NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546

November 6, 1970

REPLY TO
ATTN OF: GP

TO: USI/Scientific & Technical Information Division
Attention: Miss Winnie M. Morgan

FROM: GP/Office of Assistant General Counsel for
Patent Matters

SUBJECT: Announcement of NASA-Owned U. S. Patents in STAR

In accordance with the procedures agreed upon by Code GP and Code USI, the attached NASA-owned U. S. Patent is being forwarded for abstracting and announcement in NASA STAR.

The following information is provided:

U. S. Patent No. : 3,501,764

Government or Corporate Employee : U.S. Government

Supplementary Corporate Source (if applicable) : N/A

NASA Patent Case No. : ERC-10046

NOTE - If this patent covers an invention made by a corporate employee of a NASA Contractor, the following is applicable:
Yes ☐ No ☒

Pursuant to Section 305(a) of the National Aeronautics and Space Act, the name of the Administrator of NASA appears on the first page of the patent; however, the name of the actual inventor (author) appears at the heading of Column No. 1 of the Specification, following the words ". . . with respect to an invention of N/A."

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Enclosure
Copy of Patent cited above

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March 17, 1970 R. J. MAILLOUX ET AL **3,501,764**

ARRAY PHASING DEVICE

Filed Jan. 24, 1969 4 Sheets-Sheet 1

N71-18722 4070

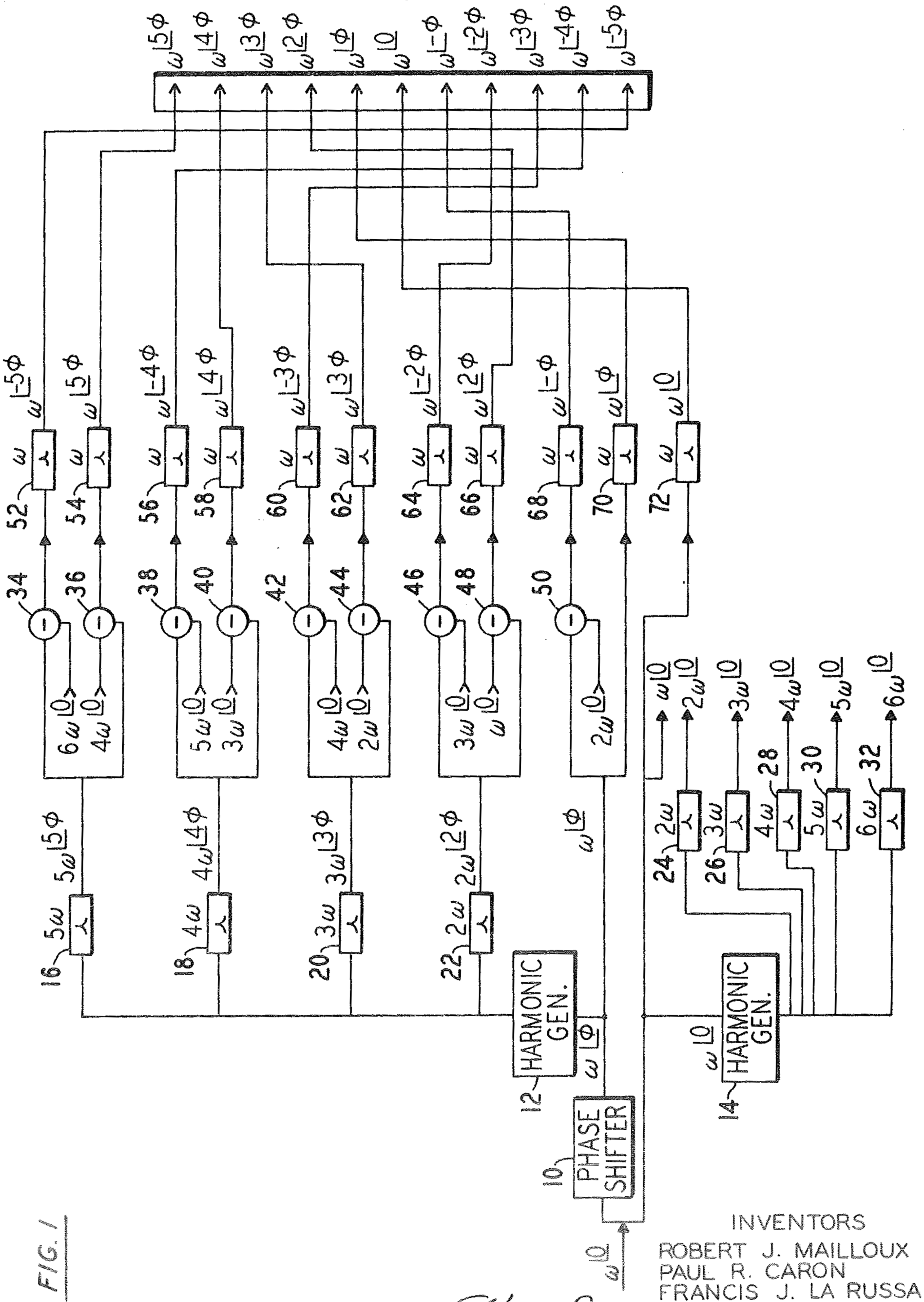

FIG. 1

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1099

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FIG. 2

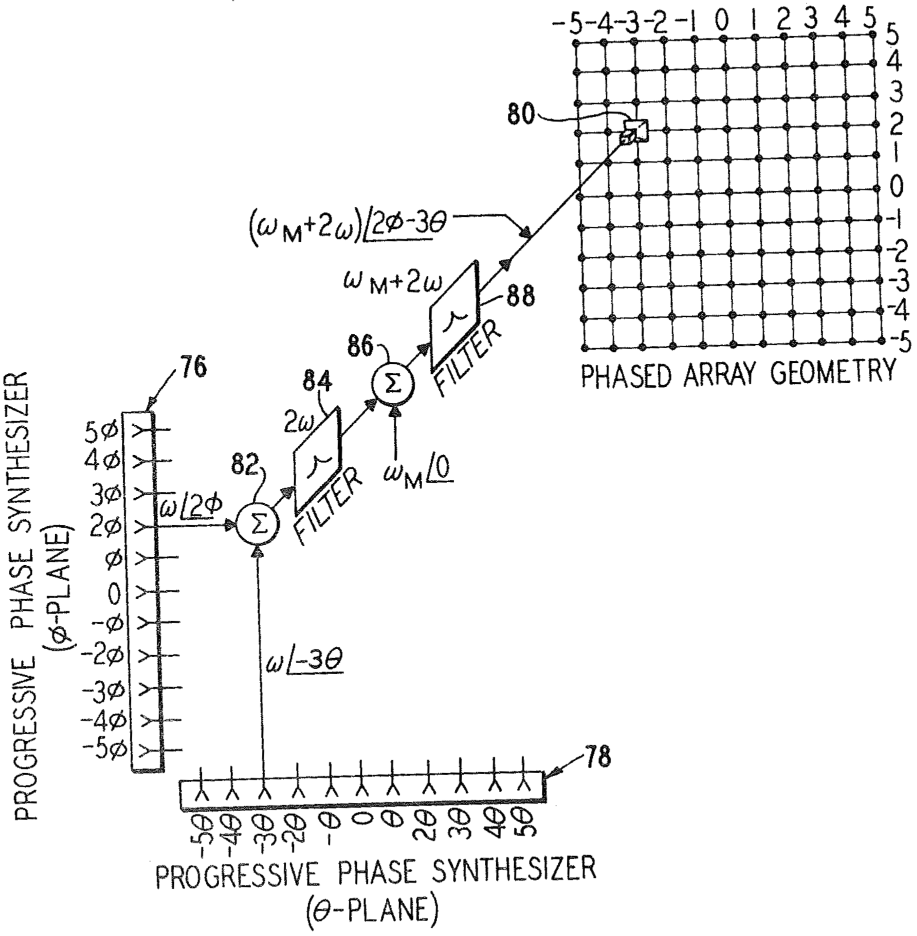

-5 -4 -3 -2 -1 0 1 2 3 4 5
5 4 3 2 1 0 -1 -2 -3 -4 -5
80
$(\omega_M+2\omega)\angle 2\phi-3\theta$
$\omega_M+2\omega$
88
86
84
76
2ω
82
$\omega\angle 2\phi$
FILTER
FILTER
$\omega_M\angle 0$
PHASED ARRAY GEOMETRY
PROGRESSIVE PHASE SYNTHESIZER (ø-PLANE)
5ø 4ø 3ø 2ø ø 0 -ø -2ø -3ø -4ø -5ø
$\omega\angle -3\theta$
78
-5θ -4θ -3θ -2θ -θ 0 θ 2θ 3θ 4θ 5θ
PROGRESSIVE PHASE SYNTHESIZER (θ-PLANE)

FIG. 5

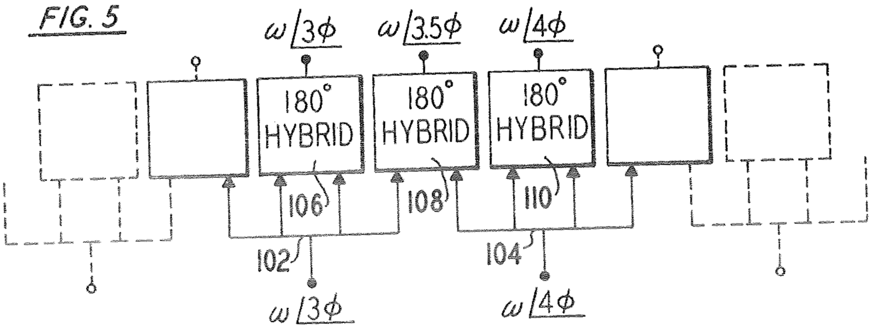

$\omega\angle 3\phi$
$\omega\angle 3.5\phi$
$\omega\angle 4\phi$
180° HYBRID
180° HYBRID
180° HYBRID
106
108
110
102
104
$\omega\angle 3\phi$
$\omega\angle 4\phi$

