United States Patent [19]

Mailloux et al.

[11] **3,877,031**

[45] **Apr. 8, 1975**

[54] **METHOD AND APPARATUS FOR SUPPRESSING GRATING LOBES IN AN ELECTRONICALLY SCANNED ANTENNA ARRAY**

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[73] Assignee: **The Unied States of America as represented by the Secretary of the Air Force,** Washington, D.C.

[22] Filed: **June 29, 1973**

[21] Appl. No.: **374,830**

[52] **U.S. Cl.** .... **343/778;** 343/100 LE; 343/854

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

[58] **Field of Search** ...... 343/777, 778, 854, 100 LE

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Primary Examiner—Eli Lieberman

Attorney, Agent, or Firm—Harry A. Herbert, Jr.; Willard R. Matthews, Jr.; Joseph E. Rusz

[57] **ABSTRACT**

Grating lobe suppression in an electronically scanned antenna array is realized by adding odd mode power to the fundamental even mode power that normally drives each radiating element of the array. The odd mode power is maintained ±90° out of phase with the even mode power at each radiating element aperture. The ratio of even mode power to odd mode power is varied as a function of main beam displacement from broadside. One class of circuit for automatically accomplishing the required functions utilize waveguide power dividers and phase shifters. An alternative embodiment comprehends the use of passive, reciprocal linear circuitry to perform the power division. In some circuits the phase difference between adjacent radiating elements is used to derive odd and even mode signals.

