Feb. 28, 1967 J. E. MEADE 3,307,189

MICROWAVE ANTENNA LOBING

Filed March 22, 1961 2 Sheets-Sheet 1

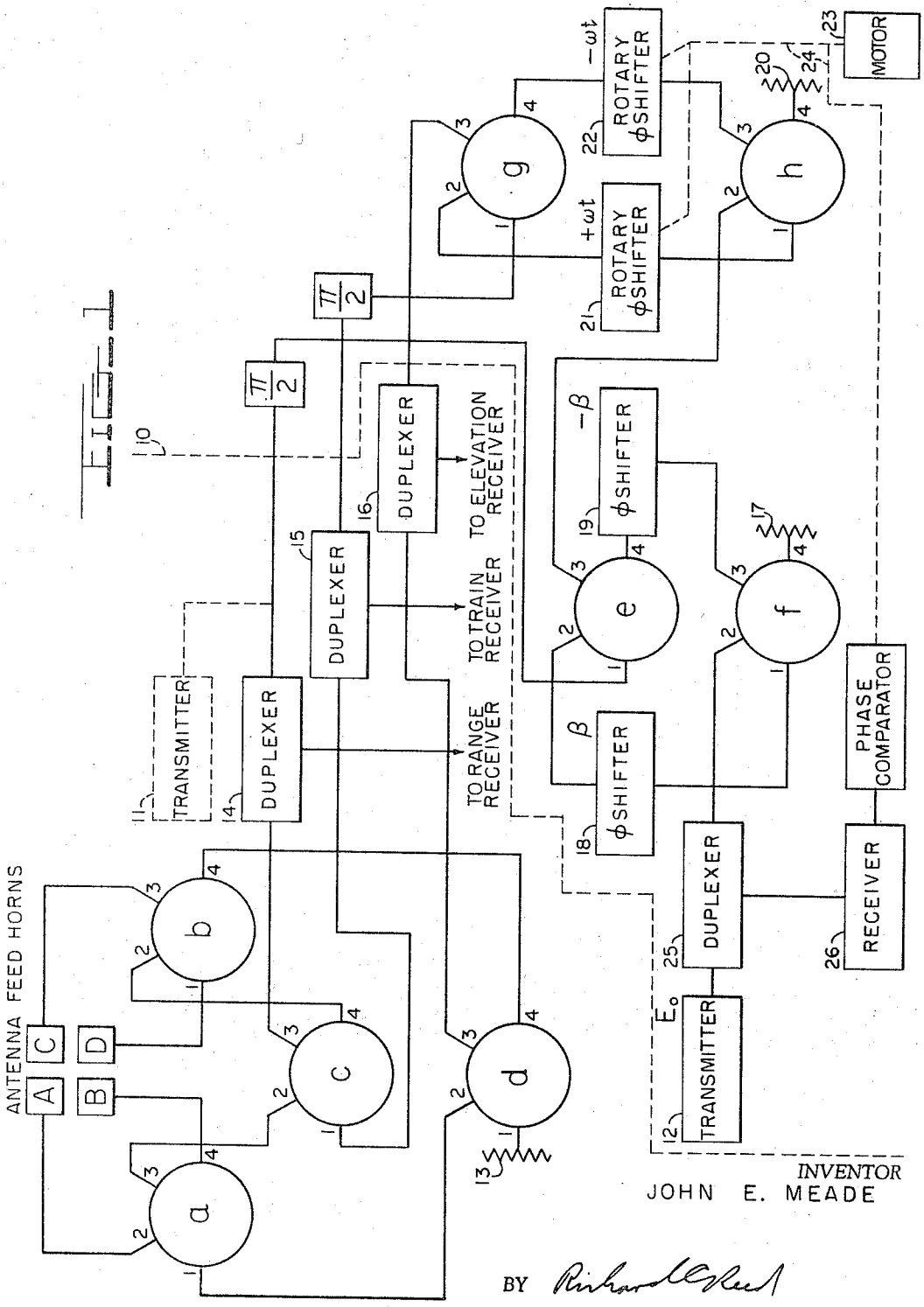

FIG. 1

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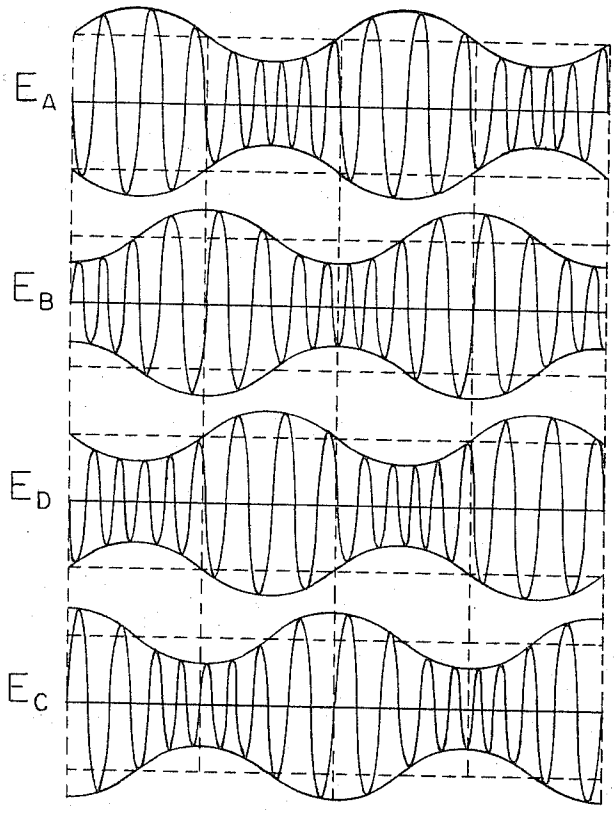
FIG. 2



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United States Patent Office 3,307,189
Patented Feb. 28, 1967

3,307,189

MICROWAVE ANTENNA LOBING

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Filed Mar. 22, 1961, Ser. No. 97,702
5 Claims. (Cl. 343—100)

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

This invention relates generally to microwave antenna lobing and more particularly to microwave multihorn radar antenna pattern lobing by amplitude modulation.

Antenna lobing is a long recognized means for improving the azimuth and elevation tracking accuracy of radars. In applications where high speed lobing is required, such as in high speed tracking, simultaneous lobe comparison techniques are employed. Simultaneous lobing is generally effected by comparing the energy simultaneously received on four antennas having slightly divergent radiation patterns. The transmitter energy is radiated from a single antenna or simultaneously from all four antennas. Inasmuch as this type of lobing produces no lobe switching effect on the transmitted pattern the advantages of the system are limited to receiver functions.

Transmitter pattern lobing may be attained if the R.F. power is switched sequentially to each of the antenna feeds. However, switching at rapid rates has not proved practical because of the high R.F. power. Another method of transmitter lobing results from sinusoidal amplitude modulation of the feed horn excitation and has been accomplished using absorption modulation. This method is obviously inefficient and impractical due to the loss of power through absorption.

It is therefore an object of this invention to provide transmitter pattern lobing without loss of power.

It is another object of this invention to provide transmitter pattern lobing by amplitude modulation of the feed excitation without loss of power.

It is another object of this invention to provide amplitude modulation of high power microwave energy without loss of power.

It is another object of this invention to provide sinusoidal amplitude modulation of high power microwave energy without loss of power.

It is another object of this invention to provide a conical scanning antenna pattern free from harmonics.

It is another object of this invention to provide a microwave conical scanning antenna pattern by effecting amplitude modulation of the microwave energy.

Other objects and many of the attendant advantages of this invention will be readily appreciated as the same becomes better understood by reference to the following detailed description when considered in connection with the accompanying drawings wherein:

FIG. 1 is a diagrammatic representation of a preferred embodiment of this invention, and

FIG. 2 is a group of waveforms showing the voltage wave at each of the radiating horns in FIG. 1.