FIG. 3

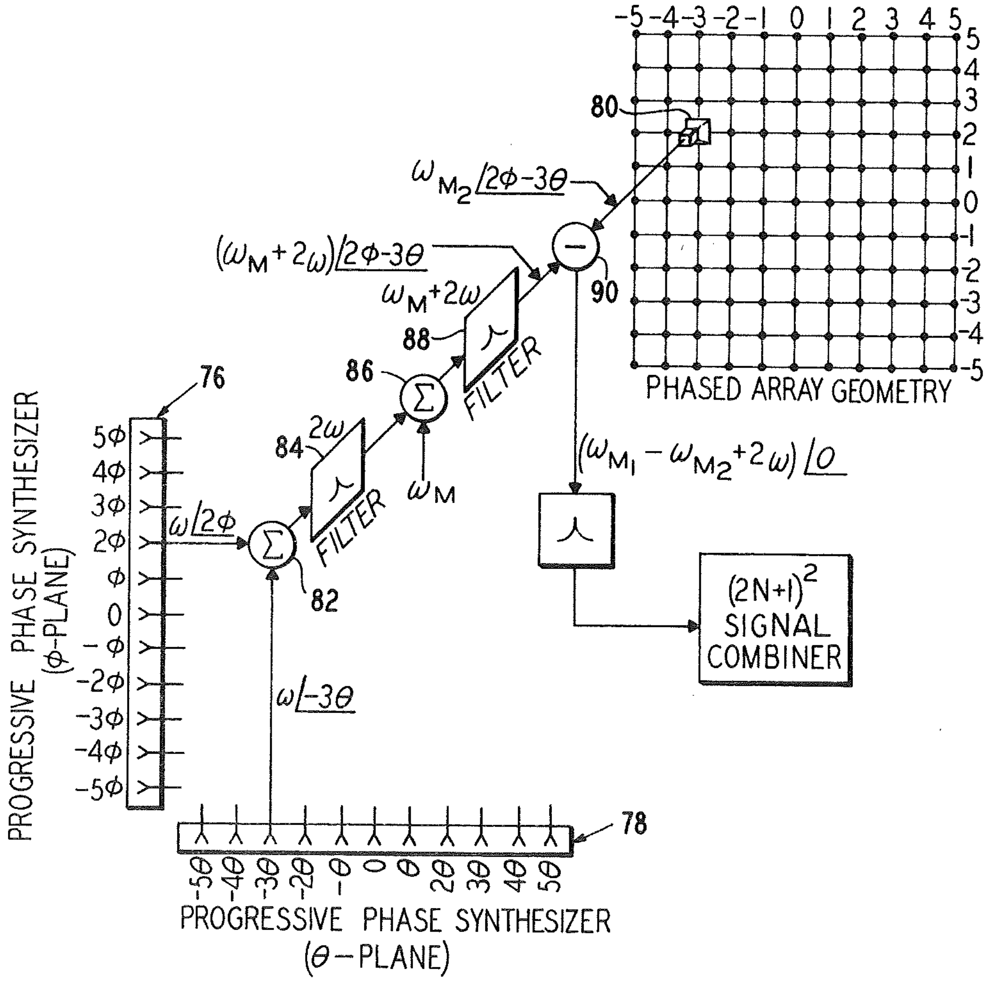
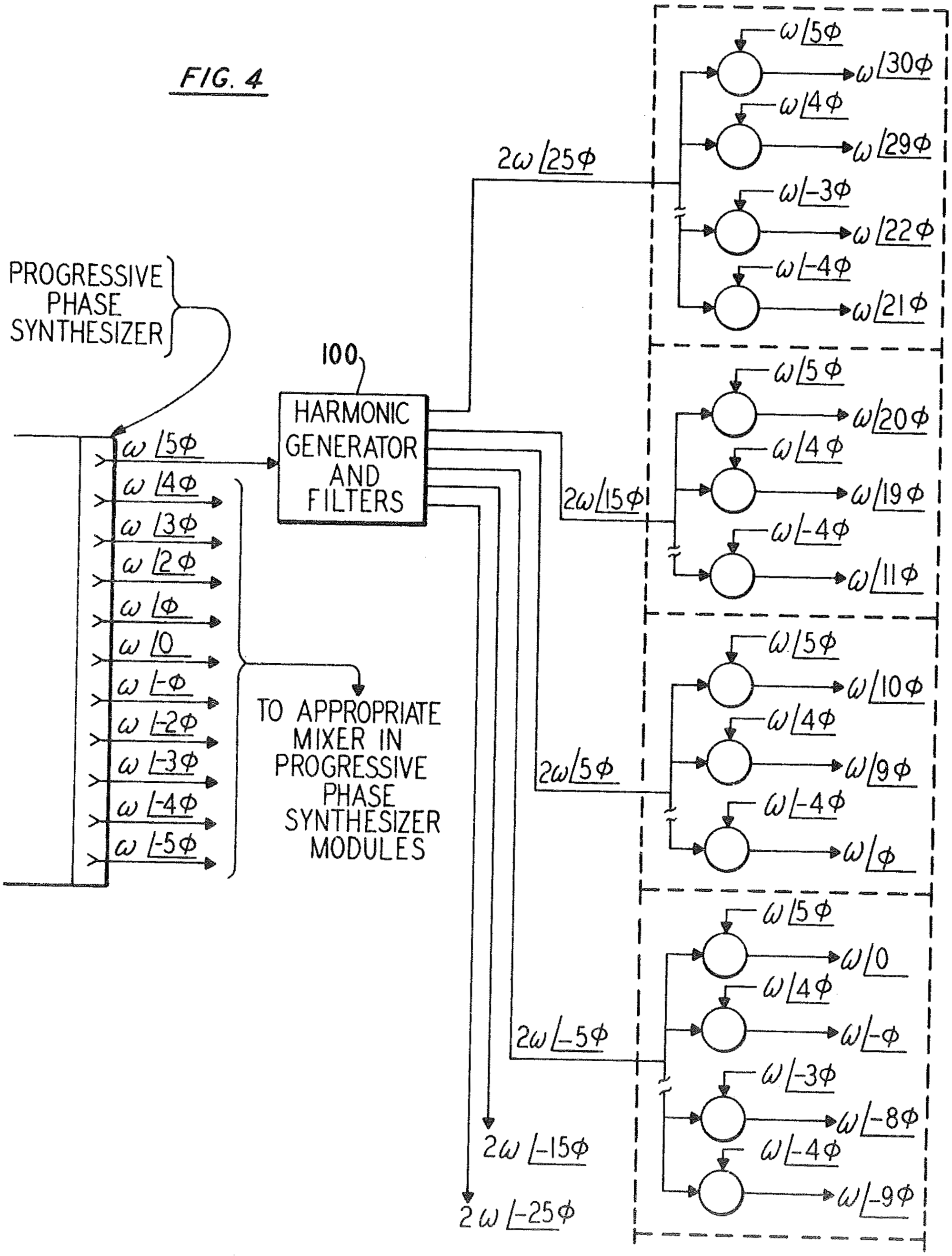