5 Claims, 16 Drawing Figures

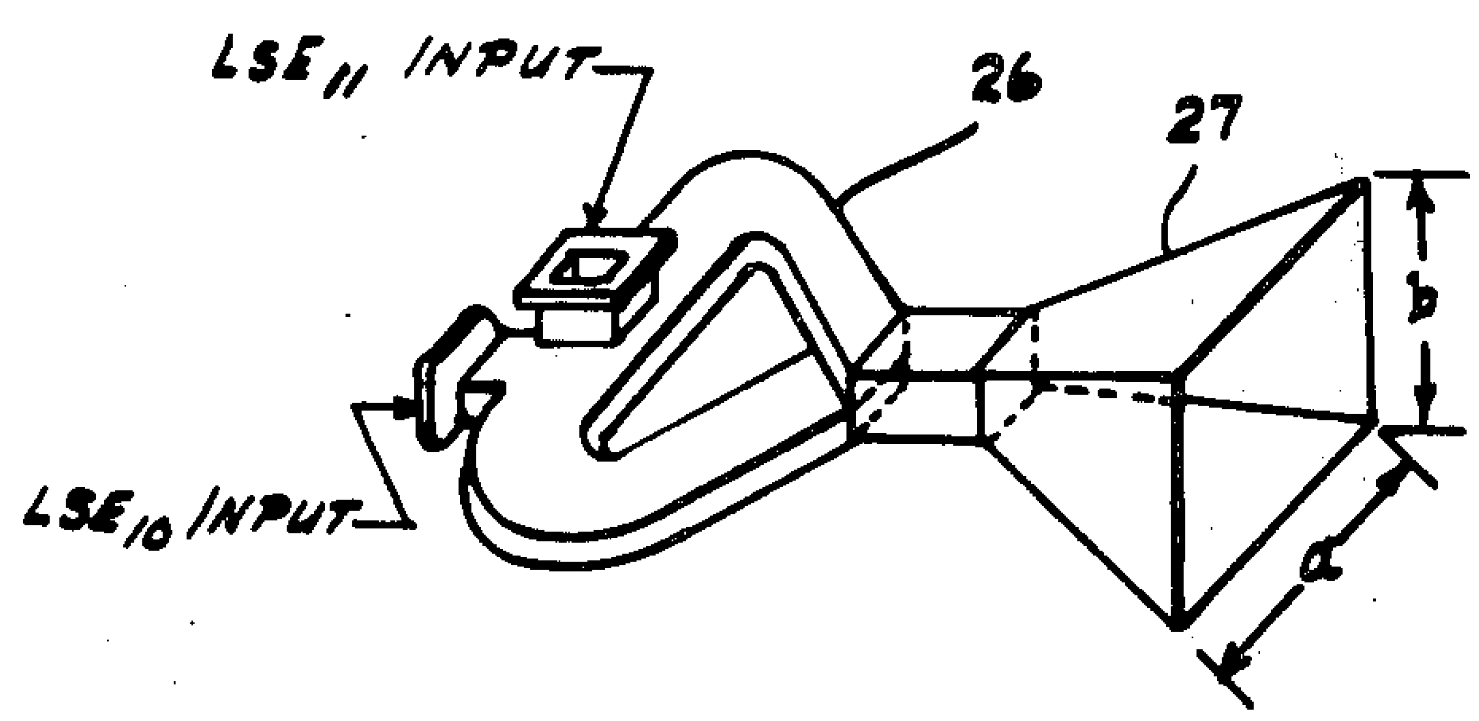


FIG. 1

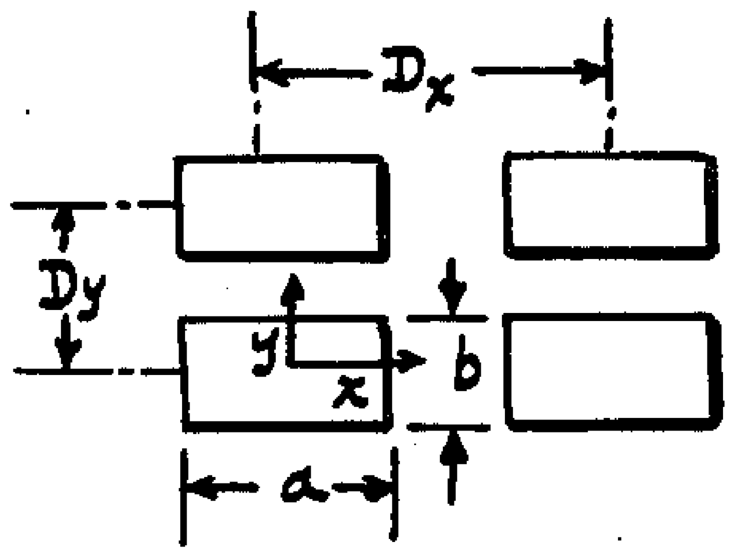
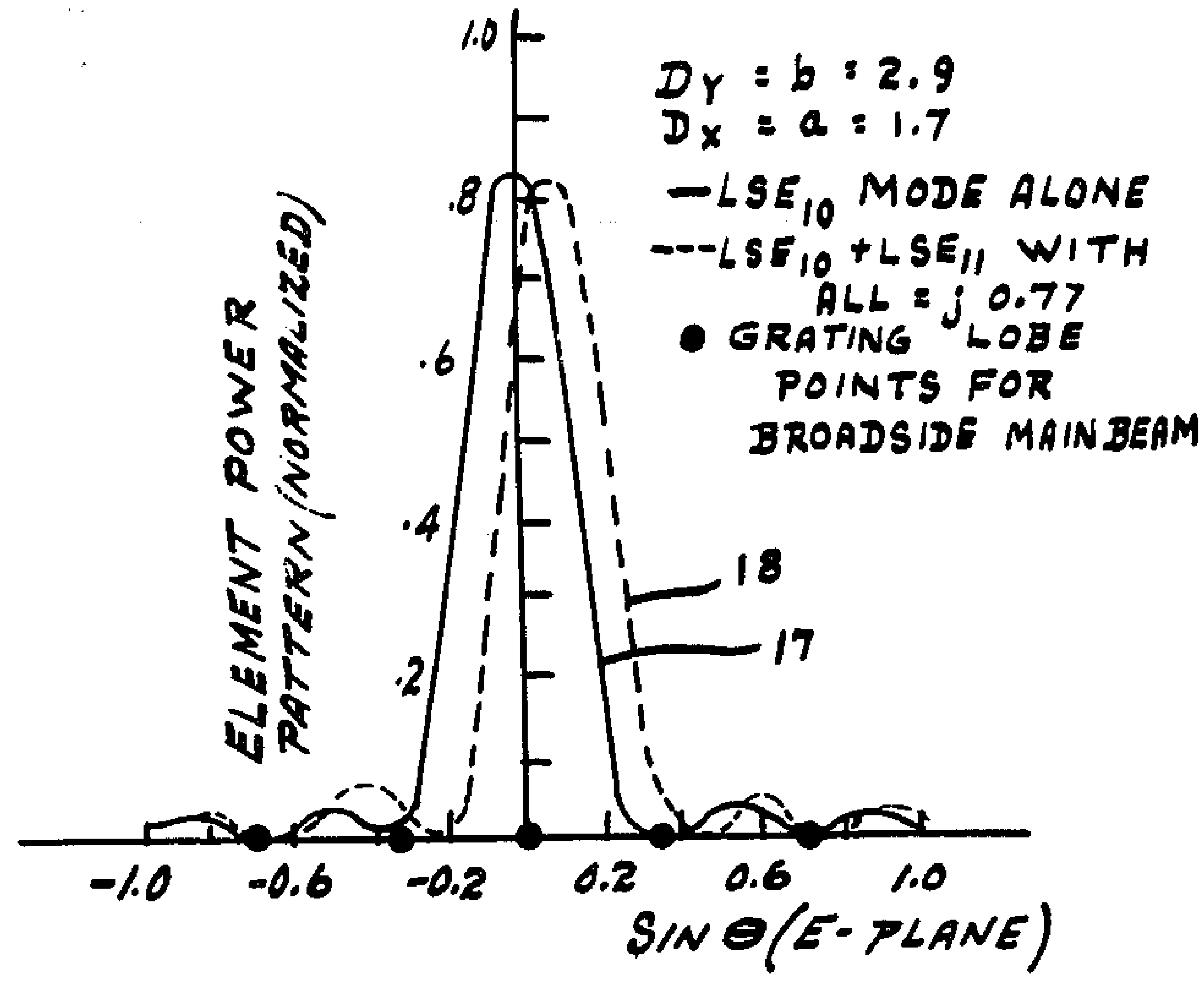


