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Wright

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[54] **AMPLITUDE MODULATION USING PHASED-ARRAY ANTENNAS**

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[52] **U.S. Cl.** .... **343/100 SA,** 343/854

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

[58] **Field of Search** .... 343/100 SA, 854; 325/160

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[57] **ABSTRACT**

An antenna system for producing an amplitude modulated signal at a receiver by properly varying the spatial amplitude distribution of the antenna beam. The antenna beam variation is accomplished by varying the relative phase of a phase-array antenna at the desired modulation rate. A variable DC bias signal is applied to each element of the antenna which is used to steer the beam in angle. An AC signal is also applied to each element which will qppear as AM modulation at a distant receiver.

9 Claims, 7 Drawing Figures

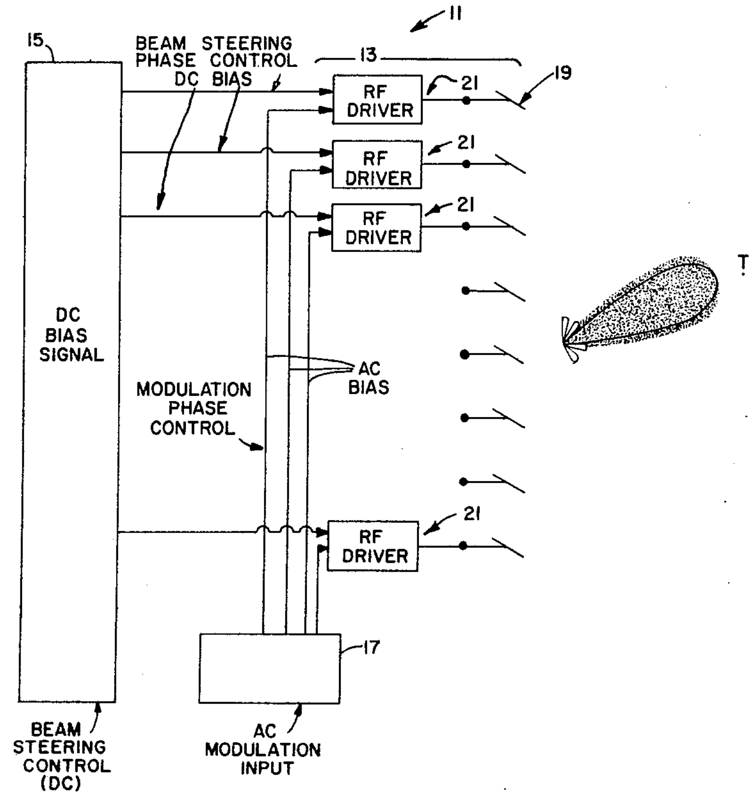


FIG _ 1

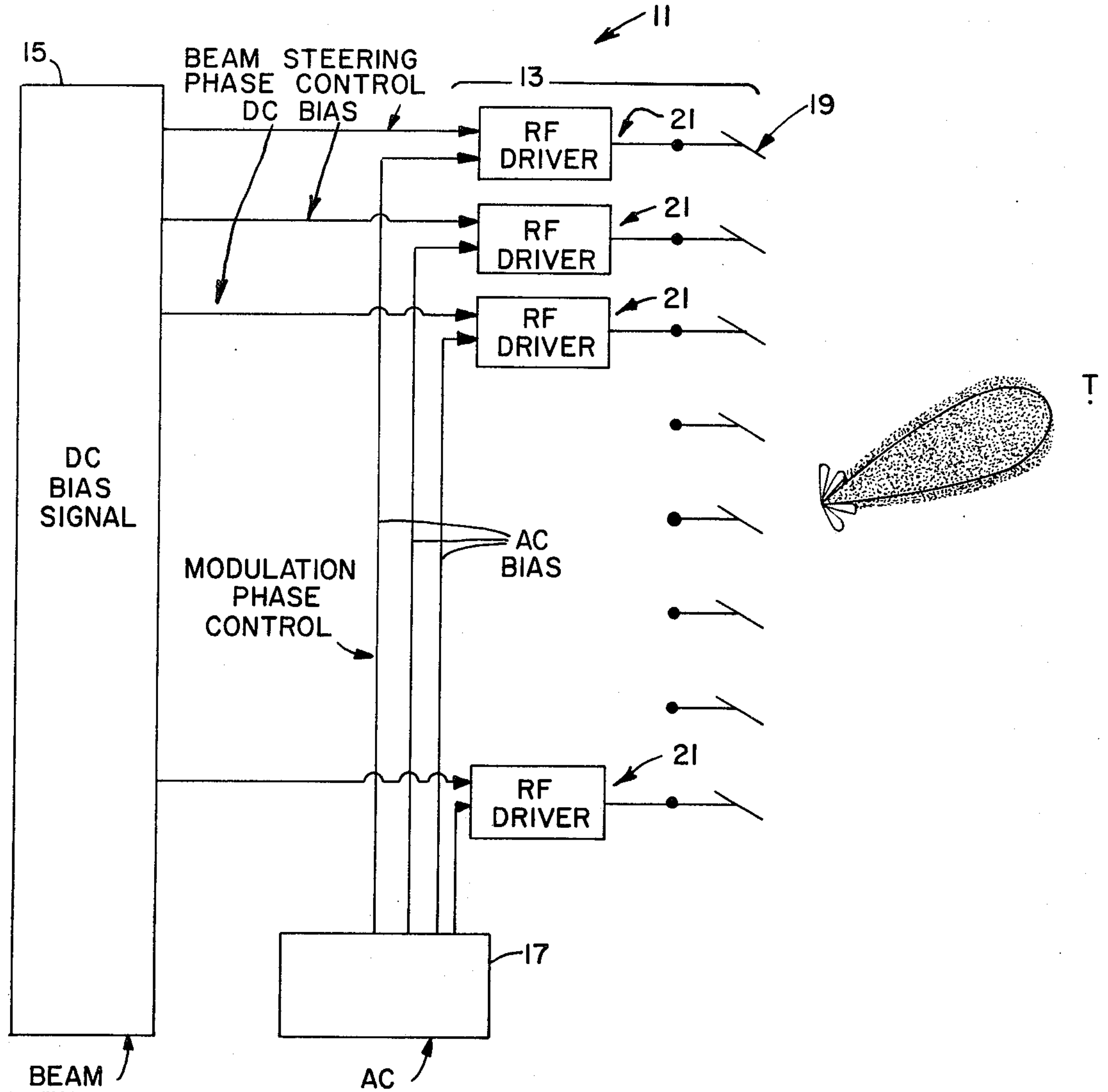


FIG _ 1a

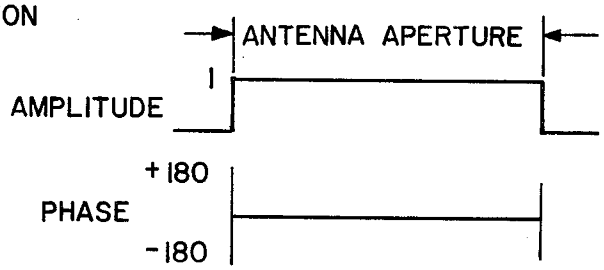


FIG _ 1b

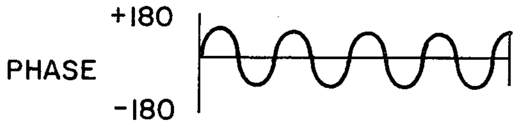


FIG_2

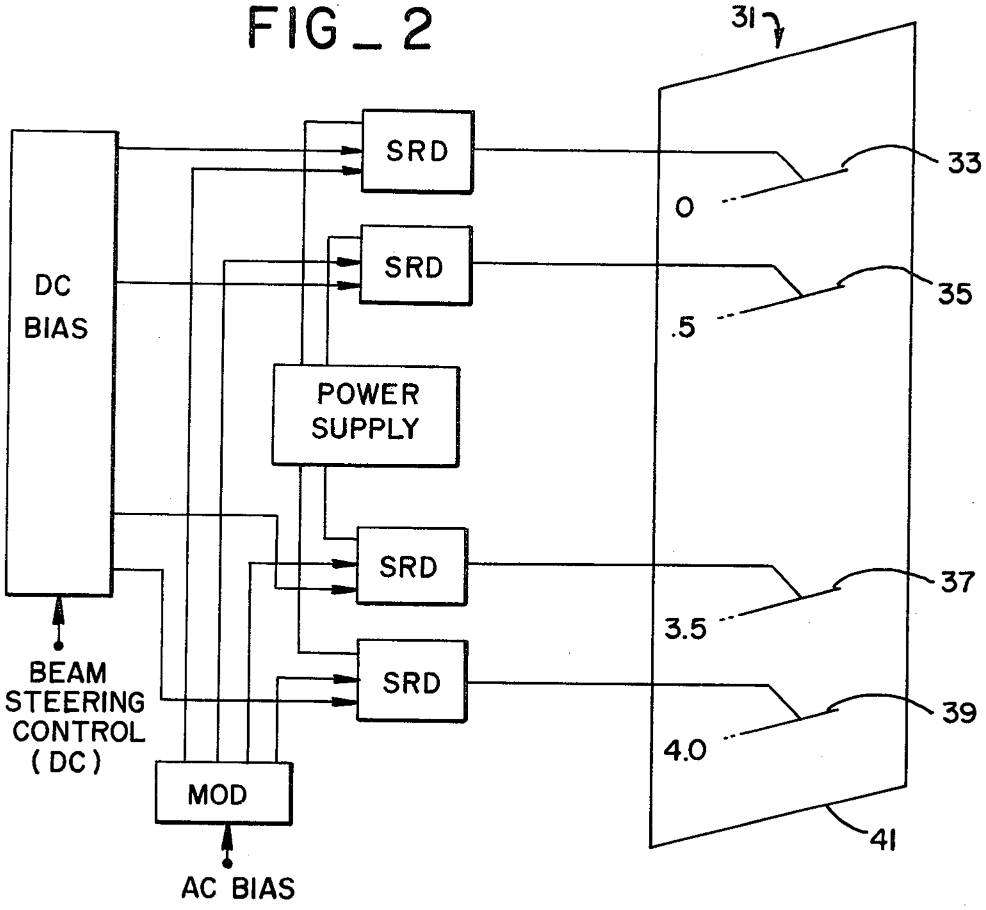


FIG_3a

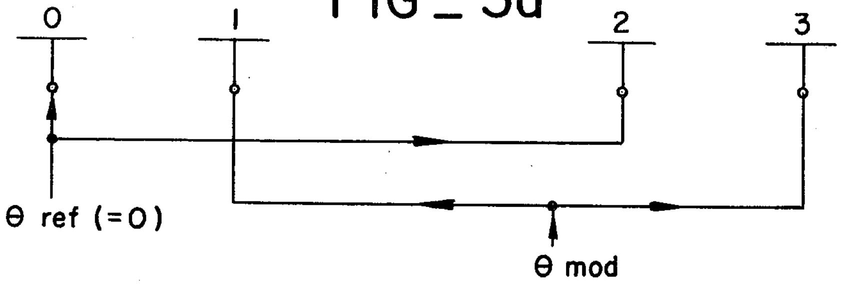