-5 -4 -3 -2 -1 0 1 2 3 4 5
5 4 3 2 1 0 -1 -2 -3 -4 -5
80
$\omega_{M_2}\underline{/2\phi-3\theta}$
$(\omega_M+2\omega)\underline{/2\phi-3\theta}$
90
$\omega_M+2\omega$
88
FILTER
86
76
PHASED ARRAY GEOMETRY
$(\omega_{M_1}-\omega_{M_2}+2\omega)\underline{/0}$
84
2ω
FILTER
ω_M
$\omega\underline{/2\phi}$
82
5ϕ
4ϕ
3ϕ
2ϕ
ϕ
0
$-\phi$
-2ϕ
-3ϕ
-4ϕ
-5ϕ
PROGRESSIVE PHASE SYNTHESIZER (ϕ-PLANE)
$(2N+1)^2$ SIGNAL COMBINER
$\omega\underline{/-3\theta}$
78
-5θ -4θ -3θ -2θ $-\theta$ 0 θ 2θ 3θ 4θ 5θ
PROGRESSIVE PHASE SYNTHESIZER (θ-PLANE)

FIG. 4


PROGRESSIVE PHASE SYNTHESIZER
100
HARMONIC GENERATOR AND FILTERS
ω /5Φ
ω /4Φ
ω /3Φ
ω /2Φ
ω /Φ
ω /0
ω /-Φ
ω /-2Φ
ω /-3Φ
ω /-4Φ
ω /-5Φ
TO APPROPRIATE MIXER IN PROGRESSIVE PHASE SYNTHESIZER MODULES
2ω /25Φ
2ω /15Φ
2ω /5Φ
2ω /-5Φ
2ω /-15Φ
2ω /-25Φ
ω /30Φ
ω /29Φ
ω /-3Φ
ω /22Φ
ω /21Φ
ω /20Φ
ω /19Φ
ω /11Φ
ω /10Φ
ω /9Φ
ω /Φ
ω /0
ω /-Φ
ω /-8Φ
ω /-9Φ

United States Patent Office

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ARRAY PHASING DEVICE

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Filed Jan. 24, 1969, Ser. No. 793,772

Int. Cl. H04b *7/00*

U.S. Cl. 343—100 13 Claims

ABSTRACT OF THE DISCLOSURE

Apparatus for generating a series of microwave signals at positive and negative progressively phased angles. The disclosed apparatus employs intermediate frequency multiplication and heterodyning to produce the desired signals through use of only one precision phase shifter for each series of signals. A phase interpolation technique which permits doubling the number of phased output signals is also disclosed.