FIG. 2



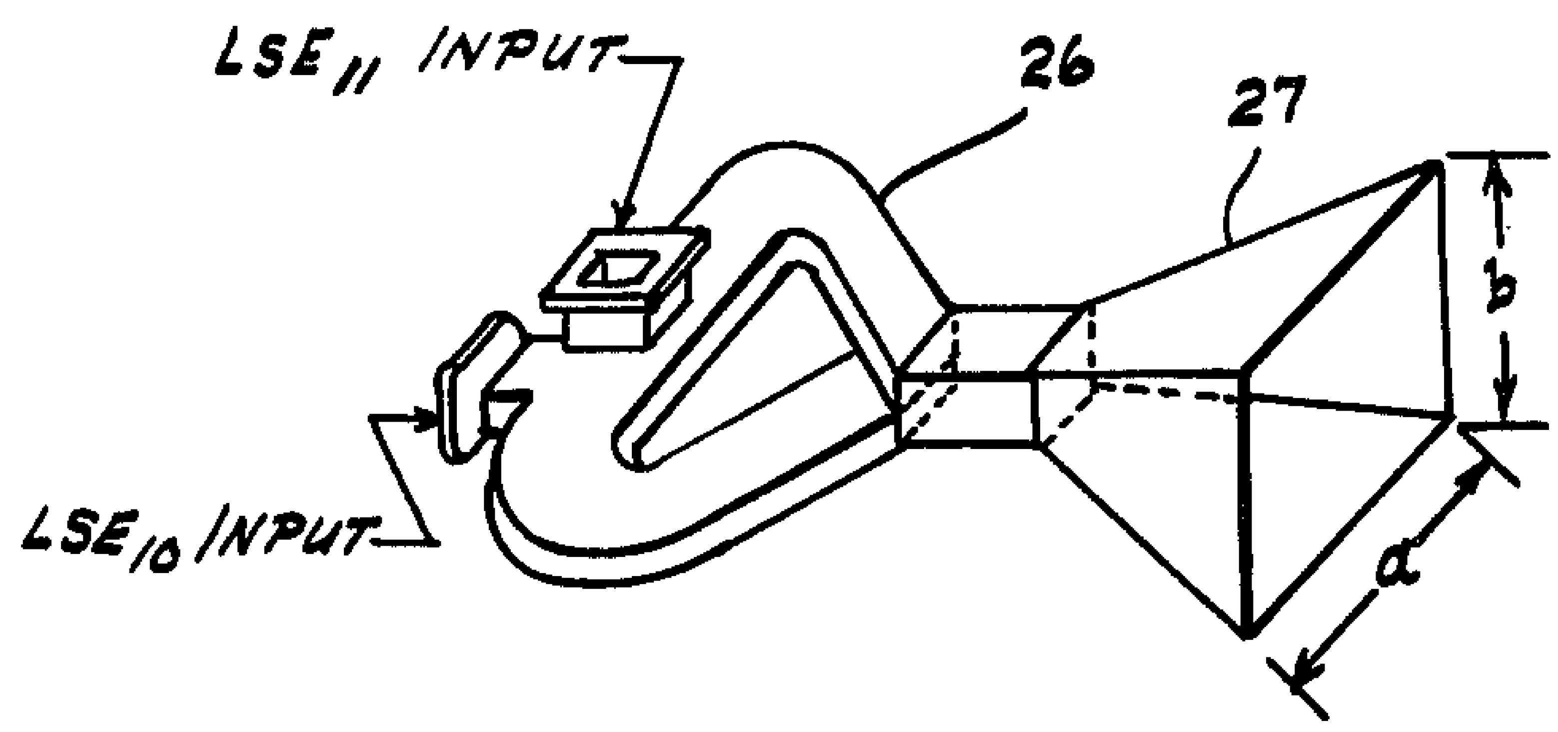


FIG. 3

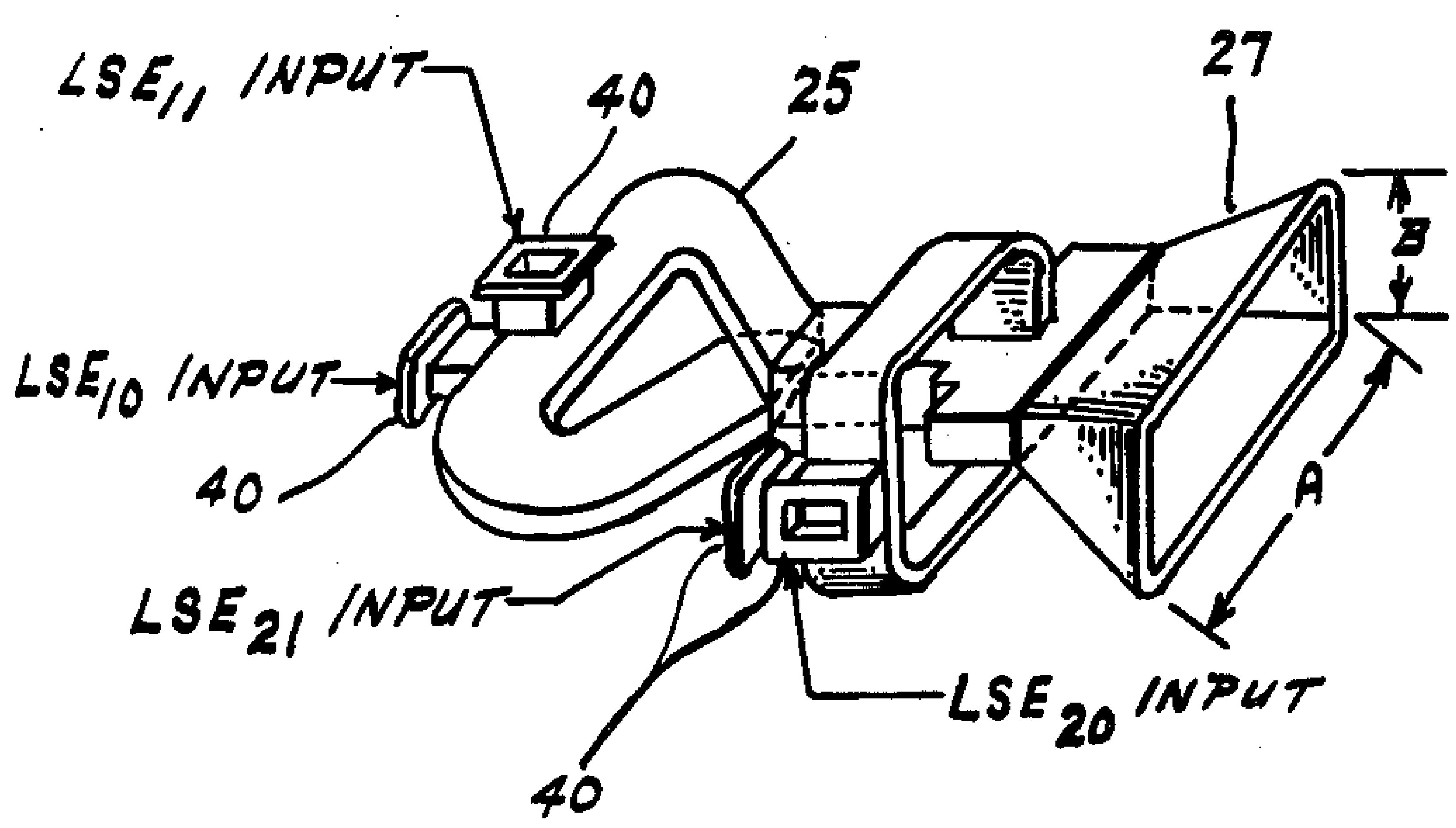


FIG. 11

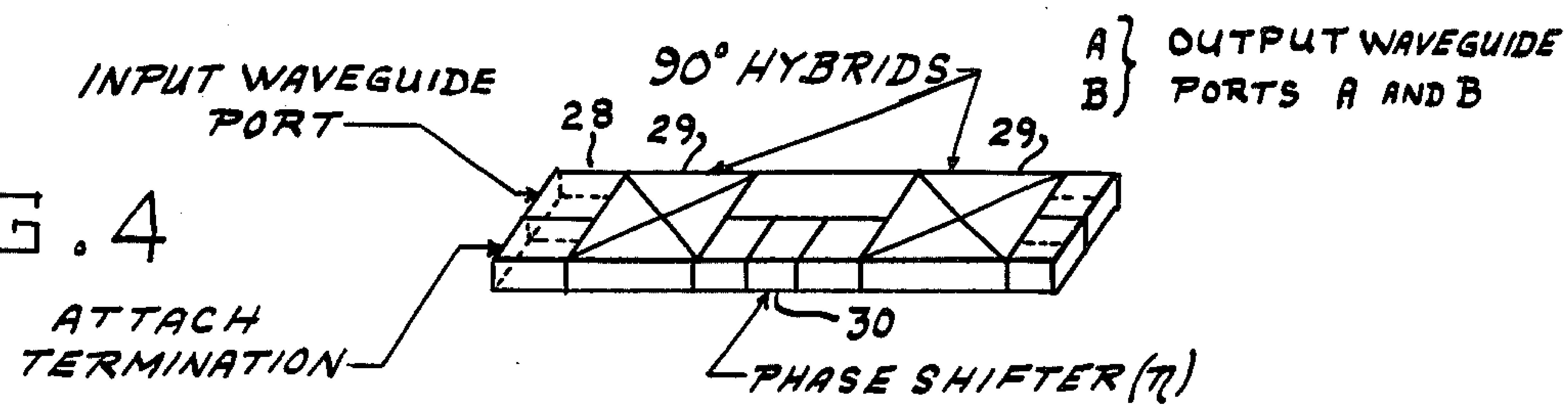


FIG. 4