Briefly this invention produces amplitude modulation of high power microwave energy by dividing the transmitter power equally into two channels, shifting the phase of each a complementary amount and then recombining and dividing the phase shifted voltages into components of different magnitude. The larger component provides the carrier and the smaller is used to generate sidebands by a second process of dividing, complementary phase shifting, and recombining. If the second phase shifting is applied continuously, the recombined voltage when

once again divided, produces a pair of variable amplitude voltages in quadrature. These two voltages may be added as sidebands to a carrier voltage to provide amplitude modulation. The sideband energy, when properly added in phase quadrature to the transmitter energy feeding a four horn antenna array, produces a conical scanning transmitter lobing pattern which lobes at a rate determined by the rate the phase is shifted. Off-axis conical scanning may be produced by introducing a synchronous sinusoidal variation of the percentage of modulation in the proper phase.

For a detailed description of this invention, reference is now made to FIG. 1. The portion to the left of dotted line **10** is a preferred antenna feed system for a simultaneous lobe comparison radar of the type disclosed in Patent No. 2,929,056 to Robert M. Page for "Simultaneous Lobe Comparison Pulse Echo Locator System." The transmitter **11** in this system is shown by dotted lines since it is replaced by transmitter **12** to the right of line **10** in the practice of the present invention. All the solid lines shown in FIG. 1 for connecting the various elements thereof represent hollow waveguide. Four antenna feed horns are represented by A, B, C, and D, as upper and lower left, and upper and lower right, respectively. The horns are fed from transmitter **12** by a number of hybrid junctions. Ring type or "rat-race" junctions are shown throughout FIG. 1 for convenience in diagrammatic showing although any equivalent junction, as for example the "magic-tee," could be used. Actually, the ring type junction here indicated is preferred for the application shown because of its superior power handling ability.

Simultaneous lobe comparison is achieved through the sum and difference properties of hybrid junctions. In the usual operation of the ring type junction the junctions are suitably spaced around the ring so that the voltage at any terminal is proportional to the sum of the voltages at terminals adjacent to it and the difference between the voltages of alternate terminals, only one of which is adjacent, the voltage of the non-adjacent terminal being subtracted from the voltage at the adjacent terminal. In FIG. 1 corresponding terminals on all junctions shown are designated **1**, **2**, **3** and **4**, respectively, and the junctions are distinguished by small letters. In this description terminals will be identified by terminal number and junction letter, and terminal voltages will be identified by terminal number and junction letter appearing as subscripts. The voltage relationship for any junction may then be expressed as follows:

(1)
$$E_1=\frac{-j}{\sqrt{2}}(E_2-E_4)$$

since only one alternate arm is adjacent to terminal **1**; and

$$E_3=\frac{-j}{\sqrt{2}}(E_2+E_4)$$

since both alternate arms are adjacent to terminal **3**. Similarly:

$$E_2=\frac{-j}{\sqrt{2}}(E_1+E_3)$$

and

$$E_4=\frac{-j}{\sqrt{2}}(E_3-E_1)$$

Therefore, from FIG. 1, the energy received by horns A and B and fed to terminals **2** and **4** of junction *a* appears as a sum at terminal **3**. Similarly, the sum of the energy received by horns C and D appears at terminal **2** of junction *b*. These two sums are respectively applied to terminals **2** and **4** of junction *c* and their vector dif-

ference appears at terminal **1**. This difference, because of horn orientation is the difference between right and left and represents the train or azimuth deviation of the target from the antenna axis. The difference energy from horns A and B is fed from terminal **1** of junction *a* to terminal **2** of junction *d*. The difference energy from horns C and D is fed from terminal **4** of junction *b* to terminal **4** of junction *d*. Since each of these differences discriminate in the up and down or vertical plane, each represent elevation deviation and their sum, at terminal **3** of junction *d* is also elevation deviation.

The energy appearing at terminal **1** of junction *d* would be the difference between the two difference components. Since this information is not required, the energy is absorbed in a terminating resistance **13**. The energy appearing at terminal **3** of junction *c* is the sum of the energy received by all four horns and is fed through duplexer **14** to the range receiver input. Duplexers **15** and **16** are shown in the feeds to the train and elevation receivers, respectively, however when used with transmitter **11** only T–R tubes would be needed.