ORIGIN OF THE INVENTION

The invention described herein was made by employees of the United States Government and may be manufactured and used by or for the Government for governmental purposes without the payment of any royalties thereon or therefor.

BACKGROUND OF THE INVENTION

Field of the invention

The present invention relates to the generation of a series of microwave signals at progressively related phase angles. More particularly, the present invention is directed to the driving of phased antenna arrays. Accordingly, the general objects of the present invention are to provide novel and improved methods and apparatus of such character.

Description of the prior act

While not limited thereto in its utility, the present invention has been found to be particularly well suited for use in the phasing of array antennas. Thus, for example, the present invention may be employed with satellite-borne phased array antennas.

Many schemes have, of course, been suggested for phasing array antennas. As extensive bibliography and comprehensive summary of prior art array phasing devices may be found in the publication entitled "A Survey of Array Theory and Techniques" authored by H. J. Moody which appeared in the RCA Victor report Number 6,501.3 issued in November 1963.

Each of the prior art schemes discussed in the aforementioned survey has inherent deficiencies and all share the common disadvantage of requiring a large number of phase shifters and/or a computer to steer the beam. Other deficiencies of prior art phasing schemes include the necessity of using signal generators employing active elements which are subject to failure. Also, it has been common practice in the art to generate the required phase related signals through the use of a series arrangement of mixers or amplifiers and this practice carries with it the inherent possibility of greatly decreased antenna performance as a result of a failure of any one of the initial components in the series.

As noted above, some attention has been directed to employing computers to steer the beam in array phasing devices. In an attempt to avoid the cost and complexity of digitally steered phased array systems, recent interest has been directed to schemes wherein a parallel or series-parallel combination of harmonic generators is

employed to derive a set of signals with positive phase angles which are progressive. Such schemes, as exemplified by the system shown in FIGURE 1 of an article entitled "Stability Analysis of a Phase Correction Scheme in the Monitor and Control Equipment of a Phased Array Radar" by R. N. Spong, which appeared at pages 236–248 of volume AES–3, No. 6, Supplement to IEEE Transactions on Aerospace and Electronic Systems, November 1967, also have a certain inherent disadvantages. For example, systems such as that disclosed in the Spong article operate with positive phase angles only.

In the driving of large antenna arrays, since the number of harmonics and therefore the frequency of the highest harmonic determines the upper limit on the number of individual antennas which may be phased, the number of harmonics which must be generated obviously becomes critical. When only positive phase angles are employed, a large number of harmonics must be generated in order to drive a large array.

Summary of the invention

The present invention uses IF (intermediate frequency) multiplication and heterodyning to obtain a series of microwave signals at both positive and negative progressively phased angles to overcome the above-discussed and other disadvantages of the prior art. Array phasing devices in accordance with the present invention accomplish the foregoing through the use of only one precision phase shifter for each direction of scan. As a result of the use of both negative and positive progressively related phase angle signals, large arrays can be driven and the system can operate with lower IF frequencies than employable in prior art devices of like character.

Also in accordance with the present invention, progressive phase synthesizers can be cascaded in a "subarraying" technique to enable the system to feed very large arrays while still using only a single phase shifter. This technique also reduces the highest harmonic of the IF frequency which must be used. The individual synthesizers of the present invention are highly reliable and eliminate the need for complicated logic systems.

The IF output signals of the progressive phase synthesizers of the present invention are sets of electrical signals with progressively related phases. Also in accordance with the present invention, this number of signals can be further increased by employing phase interpolating circuits at the output of each phase synthesizer. These circuits yield an additional set of signals by combining equal portions of adjacent signals vectorially. Each phase in this set lies mid-way between that of two adjacent signals from the original set. The two sets of signals can now be used together to nearly double the number of phased output signals.

Brief description of the drawing

The present invention may be better understood and its numerous objects and advantages will become apparent to those skilled in the art by reference to the accompanying drawing wherein like reference numerals refer to like elements in the various figures and in which:

FIGURE 1 is a block diagram of a first embodiment of the present invention.

FIGURE 2 is a schematic representation of progressive phase synthesizers such as that shown in FIGURE 1 employed to drive a typical phased array transmitting element.

FIGURE 3 is a schematic representation of phase synthesizers in accordance with the present invention employed to drive a typical phased array receiving element.

FIGURE 4 schematically shows use of progressive phase synthesizers in accordance with the present invention to achieve "subarray" scanning.

FIGURE 5 shows the phase interpolation feature of the present invention.