FIG_3b

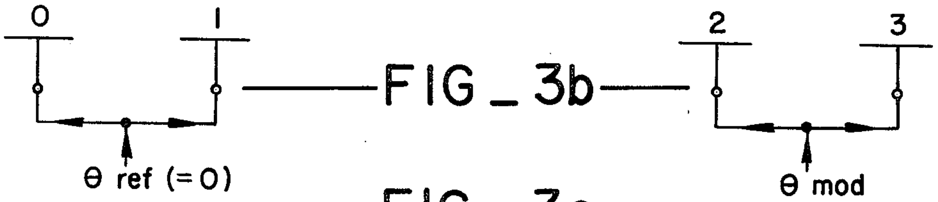
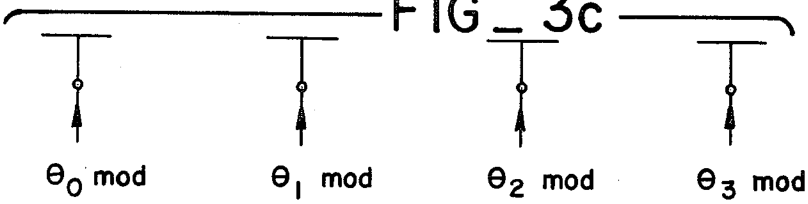


FIG_3c



AMPLITUDE MODULATION USING PHASED-ARRAY ANTENNAS

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates generally to an antenna system for producing an amplitude modulated signal at a receiver and more particularly to an antenna system which will produce an amplitude modulated signal at a receiver by varying the spatial amplitude distribution of the antenna beam.

2. Description of the Prior Art.

Prior Antenna systems required separate AM modulations which subsequently required a complicated RF source. This virtually eliminated the use of AM modulation from specialized systems such as ECM systems which use phased array antennas.

SUMMARY OF THE INVENTION

Briefly, the present invention comprises an antenna system for producing an amplitude modulated signal at a receiver by properly varying the spatial amplitude distribution of the antenna beam. The antenna beam variation is accomplished by varying the relative phase of a phase-array antenna at the desired modulation rate. A variable DC bias signal is applied to each element of the antenna which is used to steer the beam in angle. An AC signal is also applied to each element which will appear as AM modulation at a distant receiver.