The sum and difference properties by hybrid junctions present a useful function in power distribution for energy fed into a single terminal. The energy is equally divided between alternate adjacent terminals and does not appear at the remaining terminal. This function is used in feeding the horns in the system shown to the left of line **10**. Transmitter **11** is fed through duplexer **14** to terminal **3** of junction *c*. Here the power divides and is fed from terminals **2** and **4** to junctions *a* and *b* respectively where it is again divided and fed equally to the four horns. According to the teachings of this invention, transmitter **12** and the other apparatus to the right of line **10** are substituted for transmitter **11** to provide a lobe switching conical scanning transmitter pattern. Transmitter **12**, having a terminal voltage E_0, is fed to terminal **2** of junction *f*. E_0 divides evenly between terminals **1** and **3** and does not appear at terminal **4** which is terminated in the characteristic impedance **17**. The equal outputs at **1** and **3** are applied to a pair of phase shifters **18** and **19** which respectively change the phase of each voltage by an equal and an opposite amount, $+\beta$ and $-\beta$. The phase shifted outputs are applied to alternate terminals **2** and **4** of junction *e*. As will be demonstrated mathematically below, the voltage sum at terminal **3** of junction *e* is $E_0 \cos \beta$ and the voltage difference at terminal **1** is $-jE_0 \sin \beta$. Thus two voltages have been obtained from E_0 whose relative magnitudes are determined by the value of β. β is normally chosen such that one voltage is about three times the other and the larger voltage may then be utilized as the carrier and the smaller as the side bands for an amplitude modulated wave. Since two side bands are desired the smaller voltage is similarly divided. To accomplish this, terminal **3** of junction *e* is connected to terminal **2** of junction *h* and appears equally divided at terminals **1** and **3**, like in junction *f* terminal **4** is terminated in the characteristic impedance **20**. This divided voltage is recombined by connection to terminals **2** and **4** of another junction *g* after another shifting in phase. Terminal **1** of junction *h* is connected through phase shifter **21** and terminal **3** through phase shifter **22**. Phase shifters **21** and **22** apply equal but opposite phase shifts respectively to the divided voltage components and when recombined produce two more voltages as in the case of junction *e*. Phase shifters **21** and **22** are rotary phase shifters and may operate electronically or mechanically. Typically they are of the type described in the A. G. Fox article, "An Adjustable Waveguide Phase Changer," December 1947, Proc. I.R.E. Reference may also be had to the Fox Patent 2,438,119 entitled, "Wave Tranmission." The rotary phase shifters are driven by motor **23** through shaft **24** and are coupled to shaft **24** to produce a complementary phase change. Since the phase shift varies as a linear function of time it may be expressed as $+wt$ and $-wt$, respectively.

As will be further shown below, the voltage outputs from junction *g* are $E_0 \cos \beta \cos wt$ and $jE_0 \cos \beta \sin wt$. In other words, the voltage $E_0 \cos \beta$ is now amplitude modulated with respect to time by $\cos wt$. Using their amplitude modulated voltages as upper and lower side bands and adding them to the carrier voltage $E_0 \sin \beta$, the modulated carrier wave is produced. The carrier voltage is fed to duplexer **14** at the point where transmitter **11** had been connected in the unmodulated system. The side bands are applied respectively to duplexers **15** and **16**. By applying the modulated wave to horns A, B, C and D so that the modulation appears in quadrature, it is obvious that both transmitter lobing and conical scanning are effected.

As shown in FIG. 1 to the left of line **10**, range, train and elevation information may be obtained in a conventional manner by feeding separate receivers from each of duplexers **14**, **15** and **16**. As also shown in FIG. 1 but to the right of line **10**, the same receiver information may be obtained with a single receiver by inserting a single duplexer **25** between transmitter **12** and hybrid junction *f*. A receiver **26** is fed from duplexer **25**. Duplexer **25** replaces the three duplexers **14**, **15** and **16** so that radiant energy picked up by horns A, B, C and D is passed to the right of line **10** into hybrid junctions *e*, *g*, and *h*. The relative time phase of the energy picked up at each of the horns is sensed to the right of line **10** by a reversal of the transmitter process just described. By comparing the phase of receiver **25** output with the position of the shaft **24** driving phase shifters **21** and **22**, the position of the received source may be determined.

The received source illuminating horns A, B, C, and D may be a passive object reflecting energy from transmitter **12**, or transmitter **12** may be deleted and the source be totally external and either directly illuminating horn A, B, C and D or impinging on the horns after reflection from some passive object.

