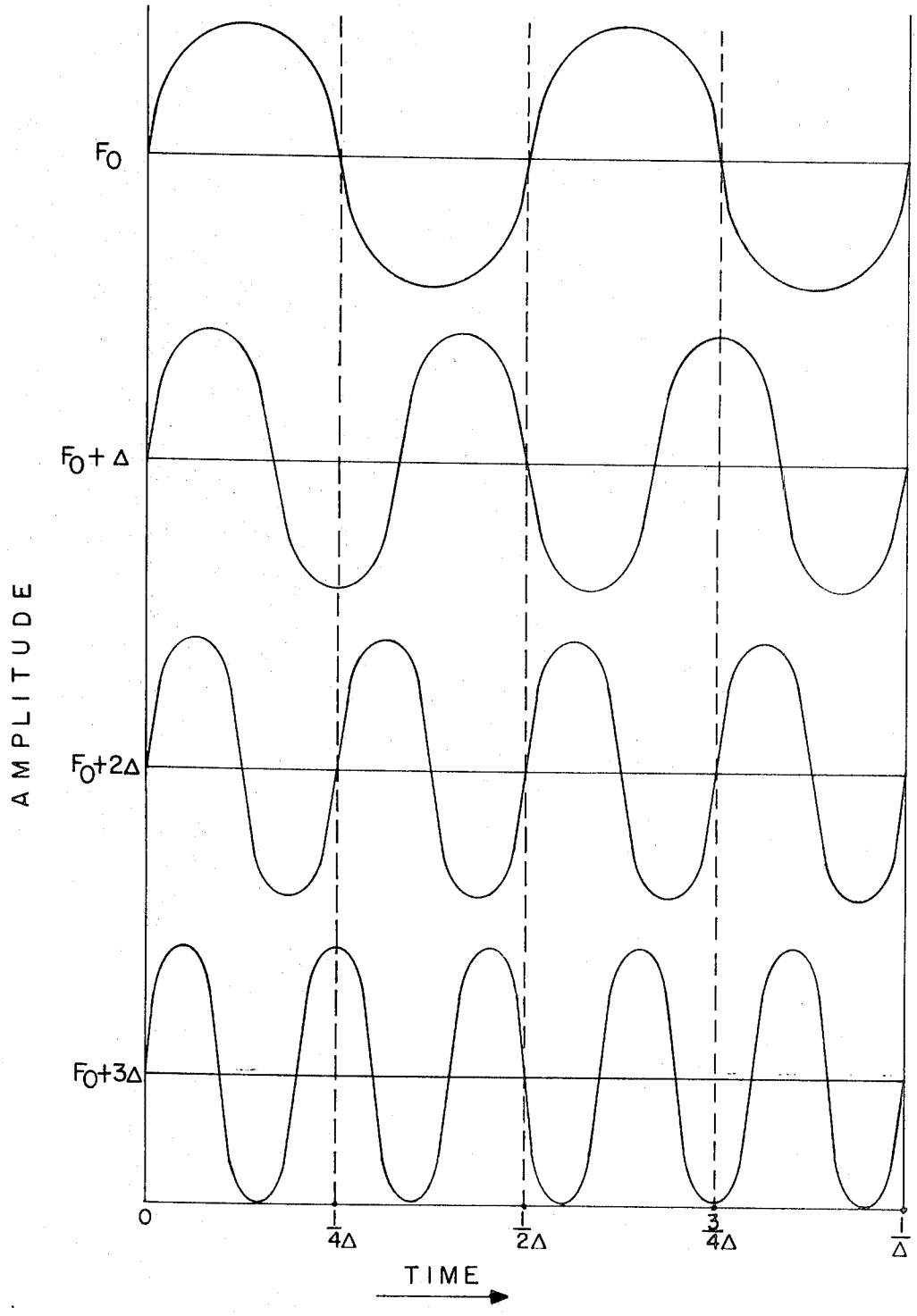


FIG. 4

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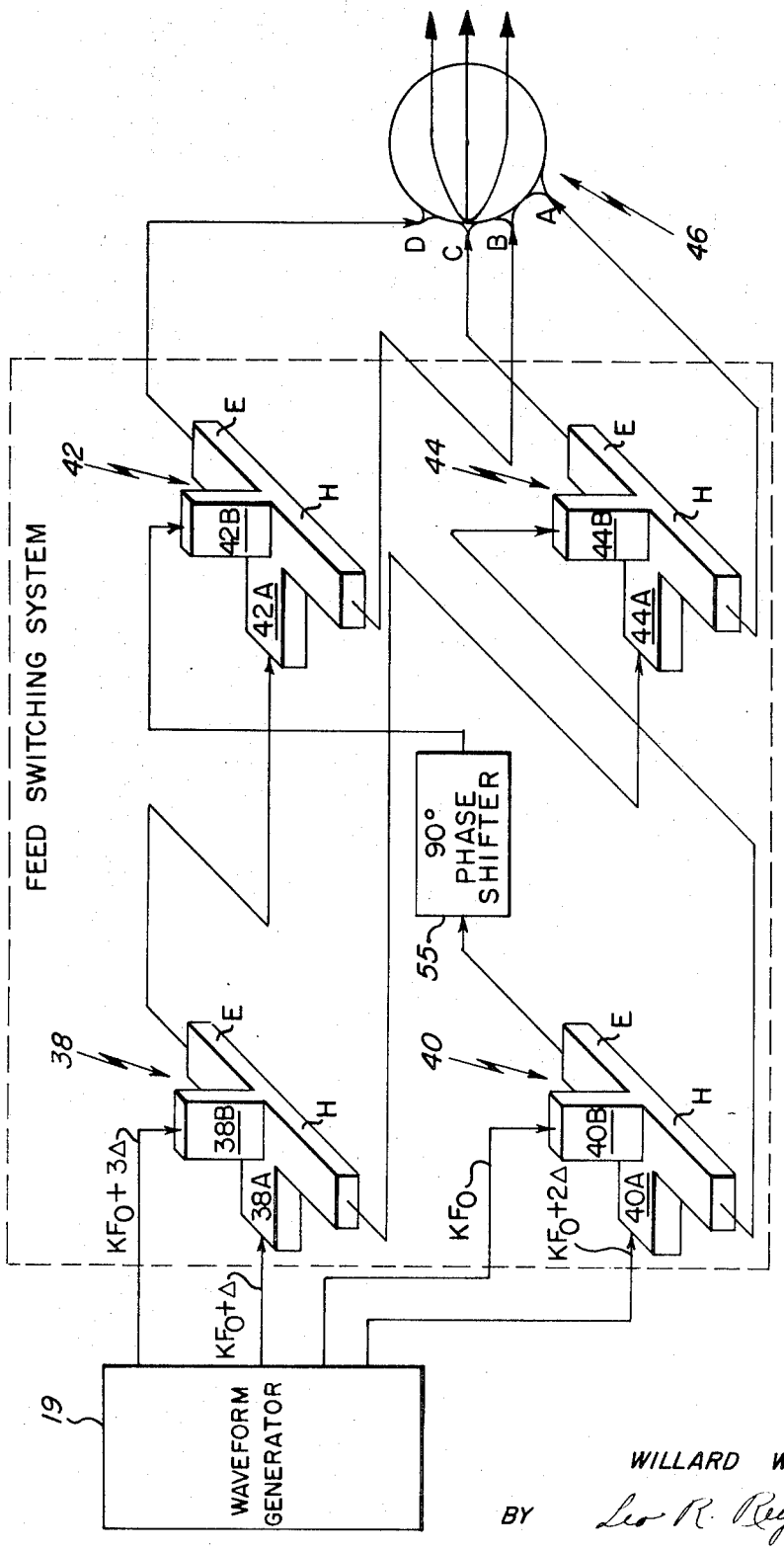


FIG. 5

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ANTENNA ARRAY SYSTEM

This invention pertains to antenna array systems and more particularly to means for electronically scanning such antenna arrays.