The advantage provided by this unique method and device, which is the subject matter of the present invention, is that a carrier wave (CW) drive can be used for the antenna RF source. This greatly simplifies the source and allows the driver to be operated in the more efficient saturated amplified mode. Moreover, no separate AM modulator is required because beam steering capability is already present in most phased-array antennas at the present time. AM modulation is not used in ECM systems because of the difficulties mentioned above; this new and unique system would allow desirable AM modulators to be employed with the present high efficiency components.

STATEMENTS OF THE OBJECTS OF INVENTION

A primary object of the present invention is to produce an amplitude modulated signal at a receiver by varying the spatial amplitude distribution of an antenna beam.

Another object of the present invention is to provide a device which amplifies the RF source and allows the driver of the system to be operated with a higher average power output.

Another object of the present invention is to provide a device to produce an amplitude modulated signal at a receiver without a separate AM modulator and provide a continuous amplitude-modulated multiple target coverage without wasting power.

Another object of the present invention is to provide a device which allows all of the RF hardware in the phased-array antenna to operate on a continuous full-power basis.

Other objects and features will be apparent from the following descriptions of the invention and from the accompanying drawings wherein:

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic diagram of the amplitude modulated phased-array antenna system;

FIG. **1***a* is the amplitude modulation and phase excitation waveform for a standard antenna array system;

FIG. **1***b* is an example of a phase print function generated from the amplitude modulated phased-array antenna system illustrated in FIG. **1**;

FIG. **2** is a schematic diagram of a four element array antenna system;

FIG. **3***a* is a schematic illustration of the four element phased-array antenna illustrated in FIG. **2**, in the beam steering mode;

FIG. **3***b* is a schematic illustration of the four element phased-array antenna illustrated in FIG. **2**, with a bias signal applied to the third and fourth element; and

FIG. **3***c* is a schematic diagram of the four element array illustrated in FIG. **2**, simulating a large aperture operation function.