Since duplexer **14** is connected to terminal **3** and duplexer **15** to terminal **1** of junction *c*, the sum of the carrier and one sideband is applied to terminal **3** of junction *a* and the difference to terminal **2** of junction *b*. Duplexer **16** is connected to junction *d* where the second side band is equally divided and fed to junctions *a* and *b* where it is combined with the carrier and the first side band to produce the quadrature modulation for the four feed horns. This may be demonstrated mathematically by applying Equations 1 to each junction of FIG. 1. A transmitter output voltage $E_0 e^{j\alpha_{rf}t}$ excites terminal **2** of junction *f* and creates output voltages E'_{f1} and E'_{f3} at terminals **1** and **3** of junction *f*.

$$E'_{f1} = E'_{f3} = \frac{-j}{\sqrt{2}} E_0 e^{j\alpha_{rf}t}$$

Shifting E'_{f1} and E'_{f3} respectively $+\beta$ and $-\beta$ radians and exciting terminals **2** and **4** of junction *e*, the output voltages E'_{e1} and E'_{e3} of junction *e* become:

$$(2) \qquad E'_{e1} = -jE_0 \sin \beta e^{j\omega_{rf}t}$$
$$E'_{e3} = -E_0 \cos \beta e^{j\omega_{rf}t}$$

Thus, E'_{e1} and E'_{e3} are quadrature R.F. voltages whose amplitudes are respectively proportional to $\sin \beta$ and $\cos \beta$.

In order to rotate the peak value of the radiation field from horn to horn of FIG. 1 at a lobing rate of ω_e radians per second in a process which is analogous to conventional amplitude modulation, voltage E'_{e3} is fed to terminal **2** of junction *h* to produce output voltages E'_{h1} and E'_{h3}.

$$(3) \qquad E'_{h1} \text{ and } E'_{h3} = \frac{j}{\sqrt{2}} E_0 \cos \beta e^{j\omega_{rf}t}$$

Shifting the phases of E'_{h1} and E'_{h3} respectively at $+\omega_e$ and $-\omega_e$ radians per second and exciting terminals

2 and 4 of junction g with the amplitude modulated voltages which are

$$E_{g2}=E'_{h1}e^{j\omega_e t}=\frac{j}{\sqrt{2}}E_0\cos\beta e^{j(\omega_{rf}t+\omega_e t)}$$

and

$$E_{g4}=E'_{h3}e^{-j\omega_e t}=\frac{j}{\sqrt{2}}E_0\cos\beta e^{j(\omega_{rf}t-\omega_e t)}$$

the output voltages of terminals 1 and 3 of junction g are:

$$E'_{g1}=\frac{E_0\cos\beta}{2}[e^{j(\omega_{rf}+\omega_e)t}-e^{j(\omega_{rf}-\omega_e)t}]$$

$$E'_{g3}=\frac{E_0\cos\beta}{2}[e^{j(\omega_{rf}+\omega_e)t}+e^{j(\omega_{rf}-\omega_e)t}]$$

Thus, these output voltages each contain an upper sideband at frequency $(\omega_{rf}+\omega_e)$ and a lower sideband at frequency $(\omega_{rf}-\omega_e)$. Since these output voltages may also be written:

(4)
$$E'_{g1}=jE_0\cos\beta\sin\omega_e te^{j\omega_{rf}t}$$
$$E'_{g3}=E_0\cos\beta\cos\omega_e te^{j\omega_{rf}t}$$

it is clear that E'_{g1} and E'_{g3} are in both R.F. and L.F. quadrature. They may be brought into R.F. phase by introducing $a-\pi/2$ phase shift to E'_{g1}.

In FIG. 1 an additional phase shift is shown advancing the phase of the output voltage of terminal 1 of junction e by $\pi/2$ radians. This is necessary to arrive at the horns with proper phases.