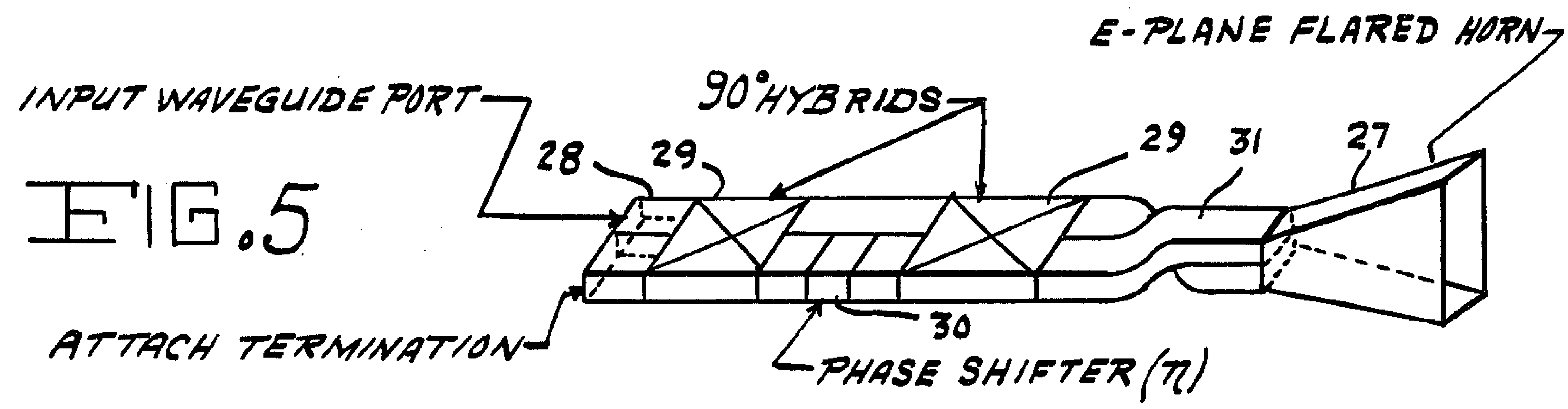


FIG. 5

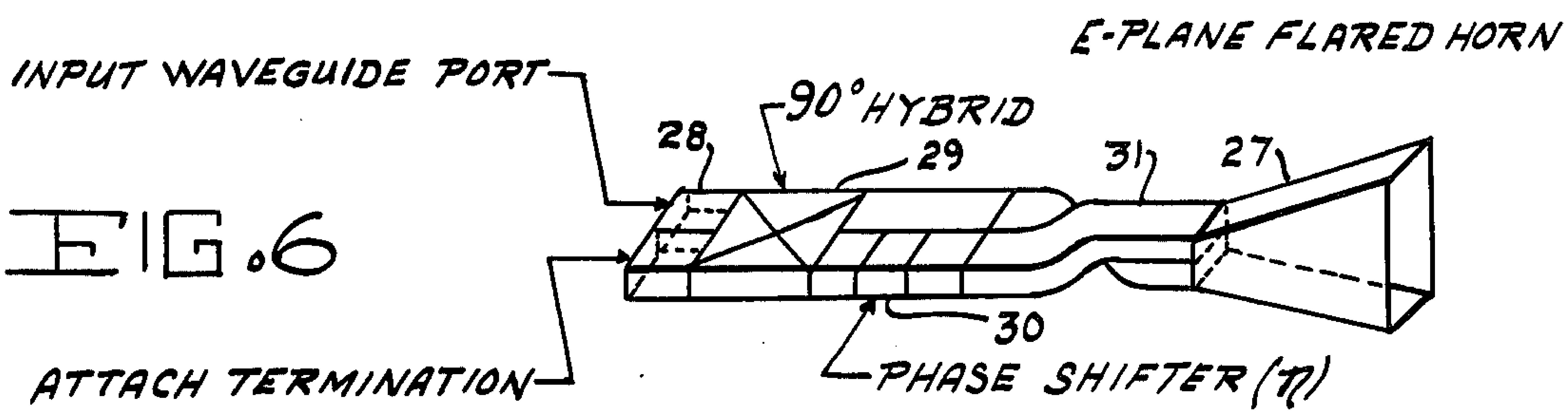


FIG. 6

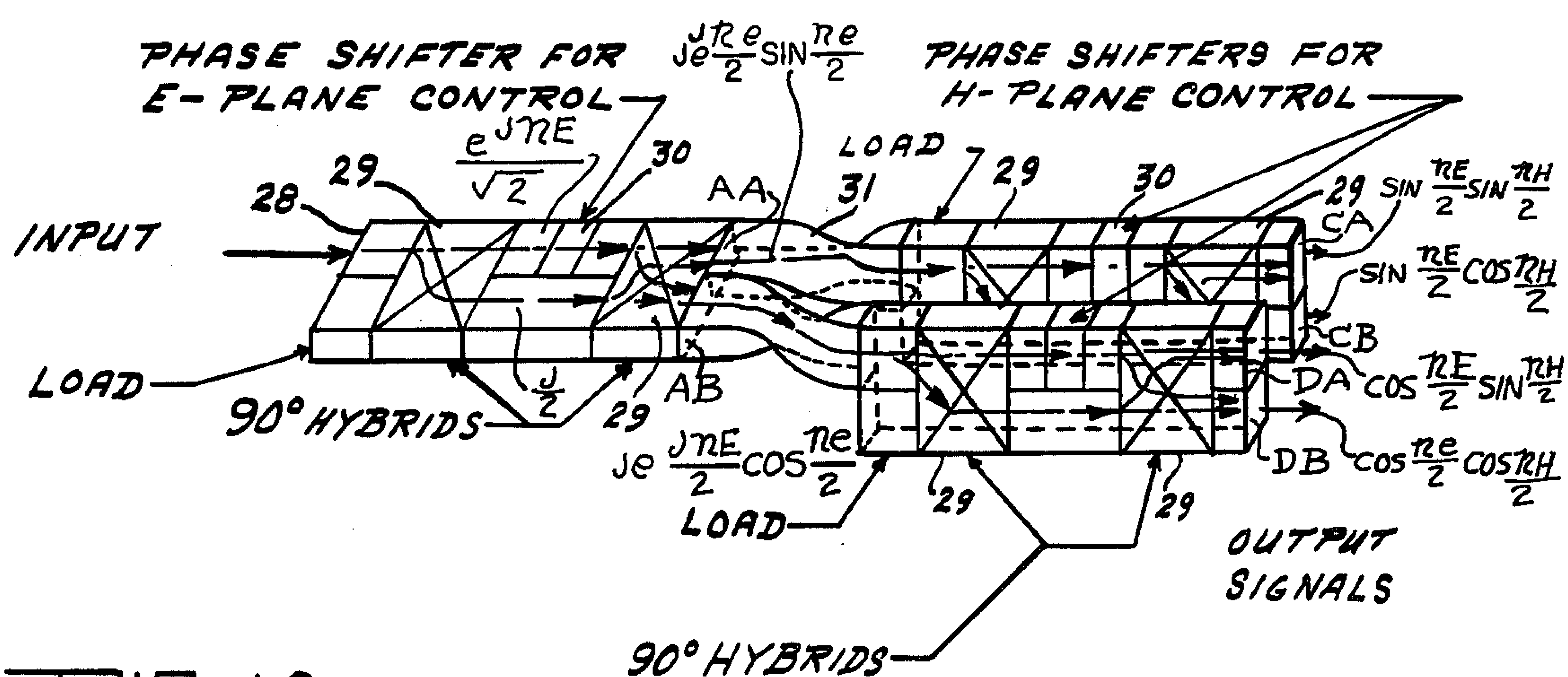


FIG. 10