Referring to FIG. **1**, the amplitude modulated antenna system **11** comprises a phased-array antenna system **13**, a beam steering control **15** and a modulation phase control device **17**. The phased array antenna system **13** further comprises a plurality of antenna elements **19** and a plurality of RF drivers **21** operatively connected to each element of the plurality of antenna elements **19**. The drivers are used to generate the RF signal to each antenna. Each RF driver **21** contains its own individual phase-shifting elements, either digital or analog. Moreover, each of the drivers is connected to a single antenna element. This portion of the antenna system is similar to most phased-array antennas as presently configured. The unique difference of the present system is the utilization of the spatially selective amplitude modulator (SPASAM) technique, hereinafter referred to as SPASAM, for control of the phase for each of the RF driver elements. A conventional phased-array antenna is intended to form a sharp beam as illustrated by the solid line in FIG. **1** and is able to steer or point the beam in the direction of target T. This aforementioned function is accomplished by driving the ensemble of RF driver elements **21** with a linear phase gradient across the antenna aperture. The signal set, required to accomplish this, is generated by the beam steering control **15**. The beam steering control **15** generates a plurality of individual DC bias outputs which are individually applied to each RF driver. The beam steering control **15** accepts a single input DC signal and specifies the direction that the beam should be pointed and subsequently generates a DC bias signal for each of the RF driver elements of the plurality of RF driver elements **21** which will shift the phase appropriately to form and point the beam in the desired direction. In most phased-arrays the antenna pattern remains nearly constant as the beam is steered to different points in space, or when modulation is applied to the RF going through the antenna. However, when spatial modulation circuitry is used, a different function results, which hereinafter will be described. The modulation phase control device **17** has a single modulation input. The input is an AC signal which can be generated by an oscillator circuit or any similar device. The modulation control device **17** then generates an appropriate modulation phase control signal or AC bias for each of the RF driver elements. The aforementioned AC and DC bias signals are generated simultaneously. This second set of phase control or bias signals allows the antenna pattern to be changed in both space and time according to the applications of the particular system. The modulated beam is illustrated by the shaded portion in FIG. 1 so that the distant target T will, at any point within this shaded beam, receive an amplitude modulated signal.

There are two broad categories of amplitude modulation generation which can be used with the amplitude modulated antenna system. The first is the beam-steering mode and the second is the unique SPASAM technique.

Referring again to FIG. **1**, assume that the beam steering control is forming and pointing the beam shown by the solid block line toward a distant target T. This function is usually accomplished by a constant phase difference between each of the adjacent RF driver elements **21.**

Modulation is generated on the antenna beam by applying a set of modulation phase-control signals to each of the RF driver elements **21.** In this case, the signal applied to each RF driver element is moderately small compared to the signal being applied to the beam-steering control and thus results in only a small perturbation of the phase of each RF driver element. If, in addition, the modulator phase control signals are applied in the same uniform phase difference pattern as the beam steering control signals, then the spatial power pattern for the antenna **19** will remain constant as a function of time. However, the position of the entire pattern will move in space at the modulation rate. This is called the beam-steering mode because the antenna power pattern remains constant in a well formed beam as a function of time. Moreover, it has been found that the relative amplitude modulation of signals will vary as the position of the receiver varies in space.

The spatially selective amplitude modulation technique or SPASAM includes all the modes of operation that are possible in which the antenna beam shape is not constant as a function of time. Using the SPASAM technique, the antenna may be made to operate as a linear amplitude modulator in which the waveform is identical to that of the modulation signal input, or it is possible to produce signals which have waveforms different from the modulation signal.

To facilitate the understanding of the SPASAM technique, a discussion of the general theory is necessary.