An antenna array consists of a plurality of radiant elements suitably spaced from one another. In an electronically scanned array, the relative phase shift of the applied energy between radiant elements is electronically controlled. By varying the relative phase shift between elements in a suitable manner, the desired radiation pattern from the combined action of all the elements is obtained.

Prior art electronically scanned arrays may be classified as either frequency or direct phase controlled devices. An example of a direct phase controlled device is the Huggins electronic phase shifter shown in FIG. 9 of the article "Recent Electronic Scanning Developments" by J. Paul Shelton, Jr. and Kenneth S. Kelleher, Conf. Proc., Fourth National Conv. on Military Electronics 1960. In the Huggins device an input signal of frequency f_0, whose phase is to be shifted an amount Φ, is mixed with a control signal of frequency f_c in a first mixer. A portion of the control frequency is passed through a delay line of length τ. The output of the delay line is a signal of frequency f_c with a phase delay Φ equal to $2\pi f_c\tau$. The phase-shifted control signal and the output of the first mixer are heterodyned in a second mixer. If the sum frequency is selected from the first mixer, the difference frequency is selected from the second mixer. The resultant output of the second mixer is a signal with the same frequency as the input signal f_0, but with the phase advanced by an amount Φ. The input signal and the control signal are fed to successive stages of time delay devices and mixers respectively with appropriately incrementally advanced or delayed phase shifted signals being tapped off at the respective second mixers and coupled to radiant elements to obtain the desired electronically controlled relative phase shift between elements. In the Huggins device as thus described, in order to scan the array, it is necessary to shift the frequency of the control signal. In other words, the pattern of the radiant elements is not automatically and continuously varied without continuously shifting the frequency of the control signal. If phase is continuously varied between radiant elements of the array the beam will be continuously scanned. A similar result may be obtained by establishing a properly phased frequency shift between each element so that the beam is periodically scanned without the necessity of continuously shifting the frequency of the control signal since a continuous phase shift is by definition a frequency shift. It is therefore an object of the invention to obtain an improved array, the scanning of which is relatively simple to control.

In the apparatus of the present invention a radiation pattern is obtained which is continuously and automatically varied across the array at a speed proportional to the frequency difference between a first control signal and a second control signal. In this manner the need for continuously shifting the frequency of the control signal, as required in the Huggins device, is obviated and a simpler mode of operation is thereby realized. In order to obtain the aforesaid continuous mode of operation, use is made of the principle that a phase shift between adjacent antenna elements may be effectively produced by separately producing a plurality of discrete frequency signals, each signal being frequency separated from one another by a progressive fixed difference such as the set of signals $F_0+n\Delta$, $F_0+(n+1)\Delta$, $F+(n+2)\Delta$,... $F_0+(n+N)\Delta$, wherein F_0 is a signal of frequency F_0, $F_0+\Delta$ is a signal of frequency $F_0+\Delta$, n is an integer such as 1, 2, 3 . . . n, Δ is a frequency difference signal of frequency Δ and m is an integer such as 1, 2, 3 . . . m and coupling separate ones of said set of signals to individual antenna elements.

The present invention provides novel apparatus for generating such set of discrete frequency signals comprising: means for generating a control signal F_0, means for generating a frequency-variable signal $F_0+\Delta$ which is frequency offset a predetermined amount Δ from said control signal, mixer means for mixing the control signal with the frequency-variable signal to derive the offset signal Δ, multiplier means for deriving harmonics of said control signal and said frequency-variable signal and means for mixing selected harmonics of said multiplier means with one another to derive the desired set of discrete frequency signals. In this manner a versatile waveform generator is provided in which the antenna beam can be formed so that the beam will sweep at any desired sweep rate, or the beam can be stopped at any desired angle and held at that angle for as long as required by merely changing the frequency of the frequency offset signal $F_0+\Delta$. With such a waveform generator it is possible to employ the antenna array system as a slowly sweeping target acquisition device or as a fast sweeping object discriminating device or it can equally well be used as a tracking device. The waveform generator can be used to drive the detectors or mixers of either a receiving array or a transmitting array, respectively, and thus a sweeping or fixed receiving or transmitting antenna beam may be produced.

It is a further feature of the invention to provide a two-dimensional antenna array system which includes the aforesaid waveform generator plus additional variable oscillator means for producing a second frequency offset signal. The added oscillator means controls scanning in, for example, the vertical dimension, while the original variable oscillator means controls scanning in the horizontal dimension of the array. The rate at which the array is scanned in either dimension can be controlled independently of the other dimension by the individual variable oscillator means. Furthermore, the array can be made to scan in either direction or slowed down and made to stop in either direction by means of said individual variable oscillator means. In addition, switching means are provided in each dimension whereby a fixed oscillator means can be substituted for the variable oscillator means feeding the multiplier circuits so as to produce a signal which, when phase shifted by a variable phase shifter and multiplier by suitably provided multiplier means, produces a progressive phase shift across the antenna array. By controlling a single one of said variable phase shifters the antenna beam can be fixed in any desired dimension while being frequency scanned in the other dimension.

In a further embodiment of the invention a frequency-swept Butler feed system is provided. A Butler feed system in general is a parallel-fed network utilizing hybrid junctions with fixed phase shifters to form n-overlapping beams in an n-element array. In the Butler feed system a signal from a master oscillator is coupled in parallel to n power drivers which in turn are separately coupled to the n input terminals of the Butler network. Beam steering is accomplished by successively programming "on" one or more of the power drivers as desired. Such a system is described in detail in the article entitled "Beam-forming Matrix Simplifies Design of Electronically Scanned Antennas" by J. Butler and R. Lowe, Electronic Design, vol. 9, pp. 170–173, Apr. 12, 1961. In accordance with the present invention it has been found that by suitably coupling the aforesaid waveform generator apparatus to a Butler feed system there is provided successive maximum outputs at elements of an antenna array during time intervals inversely proportional to the aforesaid frequency difference existing between the aforesaid control signal and the offset signal, thereby providing rapid and continuous switching of outputs of an antenna array without the need of electromechanical or other programmed switching apparatus as in the Butler system.