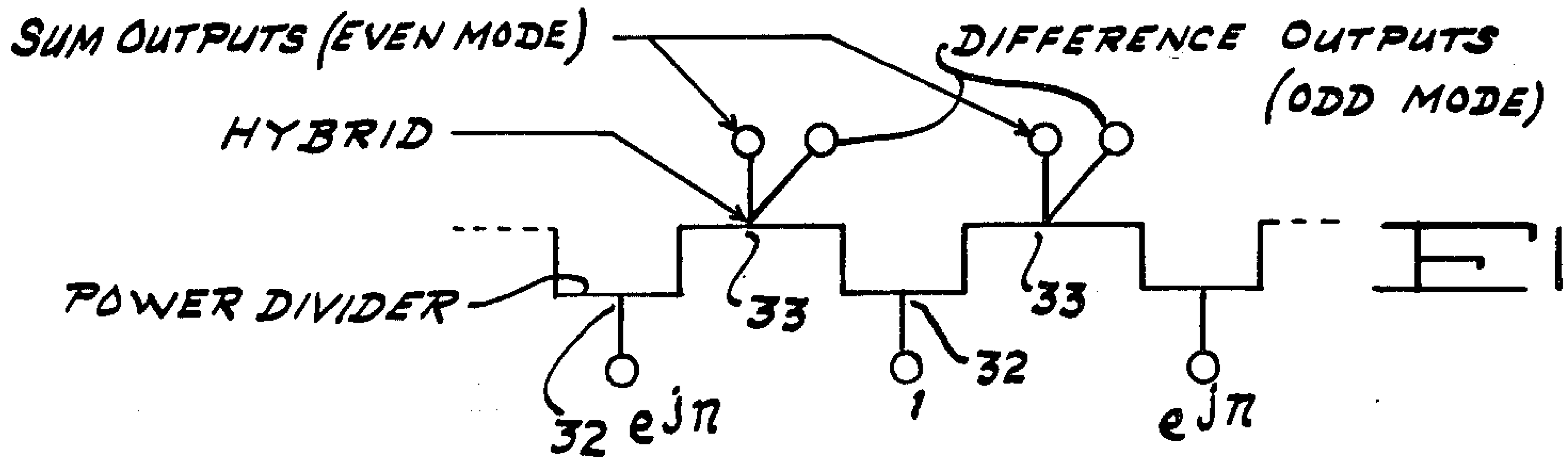


FIG. 7

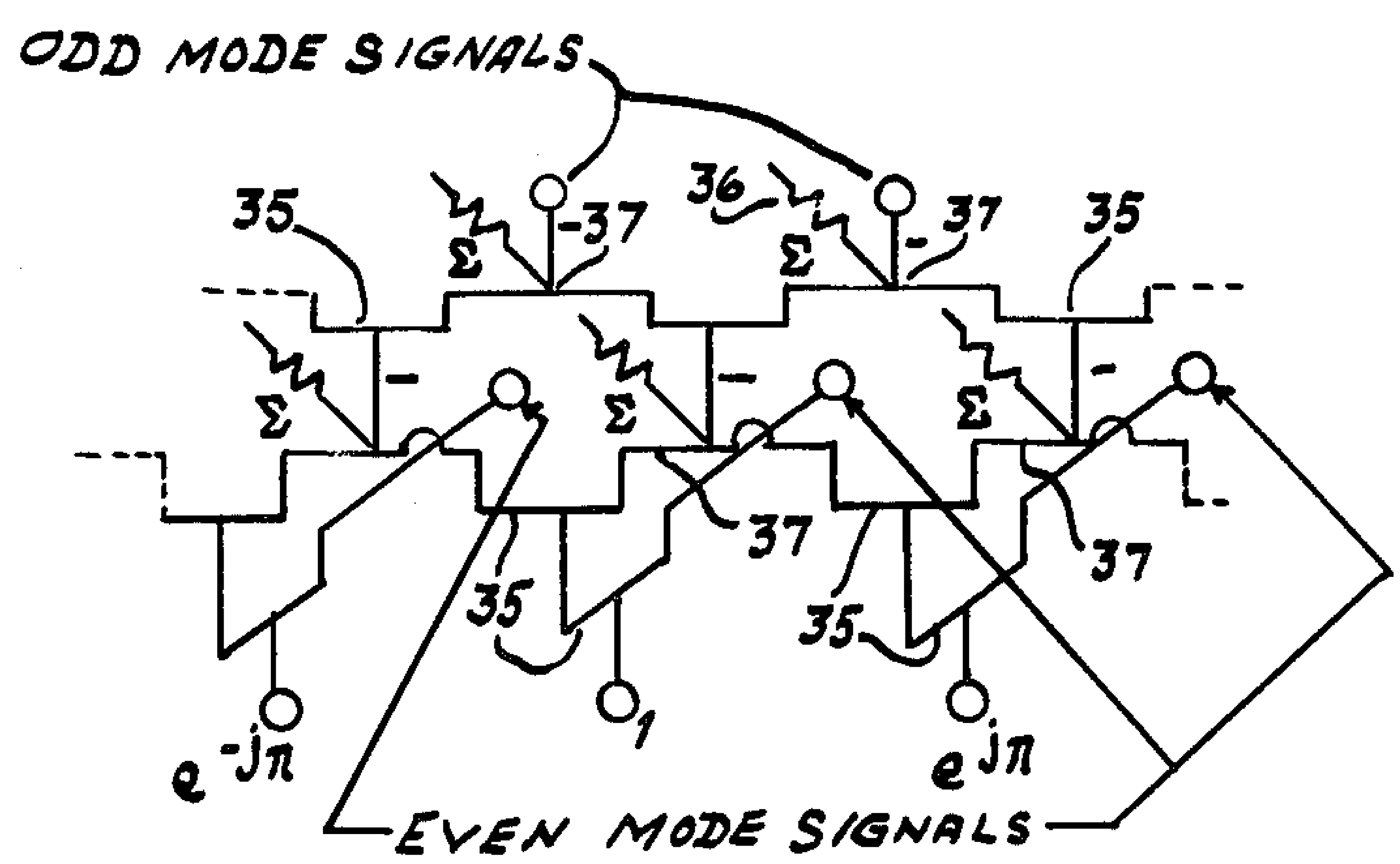


FIG. 8

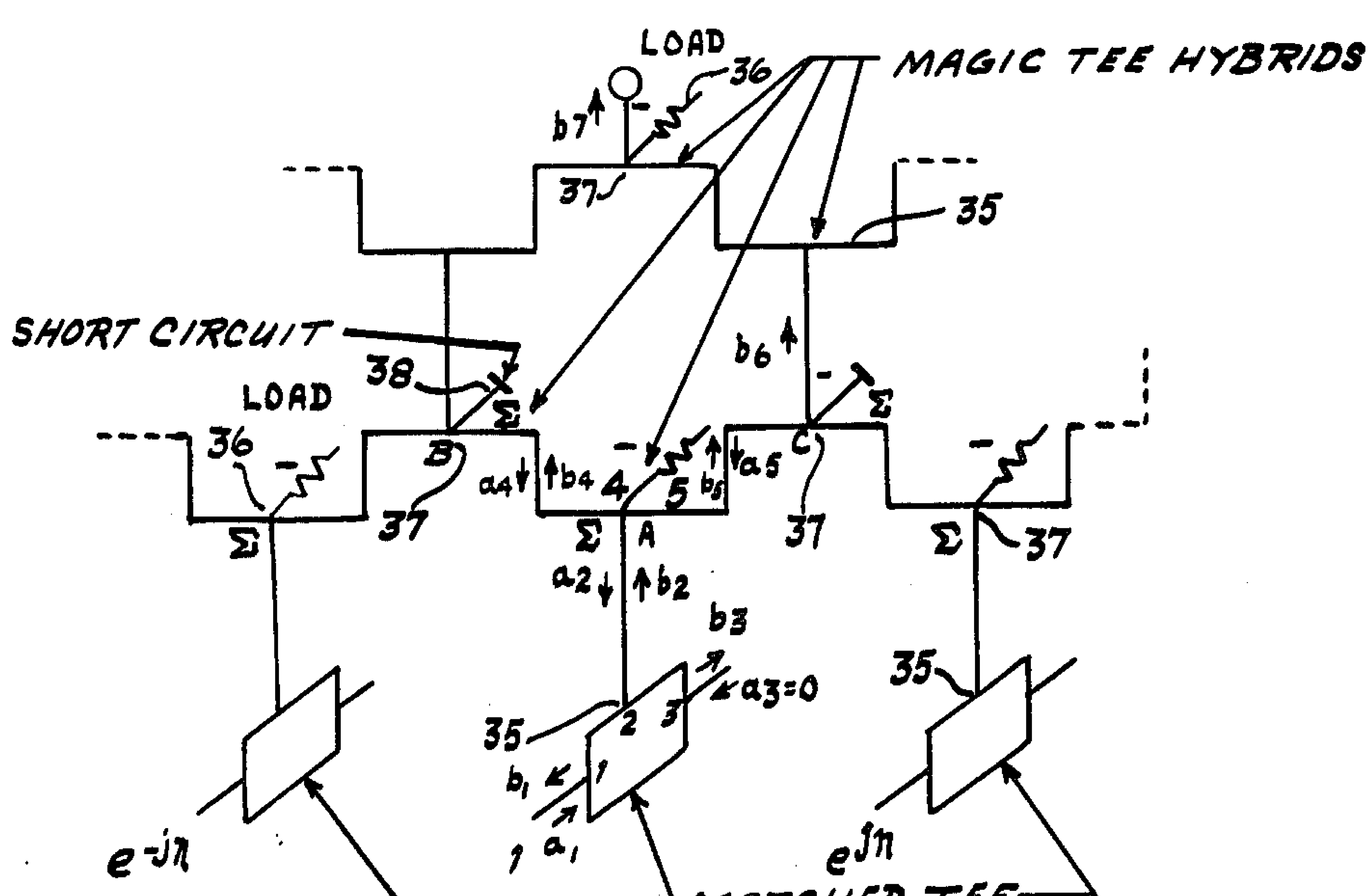


FIG. 9

