United States Patent

Glance

[15] 3,653,046

[45] Mar. 28, 1972

[54] **ELECTRONICALLY SCANNED ANTENNA ARRAY**

[72] Inventor: **Bernard Glance**, Colts Neck, N.J.

[73] Assignee: **Bell Telephone Laboratories, Incorporated**, Murray Hill, N.J.

[22] Filed: **June 9, 1970**

[21] Appl. No.: **44,716**

[52] **U.S. Cl.** ....**343/100 SA**, 331/45, 331/56

[51] **Int. Cl.** **H01q 3/26**

[58] **Field of Search** ....343/100 SA; 331/45, 56

[56] **References Cited**

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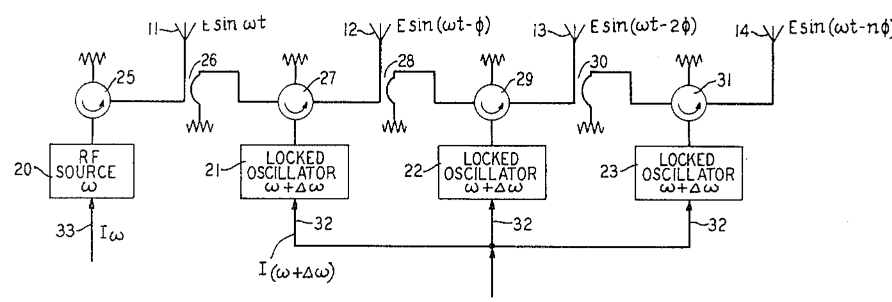
Primary Examiner—Rodney D. Bennett, Jr.
Assistant Examiner—Richard E. Berger
Attorney—R. J. Guenther and E. W. Adams, Jr.

[57] **ABSTRACT**

A phased array antenna system in which the phase of successive radiating elements is produced by a series of injection locked oscillators each driven by or locked to the signal fed to the preceding elements. Since the phase of an injection locked oscillator depends upon the difference between its natural frequency and its injected frequency, the array may be scanned either by varying the injected frequency or the natural frequency. IMPATT diode oscillators are preferred because of the ease with which they can be injection locked and/or varied in frequency.