Other objects and advantages of this invention will become apparent from the following specification taken in connection with the accompanying drawings wherein:

FIG. 1 shows in block diagram form a one-dimensional antenna array system of the invention;

FIG. 2 is an example of a suitable multiplier circuit for obtaining the necessary signal multiplication required in the waveform generator apparatus of the invention;

FIGS. 3A and 3B show a block diagram of a two-dimensional antenna array system of the invention;

FIG. 4 is a waveform diagram illustrating the effect of the progressive frequency difference signal on the phase relation of the individual outputs of the waveform generator with respect to time; and

FIG. 5 shows a frequency scanned beam switching system embodiment of the invention.

Referring now to FIG. 1, there is shown a waveform generator 19 of the invention coupled to a one-dimensional antenna array 48. The waveform generator 19 includes a fixed oscillator 18 which generates a signal of frequency F_0 which may, for example, be 20 megacycles. The fixed oscillator output is coupled to one input terminal of a well-known mixer-filter device 16. A second oscillator 14 capable of being varied in frequency an amount Δ above or below the frequency of the fixed oscillator F_0 provides a frequency signal $F_0+\Delta$ wherein Δ may, for example, be +1 megacycle. The signal $F_0+\Delta$, or, in the example, 21 megacycles, is coupled to a second input terminal of mixer-filter device 16 as shown. The two signals $F_0+\Delta$ and F_0 are heterodyned or beat in mixer-filter 16 in a well-known manner to produce sum and difference frequency signals of the input signals. The difference frequency signal Δ is passed and the sum frequency $2F_0+\Delta$ is filtered or suppressed by a suitable filter within mixer-filter 16.

The output signal from mixer-filter 16, which is the frequency difference signal Δ, is coupled to a frequency counter 12 which measures and displays the frequency of the signal Δ. As will be subsequently explained, the frequency of the signal Δ is proportional to the speed or rate at which the antenna array is swept. Accordingly, the indication at counter 12 is a measure of such rate. The frequency difference signal Δ is also coupled to the antenna control circuit 10. In the antenna control circuit the zero crossing time of the beat note of the signal Δ and hence the phase of the signal Δ is measured and displayed by well-known phase-sensitive means. The phase of the signal Δ is determinative of the position of the antenna beam as will subsequently be explained. Accordingly, by measurement of the frequency and phase of the signal Δ, the beam position and sweep rate can be readily observable by an antenna control system operator. A feedback loop is provided from the antenna control circuit 10 to the variable oscillator 14 whereby the signal Δ can be controlled from the antenna control circuit by changing the frequency of the variable oscillator 14 in any manner desired as by electrical means, mechanical means, hydraulic means or any combination thereof.

A 57 portion of the signal $F_0+\Delta$ from the variable oscillator 14 is coupled to frequency multiplier 20 wherein it is multiplied by a factor of $N+2$ or as in the present example by a factor of 3 to produce the signal $3F_0+3\Delta$.

Reference is had to FIG. 2 for a specific example of a circuit suitable for obtaining the desired multiplication of a signal by various factors as required in the multipliers of FIG. 1 and the multiplier matrices of FIGS. 3A and 3B subsequently described. As is shown in FIG. 2, a suitable multiplier such as, for example, multiplier 24, comprises a transformer coupled input circuit 210, a transformer coupled output circuit 206, tuning capacitor 202 in series connection with the secondary of the input circuit, tuning capacitor 208 in series connection with the primary of the output circuit and varactor diode intermediate said input and output circuits so as to form two resonant circuits coupled together through the common impedance of varactor diode 204. Varactor diodes are junction diodes operable at microwave frequency ranges and which have a distinct nonlinear charge versus voltage characteristic curve in the reverse bias region. This nonlinear characteristic is utilized in the device of FIG. 2 to generate harmonics of the input signal F_0 in the loop circuit 212. Loop circuit 212 may, for example, be tuned to the second harmonic of the signal F_0 in loop 214. Current divides into these two loops; the major portion of the fundamental frequency F_0 flows through loop 214 and substantially all of the second harmonic flows through the second loop 212 wherein it is coupled to the secondary of transformer 206 and provides the desired output signal $2F_0$. It can readily be seen that such multiplier stages can be cascaded to produce the desired multiplication factor or alternatively multiplier circuits can be provided with secondary loops tuned to the harmonic frequency desired. The varactor multiplier is shown herein as a preferred device for multiplying a signal by a suitable factor such as is desired in the multiplier circuits of the embodiments of the invention shown in FIGS. 1, 3A and 3B, but the invention is not thereby limited to use of varactor multipliers as it is well known that other suitable nonlinear devices such as reflex klystrons may be readily adapted for use as multipliers in the above related circuits.

Referring again to FIG. 1, a second portion of the signal from variable oscillator 14 is coupled to multiplier 24 wherein it is multiplied by a factor of $n+1$ or as in the present example, 2 to produce the signal $2F_0+2\Delta$. Similarly, a first portion of the signal from fixed oscillator 18 is coupled to multiplier 22 wherein it is multiplied by a factor K–3 wherein K may be any integer greater than the number of array elements and for illustrative purposes is chosen as 29. Thus, for example, the output signal from multiplier 22 is equal to $(K-3)F_0$ or $(29-3)\times 20$ megacycles, which equals 520 megacycles. A second portion of the signal from fixed oscillator 18 is coupled to multiplier 26 wherein it is multiplied by a factor of 27 or K–2. The resultant output from multiplier 26 is equal to 540 megacycles. A third portion of the signal from fixed oscillator 18 is coupled to multiplier 28 and multiplied by a factor of K–1 to produce an output signal equal to (for this example) 560 megacycles. A fourth portion of the signal output of fixed oscillator 18 is coupled to multiplier 30 and multiplied by the factor K to produce a 580 megacycle signal designated $29F_0$.

The outputs of the various aforesaid multipliers are coupled in the following described manner to an appropriate one of the mixer-filter devices 32, 34 and 36 so as to produce filtered sum or difference signals of the desired value for beam scanning. For example, the output of multiplier 20, $(3F_0+3\Delta)$ or (60 mc. $+3\Delta$), is mixed with the output of multiplier 22, $(K-3)F$ or 520 mc. in mixer-filter 32 and the sum product of the mixing process, (580 mc. $+3\Delta$), is passed as the output of mixer-filter 32 while the difference product is suppressed. In a similar manner the signal 580 megacycles plus 2Δ is produced at the output of mixer-filter 34 by beating the aforesaid output signal from multiplier 24 with the aforesaid output signal from multiplier 26 in mixer-filter 34 and filtering out the unwanted difference frequency signal and passing the desired sum frequency signal 580 megacycles $+2\Delta$. Likewise, the signal 580 megacycles plus Δ is produced at the output of mixer-filter 36 by mixing a portion of the output from variable oscillator 14 with the output of multiplier 28 in mixer-filter 36 and passing the sum of the mixed signals as an output of mixer-filter 36. It can thus be seen that the desired discrete frequency signals separated by a frequency difference of 1 Δ, 2Δ, and 3Δ have been produced at the outputs of mixers 36, 34 and 32 respectively. Thus, by changing the frequency of variable oscillator 14, such as by antenna control circuit 10, the scanning rate is controlled.