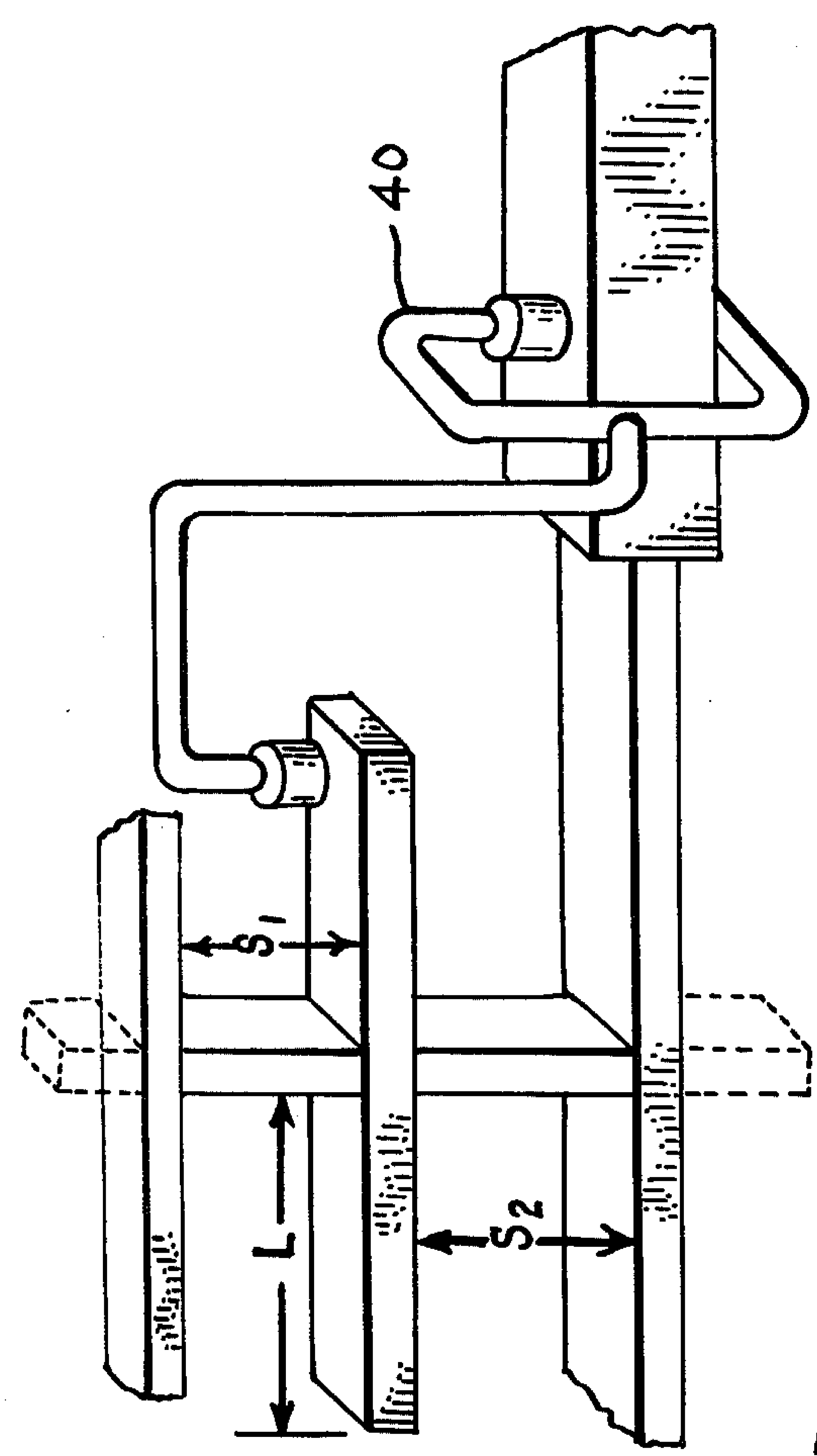


FIG. 12

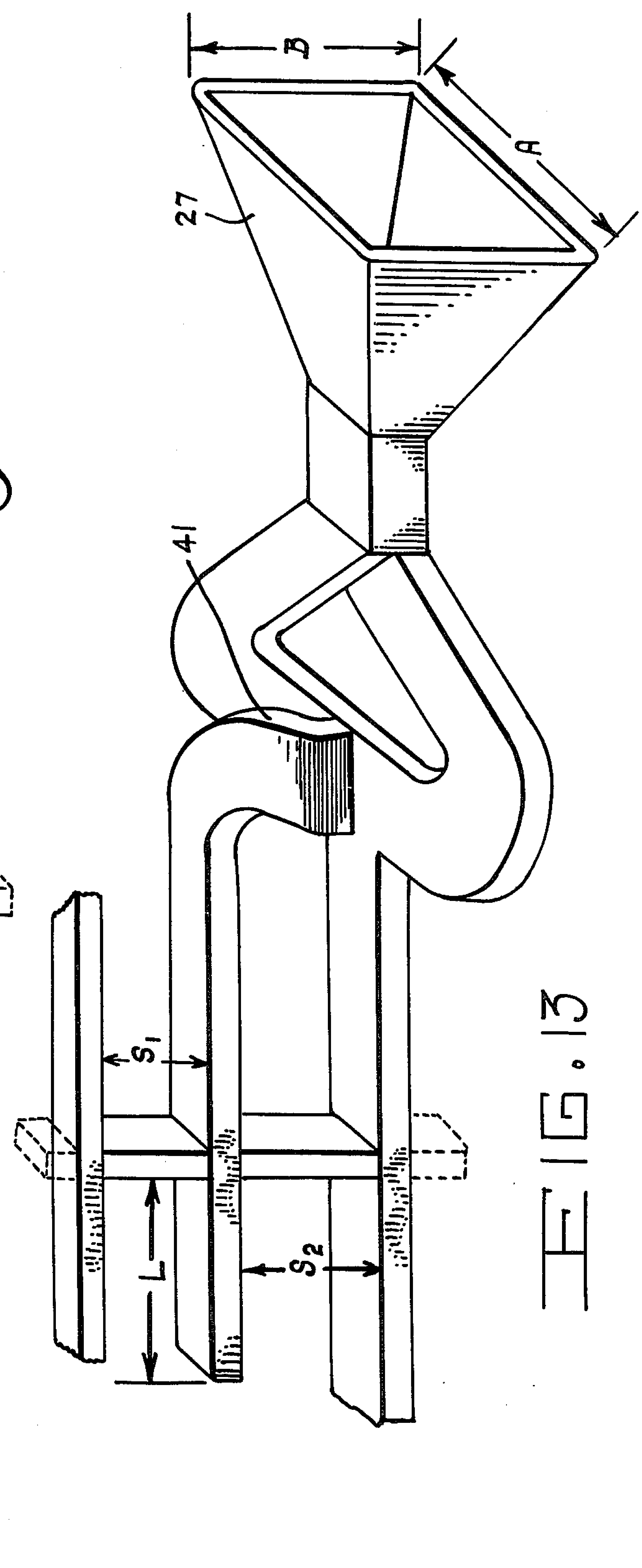


FIG. 13

FIG. 14

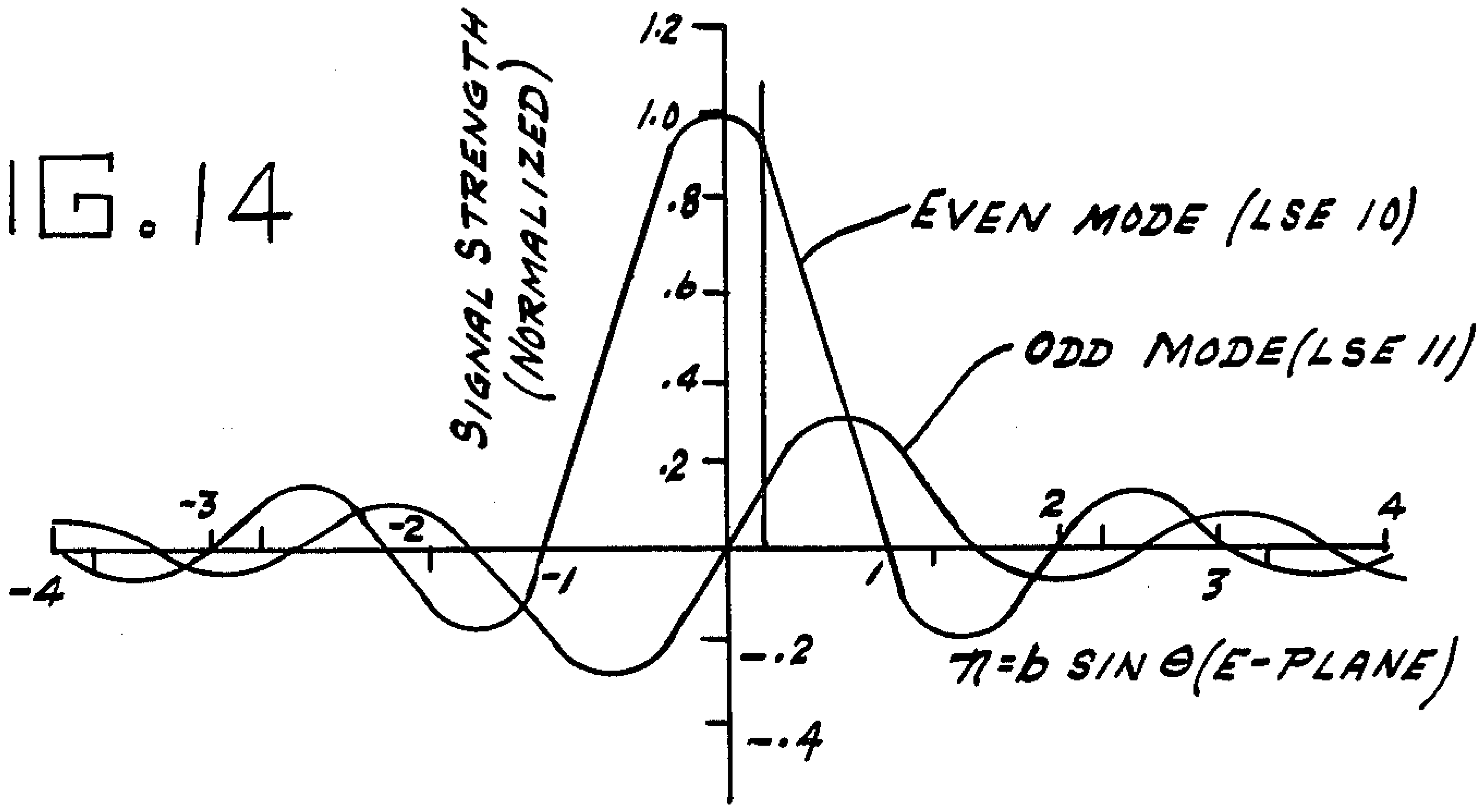


FIG. 15