7 Claims, 5 Drawing Figures



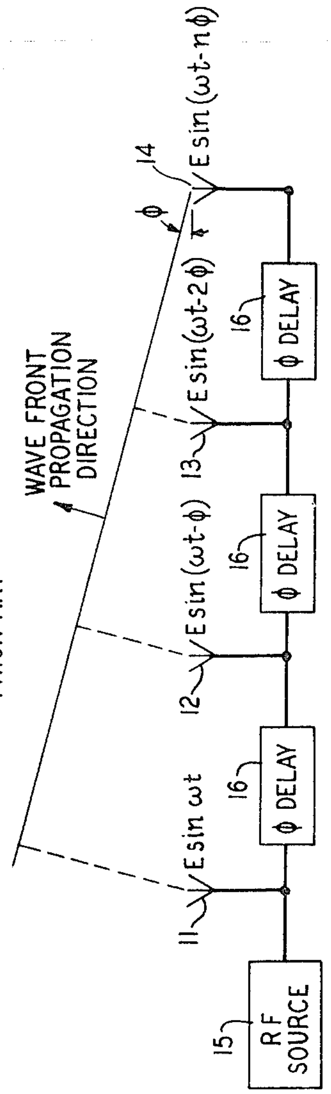


FIG. 1
PRIOR ART

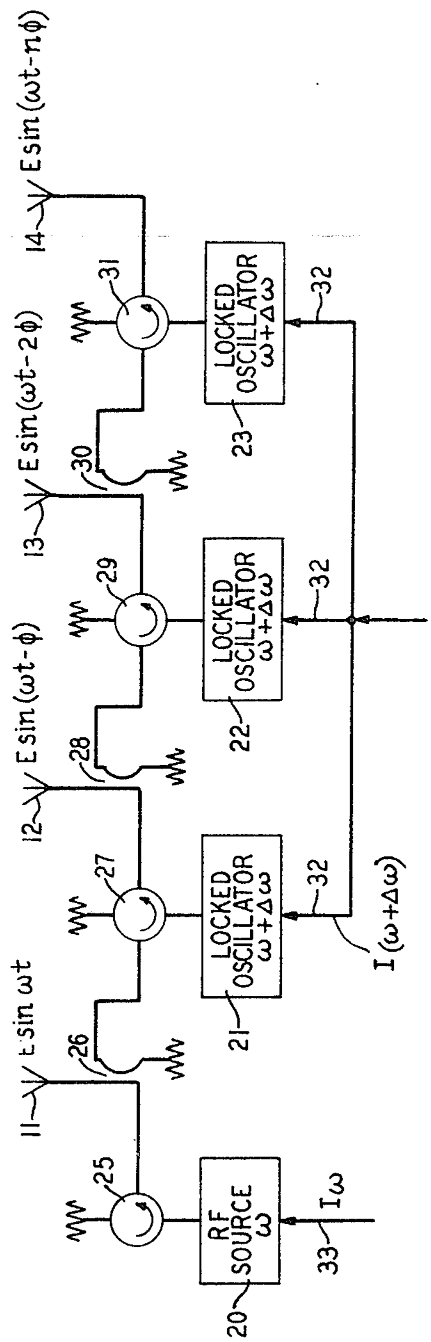


FIG. 2

INVENTOR
B. GLANCE
BY Roy M. Porter Jr.
ATTORNEY

FIG. 2A

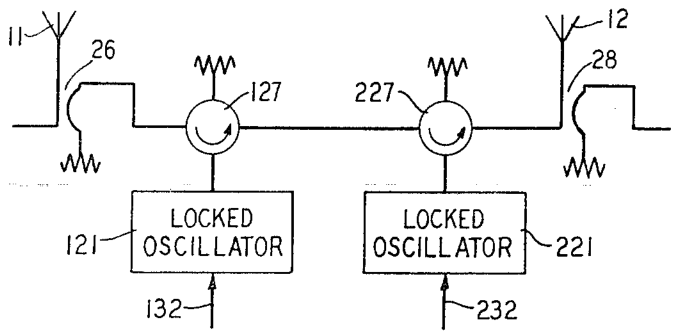


FIG. 3

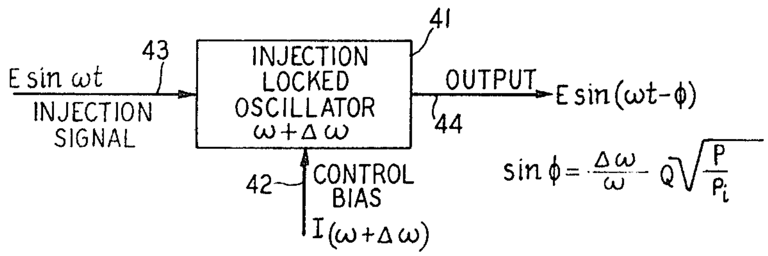
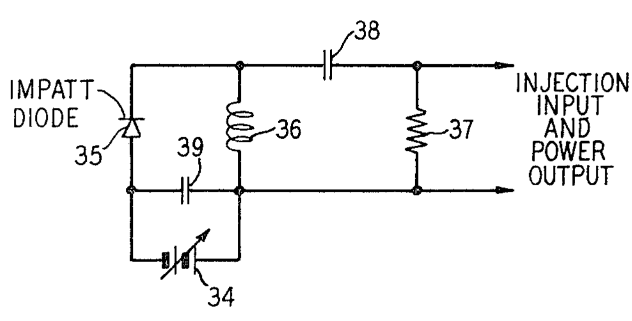


FIG. 4



ELECTRONICALLY SCANNED ANTENNA ARRAY

BACKGROUND OF THE INVENTION

This invention relates to electronically scanned antennas and, more particularly, to antennas of the type in which radiating elements of an array are excited in different phases so selected and varied with respect to each other to direct a beam in a desired direction.