The output of waveform generator 19 comprising the individual outputs from mixer-filters 32, 34 and 36 and the output of multiplier 30 are then coupled to respective radiant elements 39, 41, 43 and 45 of antenna array 48. It is to be understood that suitable power amplification stages may be interposed between the waveform generator outputs and the array elements as desired. Accordingly, it can be seen that the necessary set of discrete frequency signals has been established across the elements of antenna array 48 so that an antenna beam pattern will be produced at a distance from the transmitting array 48 as a result of the plurality of discrete frequency signals radiated from individual elements of the antenna array, each discrete frequency signal being separated from each other by a progressive frequency difference signal; $n\Delta$, $(n+1)\Delta$, $(n+2)\Delta$...$(n+)\Delta$. The radiated beam thus forms a maximum at certain intervals of time and effectively sweeps across the sky because of the continuously varying phase shift created at the antenna elements by the progressive phase shift resulting from the progressive frequency separation of the radiated elements.

The versatility of the waveform generator apparatus of FIG. 1 becomes apparent from an analysis of the effect of a change in the frequency of variable oscillator **14**. The frequency of the variable oscillator **14** can, as noted, be readily changed as by electrical or mechanical tuning. For example, assuming that oscillator **14** is a well-known klystron oscillator, tuning can be accomplished by varying the klystron repeller voltage or by mechanically changing the cavity dimensions of the klystron. The only practical restriction on the amount of frequency change for a desired scan rate will be imposed by the bandwidth of the multipliers and mixer-filter circuits. The filter bandwidths should be sufficiently narrow so as to eliminate undesired harmonics and cross-products. Thus, for a fixed oscillator frequency F_0 equal to 20 megacycles, as in the present example, Δ can be varied as much as plus or minus 1 to 2 megacycles about the fixed frequency signal F_0. With the variable oscillator set to 21 megacycles, Δ equals 1 megacycle and the antenna beam will sweep across array **48** once every microsecond. With the variable oscillator **14** tuned to 20 megacycles, (the same frequency as the fixed oscillator **18**) the beam will be stationary in a position which is dependent upon the phase difference between the two oscillators **14** and **18**. By locking the frequency of the oscillators **14** and **18** together and changing the phase relation between the two signals the beam can be made to stay fixed at any desired angle. When the variable oscillator **14** is set to 19 megacycles (Δ equals minus 1 megacycle) the beam will sweep across the array in 1 microsecond but in a direction opposite to the direction of the path of the sweeping beam for the 21 megacycle setting of the oscillator. Thus it can be seen that by controlling both the frequency and phase of the variable oscillator **14**, the rate of sweep and direction of the antenna beam of array **48** can be completely controlled. This completes the description of the operation of the device of FIGS. 1 and 2.

For a description of a two-dimensional antenna array system of the invention reference is had to FIGS. 3A and 3B. In the invention embodied in FIGS. 3A and 3B the basic principle of operation is the same as that noted in connection with the description of the single linear array of FIG. 1 except that here two variable oscillators, oscillators **72** and **82**, are employed instead of the single variable oscillator of FIG. 1. One oscillator, oscillator **72**, controls the vertical dimension and the other oscillator, oscillator **82**, controls the horizontal dimension of the array. For purposes of illustration in connection with FIGS. **3A** and **3B** it is assumed that fixed frequency oscillator **70** is fixed at a frequency of 10 megacycles and high frequency oscillator **110** is at 3K megacycles. The choice herein of the aforementioned frequency parameters is not meant to be a limitation of the scope of the invention in any manner.

As is shown in FIG. **3A**, the output of fixed frequency oscillator **70** is coupled to one input of mixer-filter **78**. At the same time, the output of variable oscillator **82** comprising signal $F_0+\Delta$ is coupled to a second input terminal of mixer-filter **78**. The two input signals F_0 and $F_0+\Delta$ are mixed in a mixer-filter **78** and the difference signal produced in the mixing process is passed out through the filter stage as the output signal Δ from mixer-filter **78**. The sum signal $2F_0+\Delta$ is suppressed by a well-known filter circuit. In a similar manner a second portion of the output of fixed frequency oscillator **70** is coupled to one input terminal of mixer-filter **76** wherein it is mixed with the output signal $F_0+\Delta'$ from variable oscillator **72** to produce at the output of mixer-filter **76** the output signal Δ'. The output signals Δ and Δ' are fed to respective counters **100** and **98** wherein the frequency of the respective signals and hence rate of sweep of the resultant antenna beam is accurately measured and displayed for the convenience of the antenna control operator. A second portion of each of the output signals Δ and Δ' is coupled to respective antenna control circuits **104** and **105**. Antenna control circuit **104** controls the frequency of variable oscillator **72** which, as will be subsequently described, results in a control of the vertical antenna beam pattern. Antenna control circuit **105** controls the frequency of the variable IF oscillator **82** and thereby effectively controls the horizontal antenna beam pattern as will be subsequently described. A second portion of the output of variable oscillator **72** comprising the signal $F_0+\Delta'$ is coupled through switch **88** to the input terminal of multiplier matrix **96** in the "on" position of switch **88** as shown. Multiplier matrix **96** comprises a set of multiplier circuits similar to that described in connection with FIG. 1 and represented herein by the units **X2**, **X3**, **X4** and **X5** in dotted lines. The input signal $F_0+\Delta'$ is internally coupled to individual multiplier circuits in multiplier **96** so as to produce the output signals 10 megacycles $+1\Delta'$, 20 megacycles $+2\Delta'$, 30 megacycles $+3\Delta'$, 40 megacycles $+4\Delta'$ and 50 megacycles $+5\Delta'$ on output leads **152** through **148** respectively. For example, the signal $F_0+\Delta'$, which in the present illustration is equal to 10 megacycles plus the offset frequency signal Δ', is multiplied in multiplier circuit **X3** by the factor **3** to produce an output signal on line **150** equal to the signal 30 megacycles $+3\Delta'$. In like manner, a portion of the output from variable IF oscillator **82** is coupled through the "on" position of switch **94** to the input lead of multiplier matrix **102** wherein it is multiplied by individual multiplier circuits, therein provided, to obtain the set of frequency signals 50 megacycles $+5\Delta$, 40 megacycles $+4\Delta$, 30 megacycles $+3\Delta$, 20 megacycles $+2\Delta$ and 10 megacycles $+1\Delta$ on lines **178** through **182** respectively. A portion of the fixed frequency signal F_0 from oscillator **70** is coupled to the input terminal of multiplier matrix **107** wherein it is multiplied in a set of multiplier circuits to produce at the output of multiplier matrix **107** five separate output signals respectfully equal to 180 megacycles, 190 megacycles, 200 megacycles, 210 megacycles and 220 megacycles on lines **154** through **158** respectively. For example, the signal F_0 from fixed frequency oscillator **70** is multiplied by a factor K+4, wherein F_0 equals 10 megacycles and K equals the factor **18**, to produce on line **158** a 220 megacycle signal. The aforementioned outputs of multiplier matrix **102** on lines **178** through **182** are mixed in mixer-filter matrix **108** with suitable output signals from lines **154** through **158** to produce the set of signals 230 mc. $+5\Delta$, 230 mc. $+4\Delta$, 230 mc. $+3\Delta$, 230 mc. $+2\Delta$ and 230 mc. $+\Delta$, respectively, on lines **166** through **170** at the output of mixer-filter matrix **108**. For example, the output signal equal to 10 megacycles plus 1Δ from multiplier matrix **102** on line **182** is mixed with the 220 megacycle signal from multiplier matrix **107** on line **158** in the mixer designated M_1 and shown in dotted lines within mixer-filter matrix **108**. The sum of the two input signals to mixer M_1 is a signal equal to 230 plus 1Δ and this signal is passed through filter F_1 to output lead **170** of mixer-filter **108**.