The antenna of any phased-array system **21** is generally specified by an amplitude and a phase function across the antenna aperture, as illustrated in FIG. **1***a*. A constant amplitude of unity with no relative phase shift across the aperture is indicated. This relationship would produce the familiar sin *x*/*x* distribution from a phased-array antenna with the beam pointed on the broadside. If the phase variation is made linear across the aperture with a constant slope the sin *x*/*x* pattern will remain, but the antenna beam will now be pointed in a different direction in space. In the SPASAM function the phase function does not vary linearly across the aperture. This has the effect of producing a different antenna pattern as the phase pattern across the aperture is changed. This additional phase variation across the aperture will be called, for various technical reasons, the phase print function for the SPASAM technique. FIG. **1***b* shows an example of a phase print function consisting of 4¼ cycles of sinusoidal phase variation across the antenna aperture. It has been found that the phase print exists only for a certain instant in time and will be a complex function of time. The set of phase print functions over a time T will be called the modulation excitation function. In order to facilitate the description of the many types of operations that are possible in SPASAM, different classes of modulation excitation functions have been generally identified by class of operation. A summary of these classes are illustrated in Table I, and a description of the various classes of modulation excitation functions will follow.

TABLE I

CLASSES OF MODULATION EXCITATION FUNCTIONS

Class	Power Pattern Stays the Same	Zero Phase Shift at Modulation Frequency	Sinusoidal Excitation Time-Waveform
1	Yes	Yes	Yes
2	No	Yes	Yes
3	No	No	Yes
4	No	Yes	No
5	No	No	No
6	No	No	No
7	No	No	No

Class	Same Time-Waveform at Each Element	Same Fourier Fundamental Frequency
1	Yes	Yes
2	Yes	Yes
3	Yes	Yes
4	Yes	Yes
5	Yes	Yes
6	No	Yes
7	No	No

As stated previously, the set of phase print functions over a Time T will define the modulation excitation function. Of the seven classes of modulation excitation functions that will be described, only the first, Class **1**, does not generate SPASAM. The description of these seven classes in Table I is as follows:

The identifying characteristic of the first class of modulation signals is that the radiation power pattern shape is kept constant in time. The driving signals from the RF drivers **21** may be quasistatic or may be a modulation signal that corresponds to the beam-steering mode of amplitude modulation, or a combination of the two. The phase print for this class is the same as the phase pattern used to steer the beam. See FIG. **1***a*.

The second class of modulation excitation function is more complex than class one, but is the simplest form of SPASAM because the radiation power pattern changes as a function of time. The phase print function is not the same as the steering phase pattern. The signal applied to each RF phase shifter has the same time waveform and differs only in magnitude. That is, the signal applied to one phase shifter will be different by a scale factor from the signal applied to another phase shifter.

It has been found by experimentation, in class three, that the modulation excitation function $f(t)$ is a sinusoidal function. The frequency of this $f(t)$ is the modulating frequency. For example, if the $f(t)$ for element **1** of the antenna is lagging, the $f(t)$ for element **2** of the antenna by some number of degrees by some number of degrees, this fact can be expressed as a phase shift by some number of degrees at the modulation frequency between element **1** and element **2.** This phase shift at the modulation frequency forms the basis for this class. The modulation excitation function in which the signal to each RF driver has the same frequency and the same peak amplitude, but a different phase shift at the same modulation frequency is exemplified by this class.

The fourth class forms a nonsinusoidal, but periodic, time waveform. This class has the same restrictions as class two, but now $f(t)$ can be any nonsinusoidal, nonlinear, but periodic function. The period for all antenna element modulation signals must be the same. In this instance, it is desirable to decompose the signal waveform into its Fourier components.

Class five allows a phase shift at the modulation frequency, as explained in class three, to occur for the same conditions as class four.

In class six a different time waveform is applied to each of the RF phase shifters. Again, however, the time waveform is restricted to having the same fundamental Fourier period from element to element, but the amplitude and phase of any or all of the components are allowed to vary from point to point. In class seven the waveform applied to each of the RF elements is different and the difference is due to a different fundamental Fourier component of the modulation signal. This set of modulation signals is approaching the maximum decorrelation of the signal from antenna element to antenna element and results in a spatially complex transmitted signal from the antenna. The limit of this example would necessarily be uncorrelated noise applied to each of the RF phase shifters.