The art is familiar with two certain forms of electronically scanned antenna arrays. The most common is the parallel fed array in which energy to be radiated from a common source is divided into portions and each portion is shifted in phase by an independent phase shifter before radiation by one element of the array. In order to scan, the phase shift introduced by each phase shifter must be changed simultaneously by a different amount related, however, by a precise mathematical relationship to the other introduced phase shifts. Thus, the phase shifters must be driven by a programmer, usually a computer, to control the phase shift of energy between the elements. The other form, which can be characterized by way of contrast as a series fed array, involves the use of a series of phase shifters each adding its own increment of shift to that of those preceding it in the series. Each element of the array is then fed from a point between adjacent phase shifters. In order to scan, each phase shifter is changed by the same amount which greatly simplifies the apparatus required to drive them. However, the problem of delivering sufficient power to the elements along the series and the problem of equalizing the power radiated by each element so that the last element in the array radiates a power equal to the power radiated by the first involve so many practical difficulties that little use has been made of series fed arrays.

SUMMARY OF THE INVENTION

In accordance with the present invention, a plurality of locked oscillators are employed in a new configuration that eliminates the disadvantages of both prior art systems, retains some of the advantages of each, yet most closely resembles the series fed system. The invention is based upon the recognition that the phase of the output from an injection locked oscillator depends upon the difference between its natural resonant frequency and the injected frequency. The signal radiated by successive elements of the array is produced by a series of injection locked oscillators each driven by or locked to a sample of the signal feeding the preceding radiating element. The power radiated by each element is that produced by each individual oscillator so that if the oscillators are the same, these powers are equal. The array may be scanned either by varying the injected frequency or the natural resonant frequency of the individual oscillators by varying whatever parameter controls the frequency of the particular oscillator form. In accordance with a preferred embodiment, IMPATT diode oscillators are employed because of their simplicity, the ease with which they can be injection locked, and the wide range over which their frequency may be varied by control of bias current. Directional couplers and circulators are used to derive a sample from the preceding radiating element for the succeeding oscillator and to provide a high degree of isolation therebetween.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram illustrating a scanning antenna arrangement in accordance with the prior art and is given for the purposes of explanation and comparison;

FIG. 2 is a block diagram illustrating an antenna scanning system in accordance with the invention;

FIG. 2A represents a modification of FIG. 2;

FIG. 3 is given for the purposes of explanation, and illustrates the properties of an injection locked oscillator as employed in the system of FIG. 1; and

FIG. 4 is a schematic of an IMPATT diode oscillator in accordance with a preferred embodiment of the invention.

DETAILED DESCRIPTION

Referring more particularly to FIG. 1, series fed array system according to the prior art is shown for the purpose of comparison. An array of equally spaced, nondirective radiating elements **11**, **12**, **13** and **14** is shown fed from a source of radio frequency energy **15**. Radiator **11** is fed by a signal E sin ωt having the same phase as that of source **15**, while each successive radiator is fed from the preceding one through a delay device **16** which adds a delay of ϕ so that the signals radiated by successive radiators are E sin $(\omega t - \phi)$, E sin $(\omega t - 2\phi)$, etc. Provided the radiating elements are identical, uniformly fed, and there is no interaction among them, it is known that the phase difference ϕ between adjacent elements, the spacing d between them and the steering angle θ determining the direction of propagation are related as

$$\phi = -(2\pi)/(\lambda)d \sin \theta \qquad 1$$

where λ is the wavelength. Varying ϕ in each delay device **16**, therefore, varies the direction of propagation. However, in a simple system such as FIG. 1, it is obvious that the elements are not uniformly fed and some provision is required to boost the power at subsequent elements relative to the earlier elements. While this would appear relatively easy when only a few radiators are involved, the problem becomes very complicated when there are many and the danger of power overload to components early in the series is serious.

Referring now to FIG. 2 successive radiating elements **12**, **13** and **14** are each fed in accordance with the invention by respective injection locked oscillators **21**, **22** and **23**, each of which has the properties to be described hereinafter with reference to FIG. 3. As in FIG. 1, the first radiating element **11** is driven by radio frequency source **20** having an angular frequency ω, preferably through a terminated circulator **25** providing isolation of source **20** from any reflections. A portion of the signal from source **20** as supplied to radiating element **11** is sampled by any suitable means such as directional coupler **26** having its sampling path connected to a circulator **27**. The output of oscillator **21** is directed by circulator **27** to radiating element **12** and any reflections are dissipated in the terminated fourth port of circulator **27**. Thus, circulator **27** serves to separate and isolate the injection signal and the output signal of oscillator **21** and to isolate adjacent radiating elements. Similarly, directional couplers **28** and **30** and circulators **29** and **31** are similarly respectively associated with oscillators **22** and **23** and radiating elements **13** and **14**.