In a similar manner the output signals from multiplier matrix **96** on lines **148** through **152** are mixed with suitable signals from multiplier matrix **107** on lines **154** through **158** in mixer-filter matrix **114** to produce a set of frequency signals respectively equal to 230 mc. $+\Delta'$, 230 mc. $+2\Delta'$, 230 mc. $+3\Delta'$, 230 mc. $+4\Delta'$ and 230 mc. $+5\Delta'$ on output lines **133** through **137** of matrix **114**.

The aforementioned signal outputs from mixer-filter **108** on lines **166** through **170** are heterodyned up in frequency in high frequency filter-mixer matrix **112** by being beat or mixed therein with a high frequency signal F_1 (equal to 3,000 megacycles) from high frequency oscillator **110**. The resultant output signals on lines **117** through **121** from high frequency mixer-filter matrix **112** are respectively as follows: 3,230 mc. $+5\Delta$, 3,230 mc. $+4\Delta$, 3,230 mc. $+3\Delta$, 3,230 mc. $+2\Delta$ and 3,230 mc. $+\Delta$. For example, the output signal on line **169** of mixer-filter **108** (equal to 230 megacycles plus 2Δ is mixed in a mixer provided in high frequency mixer-filter matrix **112** with the signal F_1 (equal to 3,000 megacycles) to produce an output signal on line **120** equal to 3,230 megacycles plus 2Δ. Each of the frequency signals on lines **117** through **121** emanating from mixer-filter matrix **112** is mixed with an appropriate one of the frequency signals on lines **133** through **137** emanating from mixer-filter matrix **114** to produce the desired set of discrete frequency signals, some of which are tabulated in chart I as follows:

Chart I

Unit	Mixer Output	Unit	Mixer Output
117–133	3K mc.−Δ′+5Δ	121–136	3K mc.+Δ−4Δ′
118–133	3K mc. −Δ′+4Δ	121–137	3K mc.+Δ−5Δ′
119–133	3K mc.−Δ′+3Δ	118–134	3K mc.+4Δ−2Δ′
120–133	3K mc.−Δ′+2Δ	118–135	3K mc.+4Δ−3Δ′
121–133	3 K mc.−Δ′+Δ	118–136	3K mc.+4Δ−4Δ′
121–134	3K mc.+Δ−2Δ′	118–137	3K mc.+4Δ−5Δ′
121–135	3K mc.+Δ−3Δ′		

It should be noted that for simplicity only a representative group of the signals from matrices **114** and **112** are shown in FIG. **3B** to be mixed, filtered, amplified and coupled to a two-dimensional antenna array. However, it is to be understood that all signals are ultimately processed in a like manner so as to produce a combined radiation pattern at a distance from the antenna array elements which pattern will sweep across the sky in a vertical or horizontal pattern because of the phase shift across individual elements of the array as produced by the progressive frequency shift of the individual frequency signals simultaneously coupled to individual antenna elements.

In the drawing of FIG. **3B** the details of only four of the final stage mixing, filtering, amplifying and radiating elements are shown, one of which is designated **400** and includes mixer **190**, filter **193**, power amplifier **197**, and radiating horn **198**. It is to be understood, however, that each of the signals on lines **117** through **121** are mixed with appropriate signals from lines **133** through **137** in the manner depicted in FIG. **3B** and partially tabulated on the above shown chart I so as to produce an antenna array comprising **25** discrete output frequency signals coupled to **25** individual radiating elements. Furthermore, it is to be understood that as many elements as may be desired may be fed by the waveform generator of the invention by adding multipliers and mixers in the manner described. The processing of a typical output stage will now be described. The signal on line **137** from mixer-filter matrix **114** which is equal to 230 megacycles plus 5Δ′ is mixed in mixer **191** with the signal 3,230 megacycles plus 2Δ on output line **120** from mixer-filter matrix **112** to produce the sum and difference signals equal respectively to 3,000 mc.−5Δ′+2Δ and 3,460 mc.+5Δ′+2Δ.

The desired difference product of the mixing process in mixer **191** is passed through filter **192** to the input of power amplifier **196** which may, for example, comprise a suitable traveling wave tube amplification stage. The difference signal is amplified in power amplifier **196** and coupled to an individual antenna array element such as horn **200**, wherein it is radiated into space and combines at some distance from the antenna array with the other frequency signals partially tabulated on chart I and simultaneously emanating from individual antenna array elements to produce the aforementioned sweeping radiation pattern.

It can be seen from an analysis of the frequency signals listed on chart I that the desired frequency distribution for a two-dimensional scanning array is obtained by the apparatus embodied in FIGS. **3A** and **3B**. It should be noted, however, that for simplicity all of the 25 outputs of the antenna array have not been tabulated. However, observing, for example, the output obtained by mixing each signal on lines **117** through **121** with the signal on line **133** and filtering out the unwanted product and passing the desired product it can be seen that the set of signals 3,000 megacycles −Δ′+5Δ, 3,000 megacycles −Δ′+4Δ, 3,000 megacycles −Δ′+3Δ, 3,000 megacycles −Δ′+2Δ and 3,000 megacycles −Δ′+Δ is obtained across the vertical dimension of the array to provide a vertical scan.

The rate at which the array is scanned in either dimension can, as noted, be controlled independently by the individual oscillators **72** and **82** in conjunction with their respective antenna control circuits **104** and **105**. The array can be made to scan in either dimension or slowed down and stopped in either dimension by varying the frequency of either variable oscillator **72** or **82**. A variation in the output of oscillators **72** and **82** produces a corresponding increase or decrease in the frequency difference signals Δ′ and Δ which in turn causes the antenna array beam to move faster or slower as desired. By setting the two oscillators **72** and **82** equal to F_0, the beam can be stopped in both directions and maintained there indefinitely since both Δ and Δ′ thereby become equal to zero. Alternatively, the beam may be stopped in one dimension and frequency sweeping may be accomplished in the other dimension by setting one of the oscillators **72** and **82** equal to F_0 and maintaining a frequency difference Δ or Δ′ in the other oscillator.