Description of the preferred embodiment

As is well known, most phased antenna arrays are made up of radiating elements which are uniformly spaced in one or two dimensions. Thus, by controlling the relative phase between adjacent elements in the direction of scan, the required element excitation for scan may be produced. Obviously, the required phase relationship between the signals supplied to the radiating elements should vary progresively along the array in order that a phase distribution of

$$0, \pm\phi, \pm 2\phi \ldots \pm N\phi$$

about the array center will cause scanning through an angle

$$\Phi=\sin^{-1}\left(\frac{\lambda\phi}{2\pi d}\right)$$

from the broadside direction in that plane, where d is the element spacing and λ the free space wavelength. A similar θ progression will scan the array about the orthogonal plane.

It is well known that certain non-linear elements produce phase addition, subtraction and integer multiplication. If a signal at angular frequency ω and phase angle ϕ, such signal being hereinafter indicated by the notation ω/ϕ, drives a general non-linear element, the following harmonics are evident in the signal appearing at the output of the element:

$$\omega/\underline{\phi},\ 2\omega/\underline{2\phi} \ldots N\omega/\underline{N\phi} \ldots$$

Harmonics generation is therefore accompanied by phase multiplication. Similarly, if two signals ω_1/ϕ_1 and ω_2/ϕ_2 are mixed, the output signals contain, among other terms, a sum term

$$(\omega_1+\omega_2)/\underline{\phi_1+\phi_2}$$

and a difference term

$$(\omega_1-\omega_2)/\underline{\phi_1-\phi_2}$$

If $\phi_1=0$ and ω_1 is greater than ω_2, this difference signal has the relative phase $-\phi_2$. Thus, a mixer or heterodyning circuit can perform the operations of summing phases, of taking the difference between phases or of forming the negative of the incident signal phase.

With reference now to FIGURE 1 a progressive phase synthesizer in accordance with the present invention is shown schematically. In FIGURE 1, the invention is depicted as feeding an eleven element antenna array. A reference or zero phase signal $\omega/\underline{0}$ at an intermediate frequency is delivered to the synthesizer and is passed through a precision phase shifter **10** to supply a signal ω at an angle ϕ. Phase shifter **10** may, for example, comprise a lumped element quadrature hybrid and a pair of L-C networks with mechanically or electrically varying parameters such as those phase shifters which are presently available, or it may comprise a delay line with mechanically or electrically varying parameters.

The $\omega/\underline{\phi}$ signal from phase shifter **10** and the reference or zero signal $\omega/0$ are used to drive respective non-linear devices **12** and **14**. Non-linear devices or harmonic generators **12** and **14**, which may comprise step recovery diode or other highly non-linear semiconductor circuits, provide harmonic output signals. Thus, the output of harmonic generator **12** comprises signals $2\omega/\underline{2\phi}$ to $N\omega/\underline{N\phi}$, whereas the output of harmonic generator **14** comprises harmonic signals $2\omega/\underline{0}$ to $N\omega/\underline{0}$. The required harmonic signals from generators **12** and **14** are individually filtered; the output of generator **12** being supplied to filters **16**, **18**, **20** and **22** while the output of generator **14** is supplied to filters **24**, **26**, **28**, **30** and **32**. In an alternate configuration, not shown in FIGURE 1, the harmonic generators **12** and **14** could be replaced by a power dividing network which feeds separate frequency multipliers for each multiple between ω and $N\omega$. Since the frequencies are separated by filtering, this does not change the basic concept significantly. Filters **16**, **18**, **20**, **22**, **24**, **26**, **28**, **30** and **32** may comprise a series of quadrature hybrid and band pass lumped L-C circuit filter networks in a cascaded arrangement, or if separate frequency multipliers are used, these may be simple L-C lumped circuit filters. The output signals from these filters are at the selected frequency and have harmonic phase shifts. The signals with harmonic phase shifts are then mixed with the zero phase shift signals from filters **24**, **26**, **28**, **30** and **32** to produce signals at frequency ω, but with positive and negative progressive phase shifts. The mixing is done in mixers **34**, **36**, **38**, **40**, **42**, **44**, **46**, **48** and **50**. Thus, for example, the signal $3\omega/\underline{3\phi}$ is mixed with signal $4\omega/\underline{0}$ and also with the signal $2\omega/\underline{0}$ to give, among other terms, the signals $\omega/\underline{-3\phi}$ and $\omega/\underline{3\phi}$. The desired signals from the mixers are filtered out by filters **52**–**72** to yield the required set of output signals at frequency ω and with phase angles 0, $\pm\phi$, $\pm 2\phi$, $\pm 3\phi$, $\pm 4\phi$ and $\pm 5\phi$. After filtering, the desired output signals may, of course, be amplified and/or limited prior to up-conversion.

For purposes of illustration, the number of phases provided by the synthesizer of FIGURE 1 was chosen to be five. However, it is to be understood that any number of phases may be selected. It is also to be noted that FIGURE 1 represents means to produce a progressive phase shift ϕ for one plane of scan. Obviously, if two planes of scan are required, the synthesizer of FIGURE 1 will be duplicated to create the two sets of required progressive phase signals.