Thus, by varying the AC and DC bias signals generated by the beam-steering control **15** and the modulation phase control **17**, we can develop the various classes of modulation excitation functions, illustrated in Table I, and respective phase print function signals, illustrated in FIG. 1*b*.

In many applications it is required that the antenna form and point beams to more than one point in space simultaneously in order to illuminate multiple targets. It has been found that the SPASAM technique allows this, and in addition, will permit each of the beams to produce the desired broadside AM signal at the target. The first class, illustrated in Table I, can perform the aforementioned function. In this case the signals driving the RF phase shifters all have the same time waveform. It should be noted that this is not beam-steering modulation. The static pattern is not being swept back and forth. The beams at the desired location are made to grow and shrink by means of a time-modulated phase print function; that is, a modulation excitation function. Power taken out of the main beam is put into modulated beams to produce these types of signals.

The classes two through seven may be used for modulation excitation functions and the multiple target problem. This group of modulation excitation functions allows a trade-off between maximum peak power and multiple target efficiency, and it is the simplest of the group of modulating functions compatible with a multiple target environment.

An example of an embodiment of the present invention, which has been found to be quite satisfactory, is illustrated in FIG. **2**.

Referring to FIG. **2**, an amplitude modulated signal is produced at the receiver by properly varying the signal to the relative element phases in a phased-array antenna at the desired modulation rate. The antenna system **31** comprises a linear array of four elements **33, 35, 37,** and **39** with non-uniform spacing and single large reflecting plane **41.** The four elements **33, 35, 37,** and **39** are individual dipole elements. The antenna beam variation is accomplished by varying the relative phases of the phase-array antenna **31.** The phase of the 3GHZ constant signal from each element can be individually voltage controlled. However, it should be noted that any method of individually controlling of each element is workable. Applied to each antenna element **33, 35, 37,** and **39** is a variable DC bias signal which is used to steer the beam in angle and an AC signal which will appear as AM modulation at a distant receiver. The array **31** may be driven by a single RF oscillator and power divider, or other similar devices.

More specifically, elements **33** and **35** are each paired and spaced by a ½ wavelength and the other two elements **37** and **39** are separated by ½ wavelengths. Element **33** is spaced 3½ wavelengths from element **37.** This spacing is chosen only to illustrate a point and not necessarily for operation. This particular configuration simulates a single antenna which is filled in over the entire four wavelength aperture. The reflecting plane **41** may be constructed of copper or an equivalent metal with similar electrical characteristics. A step recovery diode (SRD), or any similar frequency multiplier, can be used for the generation of S-band signals and the phase-shifter. Each element should be adjusted to have a voltage standing wave ratio (VSWR) of less than about 1.05 at an operating frequency of about 3 Ge. Each element is fed by a step recovery diode module (srd) that can supply about several milliwatts of power. The four step recovery diode (SRD) modules in turn are supplied from a two-watt oscillator or amplifier, as the case may be, and a four-way power divider. A bias supply feeds each module to allow for the individual and simultaneous application of DC bias, AC bias and beam-steering to each of the antenna elements **33, 35, 37, 39.** The antenna **31** may be operated over a relatively narrow phase-shift range or a wide phase-shift range, or as desired. The beam can be adjusted manually or automatically, again as desired. It should be noted that the major difference between the unique AM generation technique, which is the subject matter of the present invention, and conventional phased-array antenna techniques lies not in the hardware but in how the hardware is used.

Two classes of modulated phased-array antenna patterns with relationship to the four element array can be identified: The first involves the generation of a fixed antenna pattern shape which is moved about in space over a relatively small angle by using a suitable modulation input to the phase-shifter of the antenna. This operation is called the beam-steering mode because the general shape of the antenna beam remains fixed as it is moved or steered by the modulator or modulating signal. The second class is much more versatile and more complex; this is called spatially selective amplitude modulation (SPASAM). In this mode the entire static antenna pattern is modulated so that a new antenna pattern will appear at each instant of time as the modulation signal which is varied through its entire range. This complex modulation transfer function of the antenna can be determined in terms of static antenna-pattern measurements and will be described in conjunction with the discussion of the beam-steering mode function.