An additional feature is provided in the invention embodied in FIGS. **3A** and **3B** whereby the antenna beam may be placed in any desired position by varying the phase of signals applied to phase shifters **80** and **74**. In this mode of operation of the invention switches **88** and **94** are placed in the "off" position connecting terminals **84** and **90** respectively to multiplier matrices **96** and **102** respectively so that the fixed frequency oscillator F_0 is now connected through phase shifters **74** and **80** respectively to multiplier matrices **96** and **102** respectively. Phase shifters **74** and **80** introduce the desired amount of phase shift into the fixed frequency signal F_0 passing through said phase shifters. Since the multiplier process occurring in matrices **96** and **102** will multiply the phase shift in an identical manner as that described with respect to the frequency multiplication occurring in matrices **96** and **102** when switches **88** and **94** were in the "on" position connecting terminals **86** and **92** respectively to multiplier matrices **96** and **102** respectively, a similar progressive phase shift across the antenna array is obtained in the "off" mode of operation of switches **88** and **94**. By controlling the respective variable phase shifters **74** and **80** the antenna beam pattern can be maintained in any desired position and held stable at that position. When phase shifting rather than frequency shifting is used for maintaining beam position, the beam can be moved slowly to any position in space irrespective of the starting or stopping phase relations of the signals F_0 and $F_0+\Delta$ or $F_0+\Delta'$.

The waveform generator circuit embodied in FIGS. **3A** and **3B** can be used as a transmitter or adapted for use as a receiver. In the transmitter mode of operation the output from the waveform generator is fed to a matrix of power amplifier microwave tubes such as power amplifiers **194** to **197** as shown in FIG. **3B**. It is to be understood that for receiver operation the output signals from the waveform generator are used as the local oscillator signals for balanced mixer detectors of an antenna receiving array not shown. In this case the power amplifiers 194–197 are omitted. It is also noted that the antenna control system is independent of the carrier signal F_0 and therefore frequency coding of the transmitted signal is possible for purposes of ranging or pulse compression as required by the particular application in which the invention is used.

The following is a description of the apparatus shown in FIG. **5** taken in connection with the waveform diagram of FIG. **4**. In this embodiment of the invention the waveform generator of FIG. **1** is coupled to a set of hybrid junctions which in turn are coupled to elements of an antenna array so that there will be provided at such element's successive maximum and minimum output signals which vary in accordance with the frequency offset signal Δ from the waveform generator. Referring specifically to FIG. **4**, there is shown the time versus amplitude plot of the four signal outputs from waveform generator **19** of FIG. **1**. In the plot of FIG. **4**, Δ has been made equal to one-half the frequency of the fixed oscillator signal F_0. In FIG. **5**, this set of four output signals progressively spaced in frequency by an amount Δ is coupled to respective input arms of well-known Magic "T" hybrid devices **38** and **40** as shown.

At an instant of time, T equal to zero, all the input signals to Magic "T" devices **38** and **40** are in phase and all the power

will be coupled out of output arm H of Magic "T" device **44** as will be subsequently described. The Magic "T" device has the property that if two signals are coupled in phase to separate input arms the combined power of the two signals is passed to the H output arm and none of the power passes to the E output arm. On the other hand, if the two input signals are 180° out of phase with one another all of the power passes to output arm E and none of the power is coupled out of arm H. Accordingly, since at $T=0$ the input signals to arms **40B** and **40A** of Magic "T" **40** are in phase, the two signals will be combined in Magic "T" **40** and the combined signal will pass from arm H of Magic "T" device **40** to the input arm **44B** of Magic "T" device **44** with none of the combined power passing out output arm E. Likewise, the input signal to arm **38A** of Magic "T" device **38** will be combined with the input signal on arm **38B** of Magic "T" device **38** so that all the power is coupled out of arm H of Magic "T" **38** under the assumed in phase condition of the input signals. The output of arm H of Magic "T" **38** is coupled to input arm **44A** of Magic "T" device **44**. At $T=0$, the input signal to arm **44A** and the input signal to arm **44B** from arm H of Magic "T" **40** are in phase with one another and are combined in Magic "T" device **44** so that all the power of the combined signals is coupled out of arm H of Magic "T" **44** to antenna element **46A**.

At a later instant of time $T=\frac{1}{4}\Delta$ because of the progressive phase shift of the input signals to the input arms of Magic "T" devices **38** and **40** resulting from the progressive frequency difference Δ existing between the set of input signals, as illustrated in the graph of FIG. **4**, a phase condition will exist in which the input signal to arm **38B** is 180° out of phase with the input signal to input arm **38A**, and the input signal to arm **40A** of Magic "T" **40** is 180° out of phase with the input signal to arm **40B**, and a 90° phase lag exists between respective B-arms and between respective A-arms of devices **38** and **40**.

The above related phase conditions are conveniently summarized in chart II and are readily deduced from an analysis of FIG. **4**.

CHART II

Time	Phase Relation				
	Arm 38B	Arm 38A	Arm 40B	Arm 40A	Output
T=0	0°	0°	0°	0°	46A
T=1/4Δ	90°	270°	180°	0°	46B
T=1/2Δ	180°	180°	0°	0°	46C
T=3/4Δ	270°	90°	180°	0°	46D

Under the above conditions, at a time $T=1/4\ \Delta$ all of the input power to Magic "T" devices **38** and **40** is coupled out of the output arm H of Magic "T" **42** to antenna array element **46B**. Thus, for example, the two out-of-phase input signals to Magic "T" device **38** are coupled out of output arm E of Magic "T" device **38** to input arm **42A** of Magic "T" device **42**. The two input signals thus obtained at arms **42A** and **42B**, respectively, of Magic "T" device **42** are, because of the 90° phase advance introduced by phase shifter **55**, in phase with one another. Accordingly, all of the power from the combined signals will be coupled out of arm H of Magic "T" device **42** and thence to antenna horn element **46B**. The time period at which all of the output is coupled to output arm E of Magic "T" device **44** is equal to one-fourth of the reciprocal of the frequency difference Δ.

From the above, it becomes apparent that at a time interval corresponding to one-half of the reciprocal of the frequency difference signal Δ, the phase condition noted in chart II is obtained at the input arms of Magic "T" devices **38** and **40** and all of the input power is coupled to antenna element **46C**. Likewise, at a time $T=\frac{3}{4}\Delta$ all of the input power is coupled to antenna element **46D**.