FIGURE 2 depicts the application of two progressive phase synthesizers, indicated generally at **76** and **78** and each being of the type shown in FIGURE 1, to drive a typical element of a two-dimensional transmitting array. Both synthesizers are driven by the same source. The typical element chosen, for purposes of explantion, is labelled by the array coordinate system (−3, 2) and is represented by horn **80**. The IF signals $\omega/\underline{2\phi}$ and $\omega/\underline{-3\phi}$ are combined using the mixer **82** and the filter **84** to produce a signal 2ω with phase $-3\phi+2\theta$. FIGURE 2 shows one way of converting this IF phased signal to a microwave signal for driving one element of a phased array. This is accomplished using balanced mixer **86** and filter **88**. Horn **80** is, therefore, driven with a signal at the microwave frequency $\omega_m+2\omega$ and with a phase $-3\phi+2\theta$, and an array of such horns with appropriate progressive phases forms a beam at the angles

$$\Phi=\sin^{-1}\left(\frac{\lambda\phi}{2\pi d_1}\right)$$

and

$$\theta=\sin^{-1}\left(\frac{\lambda\theta}{2\pi d_2}\right)$$

with respect to the normal in two orthogonal planes, where d_1 and d_2 are the element spacing in the ϕ and θ planes, respectively. Many other schemes may be used for converting the IF phased signals to microwave signals. For example, the IF signals could be multiplied and/or amplified before up-conversion. Also, the low power RF signal of FIGURE 2 can be amplified or phaselocked to larger RF signals in order to increase the output power of the array. Thus, it may be seen that the desired signals for phasing a two-dimensional transmitting array may be generated through the use of only two phase shifting circuits, each circuit comprising a portion of each of the two phase synthesizers **76** and **78**.

The present invention may also be employed to drive phased array receiving antennas. FIGURE 3 schematically shows one possible way of applying the present invention to a receiving array. In the receiving mode the array functions essentially as a phased microwave local oscillator. The foregoing is accomplished by mixing the output of the system shown in FIGURE 2 with the received signal at each antenna element. Thus, again considering horn **80**, the received signal is mixed with the output of filter circuit **88** in mixer **90**. The difference signal from each mixer results in $(2N+1)^2$ IF signals, which are in phase signals, when the antenna is "pointed" in the direction of the incoming signal. These IF signals, if properly combined, result in an antenna array whose aperture properties behave similarly to standard phased array antennas.

The arrangement of FIGURE 4 extends the use of the present invention to various large antenna arrays. The apparatus shown in FIGURE 4 combines the basic synthesizer of FIGURE 1 in cascade with a similar synthesizer **100** to yield output signals at frequency 2ω and phase angles $\pm5\phi$, $\pm15\phi$ and $\pm25\phi$. These six output signals from synthesizer **100** are in turn combined with each of the eleven signals of the basic progressive phase synthesizer to produce a set of signals at frequency ω with phase angles 0 to $\pm30\phi$. In FIGURE 4 a $\pm5\phi$ basic element has been used for purposes of illustration.

FIGURE 4 illustrates the "sub-arraying" technique and it is to be understood that an almost unlimited number of signal combinations can be employed to produce the same phase angles as shown in the FIGURE 4 example and/or the geometry of the system can be slightly changed so as to provide an output signal frequency 2ω if considered advantageous. The technique shown in FIGURE 4 is a method of obtaining large progressive phase multiplication without the associated large frequency multiplications characteristic of prior art schemes. In FIGURE 4, the total phase multiplication was $\pm30\phi$ while the highest harmonic frequency was 7ω.

FIGURE 5 depicts the use of a phase interpolating circuit as applied to array scanning with the present invention. The IF output of the progressive phase synthesizer has a set of electrical signals with progressively related phases. The number of phase output signals available from the present invention can be nearly doubled by using a phase interpolation circuit. A preferred form of this circuit comprises the four-way power dividers **102** and **104** and the 180 degree hybrids **106**, **108** and **110**. It is to be noted that the 180 degree hybrids have their difference ports terminated internally by matched loads. For illustration, interpolation between only two outputs of the synthesizers are shown in FIGURE 5. In this figure two adjacent signals, $\omega/\underline{3\phi}$ and $\omega/\underline{4\phi}$ are combined vectorially to yield a signal with phase ankle 3.5ϕ. If interpolating circuits are used between each of the output terminals of the progressive phase synthesized module, then the total number of phased output signals can be doubled and, if desired, through the use of cascaded interpolating circuits, redoubled. The interpolating circuits allow more antennas to be driven by a given progressive phase synthesizer module than can be driven in their absence, and these additional antennas do not require the use of higher harmonic signals. This fact, of course, brings about important design simplifications. The phase interpolation circuits cause amplitude variations with phase change which makes it necessary to keep the phase difference ϕ small. This requires that phase and hence frequency multiplication be used for antenna array systems in which large scan angles are required.