Referring to FIGS. **3***a*, **3***b*, and **3***c*, terms ϕ_o through ϕ_3 define the phase contribution of the physical spacing of each element of the antenna and is a function of the spatial angle. The terms ϕ also include DC phase shifts introduced to steer the antenna beam in space. The deviation ϕ_o through ϕ_3 represents only those contributions caused by the AC modulating signal applied to the antenna. Two cooperating phased-arrays can be simulated by driving ϕ and ϕ_3 with an identical DC bias signal for steering and allowing ϕ and ϕ_3 to be identical and ϕ and ϕ_2 to be zero; this would simulate two cooperating phased-arrays, each operated in the beam-steering mode as illustrated in FIG. **2.** A single large antenna can be simulated for modulation purposes by driving ϕ_o through ϕ_3 with the proper bias and allowing ϕ_2 and ϕ_3 to be equal and ϕ_o and ϕ_1 to be zero. This full-size antenna simulation demonstrates the beam-steering mode.

The large aperture simulation for the general modulation transfer function mode can be simulated by allowing ϕ_o through ϕ_3 to assume any desired set of non-zero values and to be whatever phase functions that are necessary to shape the beam and to steer it in the desired direction. The unique antenna transfer function device can produce spectra that are similar to an AM suppressed carrier signal.

It should be noted that the SRD phase-shifters used in the four element array, illustrated in FIG. **2,** can be used as the phase-shifters in the multiple element array illustrated in FIG. **1.**

Many different beam modulation techniques are possible. Beam position, beam shape and the number of beams all can be changed to produce modulation.

What is claimed is:

1. An amplitude modulated phased-array antenna system comprising:

a. a plurality of antenna elements forming an aperture;
b. said plurality of antenna elements each having phase shifting device connected thereto;
c. a means for steering a radio beam operatively connected to each of said phase-shifting device said beam steering means supplying a beam-steering signal to each one of the said plurality of antenna elements; and
d. a means for generating a space-time variable non-linear phase function signal across the aperture of said plurality of antenna elements.

2. The device recited in claim **1** wherein said beam-steering means is a DC bias signal means.

3. The device recited in claim **1** wherein said means for generating a space time variable non-linear phase function is a modulator to generate a selected modulated phase control signal to each of said phase shifting devices simultaneously with the application of said beam-steering signal.

4. The device recited in claim **3** wherein each of said selected modulated phase control signals are AC signals with the same time waveform.

5. The device recited in claim **3** wherein the generated beams of energy from each one of a plurality of antenna elements are varied by varying means for generating a space time variable non-linear phase function signal over a period of time.

6. The device recited in claim **1** wherein said plurality of antenna elements of the phased-array antenna system comprises:

a. a first antenna element;
b. a second antenna element;
c. a third antenna element;
d. a fourth antenna element; and
e. each of said antenna elements being non-uniformally spaced along a reflecting means.

7. The device recited in claim **6** wherein the system further includes a RF signal generating means operatively connected to each one of said antenna elements to supply an output signal to each of said antenna elements.

8. The device recited in claim **7** wherein said RF signal generating means further comprises a means for generating beam-steering control and a means for controlling the modulation phase simultaneously to each one of said first, second, third, and fourth antenna elements located on said reflecting means wherein said DC signal provides a beam-steering signal to each one of said antenna elements.

9. The device recited in claim **8** wherein each of said antenna elements is a dipole element wherein said second antenna element is spaced one-half a wave-length from said first antenna element wherein said first antenna element is spaced three and one-half wavelengths from said third antenna element and four wavelengths from said fourth antenna element.

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