The neutral resonant frequency of oscillators **21**, **22** and **23** is controlled by appropriate information fed to them by connections **32**. For the purpose of explanation it is assumed that the controlling information is in the form of a bias current. Thus, in accordance with the invention these currents designated $I_{(\omega+\Delta\omega)}$ are adjusted to produce a free running frequency for oscillators **21**, **22** and **23** different by the frequency $\Delta\omega$ from the frequency ω of source **20**. It will be apparent that this difference may be either positive or negative.

Referring now to FIG. 3, the properties of injection locked oscillators **21**, **22** and **23** in accordance with the invention are illustrated. Block **41** represents any one of these oscillators and may be of any type having a free running frequency which can be controlled either electrically or mechanically and which is also capable of being synchronized or locked by a further signal applied to it having a frequency different from but within what is referred to as the "locking range" of the free running frequency. For this purpose oscillator **41** may be a transistor or a vacuum tube oscillator, a reflex klystron, a backward travelling wave tube oscillator or a magnetron. It may also be any one of the more recently developed oscillators employing solid state diodes. In accordance with the preferred embodiment of the invention, oscillator **41** may be one employing an IMPATT (Impact Avalanche And Transit Time) diode as described in the paper "The IMPATT Diode—A solid State Microwave Generator", 45 Bell Laboratories Record 144, May 1967 or in the copending application of B. C. De Loach, Jr. Et al., Ser. No. 883,898, filed Dec. 10, 1969 or in my copending application, Ser. No. 812,041, filed Apr. 1, 1969. Such an oscillator has a natural resonant frequency determined by the bias current through the diode as represented by the current $I_{(\omega+\Delta\omega)}$ supplied over input 42. When the oscillator is synchronized by an injection signal E sin ωt as supplied over input 43, the output 44 will comprise a signal having the same frequency ω as the injection signal but displaced therefrom by a phase ϕ which depends directly upon $\Delta\omega$ according to the relation

$$\sin \varphi=\frac{\Delta\omega}{\omega}Q\sqrt{\frac{P}{P_i}} \qquad (2)$$

where Q is the external circuit Q of the oscillator, P_i is the injected power and P is the output power of the oscillator. Thus, changing the magnitude of the bias current to the oscillator has the effect of shifting the phase of the generated signal relative to the injected signal.

FIG. 4 shows the schematic of one particular form of IMPATT diode oscillator having the properties described in FIG. 3. IMPATT diode 35 when biased into its negative resistance region by bias source 34 is equivalent to a varactor having a capacitance C in parallel with a negative resistance −R. If inductance 36 of value L and the load (represented by resistor 37 and having a value equal to −R) are added in parallel with each other across diode 35 an oscillator is formed having a natural resonant frequency equal to

$$\frac{\pi}{2}\sqrt{LC}$$

If load 37 is not inherently of the proper value, the coupling capacitor 38 may be added to transform the load resistance seen by the diode with very little effect on the frequency of the oscillator. Capacitor 39 represents the required decoupling circuit between bias source 34 and the radio frequency circuit. Both the injected signal input for locking as well as the power output appear across resistor 37; thus the need for the decoupling properties of the circulators as shown in FIG. 2. Varying the magnitude of the bias from source 34 changes the value of capacitance C and thus the natural resonant frequency of the oscillator.

In terms of the parameters defined above, the maximum variation of $\Delta\omega$ either above or below the locking frequency permitted in accordance with the invention is defined

$$\Delta\omega_{max}=\frac{\omega}{Q}\sqrt{\frac{P_i}{P_o}}$$

The full range or two times equation (3) is known as the locking range of the oscillator. Oscillator diode 35 should be biased at saturation in order to avoid power variation with bias current change. In FIG. 2, therefore, the successive oscillators produce outputs E sin (ωt −ϕ), E sin (ωt −2ϕ), etc. as required for directivity. Since each oscillator in effect amplifies and shifts the phase of its locking signal, power is continuously replaced along the series. Stated in a different way, each oscillator independently supplies the power for its own radiator much like a parallel fed array in addition to a locking signal for the next oscillator like the series fed array thereby overcoming the primary disadvantage of both forms of the prior art.