As shown in FIG. 1 the voltages applied to the feed horn junctions may be expressed from Equations 1 to 4 as follows:

(5)

$$E_{a3}=\frac{-j}{\sqrt{2}}(E_{c3}+E_{c1})=$$
$$\frac{-j}{\sqrt{2}}(E_0\sin\beta+E_0\cos\beta\sin wt)e^{j\omega_{rf}t}$$

$$E_{b2}=\frac{-j}{\sqrt{2}}(E_{c3}-E_{c1})=$$
$$\frac{-j}{\sqrt{2}}(E_0\sin\beta-E_0\cos\beta\sin wt)e^{j\omega_{rf}t}$$

$$E_{a1}=E_{b4}=\frac{-j}{\sqrt{2}}E_0\cos\beta\cos wt$$

From Equation 1 the voltages at the feed horns are:

(6)
$$E_A=E_{a3}+E_{a1}$$
$$E_B=E_{a3}-E_{a1}$$
$$E_C=E_{b2}+E_{b4}$$
$$E_D=E_{b2}-E_{b4}$$

Reducing Equation 6 we get:

(7)

$$E_A=\frac{E_0}{2}\sin\beta\left[1+\sqrt{2}\cot\beta\sin\left(\omega_e t+\frac{\pi}{4}\right)\right]\sin(\omega_{rf}t+\phi)$$

$$E_B=\frac{E_0}{2}\sin\beta\left[1+\sqrt{2}\cot\beta\sin\left(\omega_e t-\frac{\pi}{4}\right)\right]\sin(\omega_{rf}t+\phi)$$

$$E_C=\frac{E_0}{2}\sin\beta\left[1-\sqrt{2}\cot\beta\sin\left(\omega_e t-\frac{\pi}{4}\right)\right]\sin(\omega_{rf}t+\phi)$$

$$E_D=\frac{E_0}{2}\sin\beta\left[1-\sqrt{2}\cot\beta\sin\left(\omega_e t+\frac{\pi}{4}\right)\right]\sin(\omega_{rf}t+\phi)$$

Examination of Equations 7 reveals that the horn excitations are amplitude modulated, having a carrier amplitude $E_0/2\sin\beta$ and a modulation factor $\sqrt{2}\cot\beta$, while the phase of the modulation envelope differs by 90° between horns. Equations 7 also illustrate that the modulation frequency, or in other words the lobing rate, is a function of ω_e.

FIG. 2 is a plot of the horn excitation expressed in Equations 7. It will be noted that the maximum amplitude occurs sequentially at horns A, B, D and then C, thus the lobing follows as rotary pattern describing a cone. This, of course, is known as conical scanning. Conical scanning is conventionally produced with a conical scanning antenna which requires rapidly moving parts at the antenna and incidentally generates a field pattern having many harmonics. The conical scanning produced by this invention requires no moving parts at the antenna and, as may be demonstrated mathematically, produces no harmonics. This latter fact is evident from physical considerations, because the linear superposition of sinusoidal field variations cannot generate harmonics. The lobing rate is determined from the speed at which phase shifters **21** and **22** are rotated, thus permitting a very high lobing rate. Although this rotation involves only a simple mechanical function and is not restricted to low speed operation, it may be even further removed as a limiting factor in lobing speed by using two or more phase shifters in cascade in place of each phase shifter **21** and **22**. For example, two phase shifters in cascade properly connected provide a lobing rate twice the rotation rate. Therefore the upper limit of the lobing rate is the pulse repetition frequency of transmitter **12**, since it is necessary that there be at least one pulse in each lobe.

The above system as shown and described produces a conical scanning lobing pattern which is symmetrical about the axis of the horns. The angle of departure from the axis, or in other words the strength of the field along the axis, may be varied by varying the angle β. This is sometimes referred to as "squint angle." The strength or percentage of modulation varies with adjustment of β. For example, when $\beta=\pi/2$ radians, the modulation terms of Equation 7 vanish and there is no amplitude modulation at all, and the on-axis field strength is maximum. For this value of β operation would be the same as for the system disclosed to the left of line **10**.

Should it be desirable to vary β with respect to time, a convenient means is found in U.S. Patent No. 2,716,221 to Philip J. Allen for "Rotatable Dielectric Slab Phase Shifter for Waveguide." The Allen phase shifter broadly comprises a dielectric disc of variable thickness which is insertable in a pair of waveguides so that when the disc is rotated the total amount of dielectric in each waveguide varies sinusoidally. By making the insertion depth adjustable, the range of phase variations may be adjusted.