It has thus been shown that by coupling the output signals from waveform generator **19** to the hybrid matrix of FIG. **5** a continuously moving beam output is obtained at elements **46A–D** of antenna **46**. This beam moves from element to element at a rate proportional to the reciprocal of the frequency difference signal Δ. The beam produced at point sources A, B, C and D is converted to a plane wave by passing said beam through the Luneberg Lens **46** of FIG. **5**. The Luneberg Lens is a variable-index-of-refraction lens which is spherically symmetric so that a plane wave incident on the sphere is focused to a point on the diametrically opposite side of the sphere. The converse of this feature is likewise true and is used in the present embodiment of FIG. **5** to produce a plane wave from the point sources **46A–D**. It is noted that a plane wave front may also be produced by use of well-known reflector elements such as the Cassegrain antenna in place of the Luneberg of FIG. **5**. It is to be understood that many more signals can be produced by the waveform generator of the invention and the use herein of only four is in no wise meant to be a limitation. Furthermore, by suitably connecting hybrid couplers in the manner described in connection with FIG. **5** any desired number of 2^n or binary elements can be fed by said waveform generator. In addition, a two-dimensional continuously sweeping Butler array can be achieved by utilizing the two-dimensional waveform generator of FIGS. **3A** and **3B** in connection with a suitably adapted hybrid coupler matrix of FIG. **5**.

It is further noted that, for example, where wide frequency separation between adjacent antenna elements is desired, the signal $F_0+\Delta$ from the variable oscillator of FIG. **1** may be first mixed with a carrier oscillator signal F_c to produce the signal $F_0+F_c+\Delta$. Then, by subtracting in a mixer the signal F_0 from the fixed oscillator from the aforesaid signal $F_0+F_c+\Delta$ signal a first output signal $F_c+\Delta$ is produced. By adding the original variable oscillator signal back on to a portion of the output signal the signal $F_0+F_c+2\Delta$ is obtained from which a second output signal $F_c+2\Delta$ is obtained by subtracting therefrom the signal F_0. By repeating this process any number of output signals having the form $F_c \pm n\Delta$, wherein n is an integer progressing from 1 to n, may be derived.

This completes the description of the preferred embodiments of the invention. However, many modifications thereof will be apparent to those skilled in the art. Accordingly, it is intended that this invention not be limited except as defined by the following claims.

What is claimed is:

1. In combination:
first oscillator means for generating a first signal;
second oscillator means for generating a second signal;
means for obtaining frequency multiples of said first and second signals;
means for mixing predetermined multiples of said first signal with predetermined multiples of said second signal to derive a set of signals differing in frequency by an amount equal to the frequency difference between said first and second signals;
and means for varying the frequency of at least one of said first and second signals.

2. In combination:
first oscillator means for generating a first signal;
second oscillator means for generating a second signal;
means for deriving signals proportional to multiples of the frequency of said first signal;
means for deriving signals proportional to multiples of the frequency of said second signal;
means for mixing predetermined multiples of said first signal with predetermined multiples of said second signal to derive a set of signals differing in frequency an amount proportional to the frequency difference between the first and second signals;
means for varying the frequency of at least one of said first and second signals;
and a radiant element for receiving each of said frequency difference signals.

3. In combination:
first oscillator means for generating a first signal;
second oscillator means for generating a second signal;

means for obtaining frequency multiples of said first and second signals;

means for mixing predetermined multiples of said first signal with predetermined multiples of said second signal to derive a set of signals proportional to the frequency difference between the said first and second signals;

means for varying the frequency of at least one of said first and second signals;

coupler means having an input terminal and an output terminal for receiving each of said frequency difference signals and for providing a power split and phase reversal of signals applied to said input terminal;

and element means for radiating signals, said element means coupled to the output terminals of said coupler means.

4. In combination:

means for generating a fixed frequency signal;

means for generating a variable frequency signal;

means for multiplying said fixed frequency signal in individual multiplier circuits to produce a first set of signals proportional to frequency multiples of said fixed frequency signal;

means for multiplying said variable frequency signal in individual multiplier circuits to produce a second set of separate signals proportional to frequency multiples of the variable frequency signal;

means for mixing selected ones of said first set of separate signals with selected ones of said second set of signals to produce sum and difference frequency signals thereof;

and means for filtering out selected ones of said sum and difference frequency signals to derive a set of frequency signals proportional to said fixed frequency signal and a progressive multiple of the frequency difference between said fixed frequency signal and said variable frequency signal.

5. In combination:

means for generating a fixed frequency signal;

means for generating a variable frequency signal;

means for mixing said fixed frequency signal with said variable frequency signal to produce sum and difference products of such signals;

filter means for filtering out one of said products to derive a frequency difference signal;

means for multiplying said fixed frequency signal in individual multiplier circuits to produce a first set of separate signals proportional to multiples of said fixed frequency signal;

means for multiplying said variable frequency signal in individual multiplier circuits to produce a second set of separate signals proportional to multiples of the variable frequency signal;

means for mixing selected ones of said first set of separate signals with selected ones of said second set of separate signals to produce sum and difference frequency signals thereof;

and means for filtering out selected ones of said sum and difference frequency signals to derive a set of frequency signals proportional to said fixed frequency signal and a progressive multiple of said frequency difference signal.

6. In combination:

means for generating a fixed frequency signal;

means for generating a variable frequency signal;

means for mixing said fixed frequency signal with said variable frequency signal to produce sum and difference products of such signals;

filter means for filtering out one of said products to derive a first frequency difference signal;

means for multiplying said fixed frequency signal in individual multiplier circuits to produce a first set of signals proportioned to multiples of said fixed frequency signal;

means for multiplying said variable frequency signal in individual multiplier circuits to produce a second set of separate signals proportioned to multiples of the variable frequency signal;

means for mixing selected ones of said first set of separate signals with selected ones of said second set of signals to produce sum and difference frequency signals thereof;

means for filtering out selected ones of said sum and difference frequency signals to derive a set of frequency signals proportional to said fixed frequency signal and a progressive multiple of said first frequency difference signal;

and means for varying said variable frequency signal so as to vary the value of said first frequency difference signal.

7. In combination:

means for generating a fixed frequency signal;

means for generating a variable frequency signal;

means for mixing said fixed frequency signal with said variable frequency signal to produce sum and difference products of such signals;

filter means for filtering out one of said products to derive a frequency difference signal;

first multiplier means for generating a plurality of frequency signals each proportional to a multiple of said variable frequency signal; second multiplier means for generating a plurality of frequency signals each proportional to a multiple of said fixed frequency signal;

mixer means for mixing selected ones of said first multiplier means signals with selected ones of said second multiplier means signals to derive sum and difference products of said selected signals;

means for passing one of said mixer products of each of said selected and mixed signals to derive a set of discrete frequency signals proportional to said fixed frequency signal and a progressive multiple of said frequency difference signal;

and means for varying said variable frequency signal so as to vary the value of said frequency difference signal.