To summarize the advantages of the present invention, only two phase shifters are used to scan a microwave beam in two dimensions, independent of the number of elements in the array. Furthermore, the present invention introduces three new techniques which relate to scanning larger arrays than hitherto possible using prior systems with the same number of harmonic signals. Moreover, since the progressive phasing is performed at low frequency, the present invention can be used to phase an array at almost any microwave frequency.

While preferred embodiments have been shown and described, various modifications and substitutions may be made thereto. For example, the synthesizer of FIGURE 1 can be designed to provide a progressively phased output at any frequency which is an integral multiple of the original input frequency.

What is claimed is:

1. Apparatus for generating, from a single alternating input signal, a series of output voltages having the same frequency and progressively related phase angles, said apparatus comprising:

phase shifter means responsive to the input signal for generating a first signal having a preselected phase relation to the input signal;

first harmonic generator means connected to said phase shifter means and responsive to said first phase related signal for providing a plurality of signals which are harmonics of said first signal;

second harmonic generator means responsive to the input signal for providing a plurality of signals which are harmonics of the input signal; and

first means for mixing each of said first harmonic generator means provided signals with next higher and next lower harmonic signals provided by said second harmonic generator means to produce a first series of signals at the input signal frequency and with positive and negative progressive phase shifts.

2. The apparatus of claim **1** wherein said first mixing means comprises:

a plurality of mixers, each of said mixers being responsive to a harmonic signal from each of said harmonic generator means; and

first filter means connected to each of said mixers for passing only signals at the input signal frequency.

3. The apparatus of claim **2** wherein said harmonic generator means each comprise:

non-linear circuit means for generating an output signal rich in harmonics in response to application of the alternating input signal thereto; and

second filter means connected between said non-linear circuit means and said mixing means for passing a plurality of signals at different harmonic frequencies of the input signal to pairs of said mixers.

4. The apparatus of claim **3** further comprising:

third harmonic generator means connected to said first filter means and responsive to the signals produced by said first mixing means for providing signals at preselected phase angles and at the first harmonic frequency of the input signal; and

second mixing means responsive to said first harmonic signals and to the signals produced by said first mixing means for generating a second series of signals at the input signal frequency and with positive and negative progressive phase shifts.

5. The apparatus of claim **3** further comprising: means connected to said first filter means and responsive to pairs of signals passed thereby for vectorially combining signals adjacently related in phase to produce signals at phase angles intermediate those of said first series.

6. The apparatus of claim **5** wherein said signals of said first series are at microwave frequency and said means for vectorially combining signals comprises:

a plurality of power divider means, each divider means being responsive to a signal passed by said first filter means for generating a plurality of signals at each of the phase angles provided by said first mixing means; and

a plurality of 180 degree hybrids, each hybrid being connected to a pair of said power divider means.

7. The apparatus of claim **2** further comprising: means connected to said first filter means and responsive to pairs of signals passed thereby for vectorially combining signals adjacently related in phase to produce signals at phase angles intermediate those of said first series.

8. The apparatus of claim 7 wherein said signals of said first series are at microwave frequency and said means for vectorially combining signals comprises:
 a plurality of power divider means, each divider means being responsive to a signal passed by said first filter means for generating a plurality of signals at each of the phase angles provided by said first mixing means; and
 a plurality of 180 degree hybrids, each hybrid being connected to a pair of said power divider means.

9. The apparatus of claim **1** wherein said harmonic generator means each comprise:
 non-linear circuit means for generating an output signal rich in harmonics in response to application of the alternating input signal thereto; and
 second filter means connected between said non-linear circuit means and said mixing means for passing a plurality of signals at different harmonic frequencies of the input signal to said first mixing means.

10. The apparatus of claim **1** further comprising:
 third harmonic generator means responsive to the signals produced by said first mixing means for providing signals at preselected phase angles and at the first harmonic frequency of the input signal; and
 second mixing means responsive to said first harmonic signals and to the signals produced by said first mixing means for generating a second series of signals at the input signal frequency and with positive and negative progressive phase shifts.

11. A method of providing a series of alternating signals at positive and negative progressively related phase angles comprising the steps of:

 generating a first signal having a predetermined phase shift with respect to a reference signal;
 producing a plurality of harmonics of the reference and phase shifted signals;
 combining the harmonics of the reference and phase shifted signals in pairs; and
 filtering the combined harmonic signals to obtain signals at the reference signal frequency with positive and negative progressively related phase angles.

12. The process of claim **11** wherein the step of combining comprises:
 separately mixing each of a plurality of harmonics of the phase shifted signal with next higher and next lower harmonics of the reference signal.

13. The process of claim **12** further comprising: vectorially combining adjacent phase related signals at the reference signal frequency to provide signals at intermediate phase angles.

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U.S. Cl. X.R.

343—854