Scanning may be accomplished by varying the bias current $I_{(\omega+\Delta\omega)}$ to all oscillators 21 through 23, simultaneously, while the first oscillator 20 operates at a fixed frequency ω. This causes ϕ to vary simultaneously in all outputs thus maintaining the proper ratio of the phases between the radiating elements. Alternatively, the control current I_ω on lead 33 to the first oscillator 20 may be varied while holding the free running frequency of the subsequent oscillators 21, 22 and 23 constant. While this varies ϕ, $\Delta\omega$ is varied in much larger proportion and, so long as the variation is restricted to the range of locking, ϕ through each subsequent oscillator is varied. Thus, scanning is accomplished by a control applied only to the first oscillator 20.

Apart from the restriction on locking range, it should be noted that the maximum phase shift ϕ obtained through one locked oscillator stage is $\pm\pi/2$. However, a plurality of stages may be cascaded as shown in FIG. 2A to increase the phase shift as required. Thus, between any two radiating elements such as 11 and 12, two oscillators 121 and 221 are included to replace oscillator 21 of FIG. 2 and to produce a total phase shift of $\pm\pi$. Any number may be included but two is sufficient for the usual application. Oscillators 121 and 221 are coupled in cascade by circulators 127 and 227, replacing circulator 27 of FIG. 2. Thus, the power from oscillator 121, shifted in phase from its locking signal, is fed as the locking signal to oscillator 221 which adds an additional phase shift before the power is delivered to radiating element 12. The oscillators may or may not have the same natural resonant frequencies as determined by the bias applied to the respective inputs 132 and 232. It is, however, preferred that the first oscillator in the chain operate at a much lower power than the following to obtain a power ratio consistent with that as set forth in Equation (2) above.

The preceding description treats the invention in terms of a transmitted, unmodulated signal as might be found in radar. It should be clear, however, that if it is required to introduce modulation onto the scanned beam, any appropriate form of modulator may be inserted in series with each radiating element so that each oscillator becomes the local power source for its particular modulator.

In all cases it is understood the above-described arrangement is merely illustrative of a possible application of the principles of the invention. Numerous and varied other arrangements in accordance with these principles can readily be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. High frequency directional apparatus comprising a plurality of radiators arranged in a linear array,
   means for feeding a first of said radiators with high frequency wave energy of given frequency,
   a plurality of oscillator means one each associated with each of the remainder of said radiators and each having a natural resonant frequency different by a given amount from said given frequency,
   and means for driving each successive one of said oscillators with a sample of the signal fed to the one of said radiators preceding the radiator with which that one oscillator is associated.

2. High frequency directional apparatus comprising a plurality of antenna elements arranged in a linear array,
   means for feeding a first of said elements with high frequency wave energy of given frequency,
   a plurality of oscillator means one each associated with each of the remainder of said elements and each capable of being locked to the frequency of said energy applied to said first element when said frequency is different from the natural resonant frequency of that oscillator,
   and means for locking each successive one of said oscillators to the signal fed to the one of said elements preceding the element with which that one oscillator is associated.

3. The apparatus according to claim 2 wherein each of said plurality of oscillator means includes means for varying said natural resonant frequency over a range including frequencies slightly different from the frequency of energy applied to said first element.

4. The apparatus according to claim 2 wherein said means for feeding said first element includes means for varying the frequency of said wave energy within the locking range of said plurality of oscillators

5. The apparatus of claim 2 wherein each of said oscillators is a negative resistance oscillator of the IMPATT diode type and wherein each is connected to one of said antenna elements through a circulator.

6. The apparatus of claim 5 including means for supplying a bias to said diode to set said natural resonant frequency of said

oscillator at a frequency different from said frequency of said energy applied to said first element.

7. In combination, a plurality of antenna elements arranged in a linear array,

a plurality of negative resistance oscillators, one each associated with each of said elements,

means for locking each successive one of said oscillators to

the signal fed to the one of said elements preceding the element with which that one oscillator is associated and for producing an output from said one oscillator that is shifted in phase from the signal fed to said one elements,

and means for applying said output to that element associated with said one oscillator.

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