To vary the values of $+\beta$ and $-\beta$ introduced by phase shifters **18** and **19**, the Allen phase shifter may be substituted for devices **18** and **19** and disposed so that the dielectric disc enters the two waveguide connecting terminals f_1 and e_2, and f_3 and e_4 respectively.

Another important feature of this invention is found in the fact that it does not interfere with the normal operation of the simultaneous lobe comparison system as disclosed to the left of line **10**. Since normal operation is concerned with the presence or absence of deviation signals at the train and elevation receivers and not the magnitude of deviation signals, amplitude modulation of the deviation signals is of no consequence. When more than an integrated value of the magnitude of deviation signals is desired, $+\beta$ and $-\beta$ may be adjusted to $\pi/2$ to halt the lobing and scanning action of the transmitter pattern.

It will be understood that the principles of this invention need not be limited to the specific apparatus illustrated and described and modifications may, of course, be made without departing from the spirit and scope of the invention as defined by the appended claims.

What is claimed is:

1. A system for amplitude modulating microwave energy comprising, a source for producing microwave energy, means for dividing energy from said source into a carrier component and a sideband component, means dividing said sideband component into two equal sub-

components, means introducing an equal but opposite and continuously variable phase shift to each of said subcomponents, and means for recombining said phase shifted subcomponents with said carrier component as upper and lower sidebands.

2. A conical scanning transmitter antenna system for high power microwave energy comprising, four fixed radiating elements, a transmitter, a dividing means connected to said transmitter to divide energy from said transmitter into a carrier component and a sideband component, means dividing said sideband component into two equal subcomponents, means introducing an equal but opposite and continuously variable phase shift to each of said subcomponents, and means for combining and applying said carrier component and said phase shifted subcomponents to said fixed radiating elements as an amplitude modulated carrier having the modulation phase relation of adjacent elements in quadrature.

3. A transmitter pattern lobing system for a radio locator system having at least four antenna feed horns comprising, a transmitter, a first voltage dividing means connected to said transmitter, a first recombining and dividing means, a first pair of phase shifters respectively connecting the divided output of said first dividing means to the recombining terminals of said first recombining and dividing means to produce a first pair of voltages of relative amplitude dependent on the respective phase shifts, a second voltage dividing means, a second pair of phase shifters and a second recombining and dividing means, one of said first pair of voltages being connected to said second dividing means, said second pair of phase shifters respectively connecting the divided output of said second dividing means to the recombining terminals of said second recombining and dividing means, said second devices all being similar to their corresponding first devices except that said second pair of phase shifters are continuously variable, producing a second pair of voltages from said second recombining and dividing means each having an amplitude which varies in relation to the rate of variation of said second pair of phase shifters, means for adding said variable voltages as upper and lower sidebands to the other of said first pair of voltages as the carrier, and means feeding the carrier and sidebands to said feed horns with the sidebands phased in quadrature.

4. A system for modulating microwave energy comprising, means for equally dividing the microwave energy, means for introducing fixed complementary phase shifts to each divided component, means for combining and redividing the phase shifted components into unequal components having a relative magnitude determined by said phase shift, means for dividing said smaller component into second equal components, means for introducing continuously variable complementary phase shifts to each of said second equal components, means for recombining and redividing said phase shifted second components into two third components having continuously variable amplitude in phase quadrature.

5. A mircowave circuit connected between a first and second terminus and having three transmission lines at said first terminus and one transmission line at said second terminus, comprising a first power divider having its sum terminal connected to said second terminus, first and second four terminal ring type hybrid junctions, a first pair of complementary phase shifters connecting the difference terminals of said power divider to alternate arms of said first junction, a second power divider, the remaining alternate arms of said first junction being connected respectively to one of the three transmission lines at said first terminus and to the sum terminal of said second power divider, a second pair of complementary phase shifters connected between the difference terminals of said second power divider and alternate arms of said second junction, means for continuously varying the phase shift of said second pair of complementary phase shifters, the remaining alternate arms of said second junction being connected to the remaining transmission lines at said first terminus.

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