8. In combination:

means for generating a fixed frequency signal;

means for generating a variable frequency signal;

means for mixing said fixed frequency signal with said variable frequency signal to produce sum and difference products of such signals;

filter means for filtering out one of said products to derive a frequency difference signal;

means for multiplying said fixed frequency signal in individual multiplier circuits to produce a first set of signals proportional to multiples of said fixed frequency signal;

means for multiplying said variable frequency signal in individual multiplier circuits to produce a second set of separate signals proportional to multiples of the variable frequency signal;

means for mixing selected ones of said first set of separate signals with selected ones of said second set of signals to produce sum and difference frequency signals thereof;

means for filtering out selected ones of said sum and difference frequency signals to derive a set of discrete frequency signals proportional to said fixed frequency signal and a progressive multiple of said frequency difference signal;

element means for receiving individual ones of said discrete frequency signals for providing an antenna array device producing a sweeping radiant energy beam at a distance from such array which beam sweeps at a rate proportional to said frequency difference signal;

and means for varying the sweep rate of said radiant energy beam comprising means for varying the frequency of said variable frequency signal;

9. In combination:

means for generating a fixed frequency signal;

means for generating a variable frequency signal;

means for deriving a frequency difference signal proportional to the frequency difference between said fixed frequency signal and said variable frequency signal;

means for multiplying said fixed frequency signal in individual multiplier circuits to produce a first set of signals proportional to multiples of said fixed frequency signal;

means for multiplying said variable frequency signal in individual multiplier circuits to produce a second set of separate signals proportional to multiples of the variable frequency signal;

means for mixing selected ones of said first set of separate signals with selected ones of said second set of signals to produce sum and difference frequency signals thereof;

means for filtering out selected ones of said sum and difference frequency signals to derive a set of discrete frequency signals proportional to said fixed frequency signal and a progressive multiple of said frequency difference signal;

means for coupling said set of discrete frequency signals to elements of an antenna array to produce a progressive phase shift across the antenna array;

and means for varying said progressive phase shift comprising means for varying the frequency of said variable frequency signal.

10. Apparatus for generating a set of discrete frequency signals comprising:

means for generating a control signal F_0;

means for generating a frequency variable signal $F_0+\Delta$ which is frequency offset a predetermined amount Δ from said control signal;

multiplier means for deriving harmonics of said control signal and said frequency variable signal;

and means for mixing selected harmonics of said multiplier means with one another to derive the set of discrete frequency signals.

11. Apparatus for generating a set of discrete frequency signals comprising:

means for generating a control signal F_0;

means for generating a frequency variable signal $F_0+\Delta$ which is frequency offset a predetermined amount Δ from said control signal;

mixer means for mixing the control signal with the frequency variable signal to derive the offset signal Δ;

multiplier means for deriving harmonics of said control signal and said frequency variable signal;

means for mixing selected harmonics of said multiplier means with one another to derive the set of discrete frequency signals;

and means for displaying the frequency and phase of said offset signal Δ.

12. In combination:

first oscillator means for generating a first signal;

second oscillator means for generating a second signal;

a third oscillator means for generating a third signal; means for deriving frequency multiples of said first, second and third signals;

first mixer means for mixing predetermined multiples of said second signal with predetermined multiples of said first signal to derive a first set of signals proportional to the frequency difference between said first and second signals;

second mixer means for mixing predetermined multiples of said first signal with predetermined multiples of said third signal to derive a second set of signals proportional to the frequency difference between the first and third signals;

and matrix means for mixing selected ones of said first set of signals with selected ones of said second set of signals to derive a third set of signals proportional to the frequency difference between said selected signals.

13. In combination:

means for generating a first signal;

means for generating a second signal;

means for generating a third signal;

means for deriving frequency multiples of said first, second and third signals;

first mixer means for mixing predetermined multiples of said first signal with predetermined multiples of said second signal to derive a first set of signals proportional to the frequency difference between the predetermined multiples mixed;

second mixer means for mixing predetermined multiples of said first signal with predetermined multiples of said third signal to derive a second set of signals proportional to the frequency difference between the predetermined multiples mixed;

matrix means for mixing selected ones of said first set of signals with selected ones of said second set of signals to derive a third set of signals proportional to the frequency difference between said selected signals;

and radiant element means for receiving each signal of said third set of signals for providing a two-dimensional array having a beam pattern which continuously sweeps across the array in one dimension in proportion to the frequency difference between said first and second signals and in the remaining dimension in proportion to the frequency difference between said first and third signals.

14. In combination:

first oscillator means for generating a first signal;

second oscillator means for generating a second signal;

third oscillator means for generating a third signal;

means for deriving frequency multiples of said first, second and third signals;

first mixer means for mixing predetermined multiples of said first signal with predetermined multiples of said second signal to derive a first set of signals proportional to the frequency difference between the predetermined multiples mixed;

second mixer means for mixing predetermined multiples of said third signal with predetermined multiples of said first signal to derive a second set of signals proportional to the frequency difference between the predetermined multiples mixed;

matrix means for mixing selected ones of said first set of signals with selected ones of said second set of signals to derive a third and fourth set of signals respectively proportional to the frequency difference between said first and second signals and said first and third signals;

phase-shifter means coupled to said first oscillator for phase shifting said first signal a variable amount;

and switching means for uncoupling one of said second and third signals from their respective mixer means and coupling in place thereof the phase shifted signal from said phase shifter means.

15. In combination:

means for deriving a plurality of signals spaced apart in frequency by progressive frequency differences;

an initial plurality of coupling means each having a pair of input arms and a pair of output arms and responsive to signals applied to said input arms so as to produce an output at only one output arm when said applied signals are in-phase and an output only at the other output arm when said applied signals are out-of-phase;

means for applying individual ones of said plurality of signals to individual ones of said input arms;

and an additional plurality of coupling means each having a pair of input arms and output arms, said input arms being coupled to predetermined ones of said initial coupling means output arms.

16. In combination:

means for deriving a plurality of signals spaced apart in frequency by progressive frequency differences;

an initial plurality of hybrid means, each having a pair of input arms and a pair of output arms and responsive to signals applied to said input arms so as to produce an output at only one output arm when said applied signals are in phase and an output only at the other output arm when said applied signals are out-of-phase;

means for coupling individual ones of said plurality of signals to individual ones of said input arms;

an additional plurality of hybrid means each having a pair of input arms and output arms, said input arms being coupled to predetermined ones of said initial hybrid means output arms;

and antenna element means coupled to predetermined output arms of said additional hybrid means.

17. In combination:

means for generating a first frequency signal;

means for generating a second frequency signal;

means for generating a third frequency signal;

means for deriving a first plurality of signals spaced apart in frequency by progressive multiples of the frequency difference between said first and second frequency signals;

means for deriving a second plurality of signals spaced apart in frequency by progressive multiples of the frequency difference between said first and third frequency signals;

matrix means for mixing selected ones of said first plurality of signals with selected ones of said second plurality of signals to derive a third plurality of signals proportional to the frequency difference between said selected signals;

a plurality of radiant elements for receiving individual signals of said third plurality of signals to provide a beam pattern which sweeps across said radiant elements in two dimensions;

and means for controlling the rate of sweep of said beam in at least one dimension comprising means for varying the frequency difference between said first signal and at least one of said second and third signals.

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