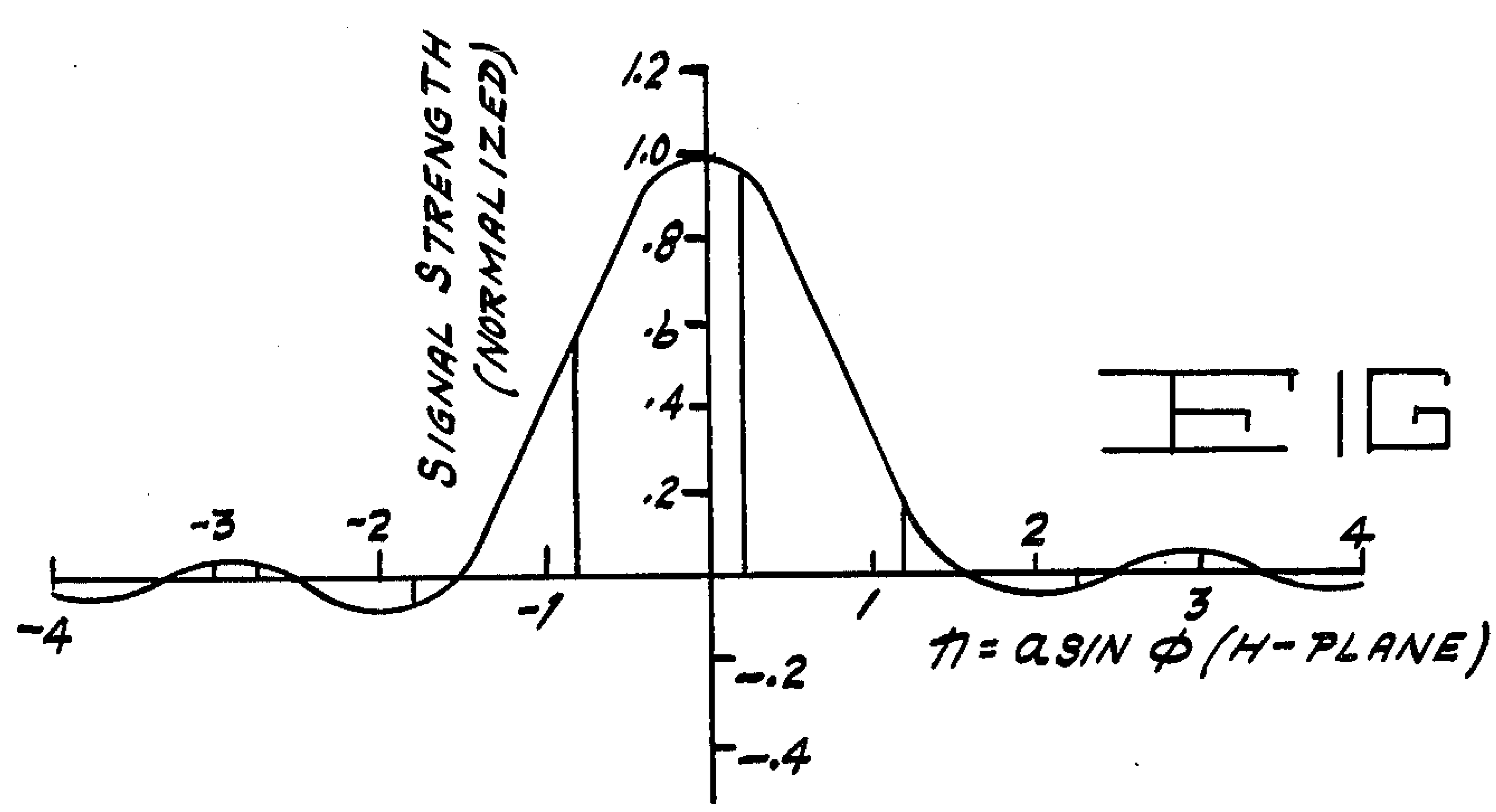
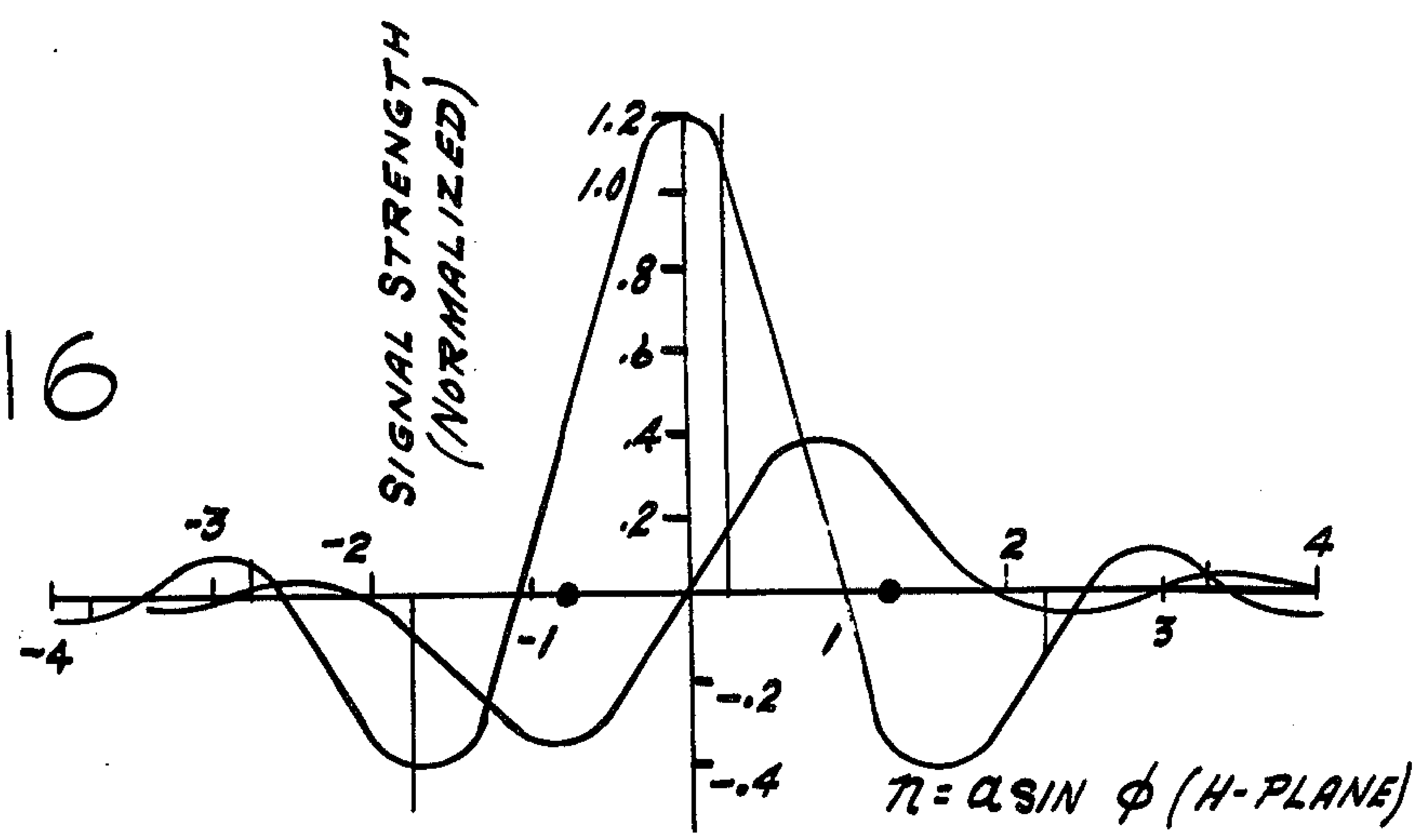


FIG. 16



METHOD AND APPARATUS FOR SUPPRESSING GRATING LOBES IN AN ELECTRONICALLY SCANNED ANTENNA ARRAY

BACKGROUND OF THE INVENTION

This invention relates to the suppression of grating lobes in electronically scanned antenna arrays, and more particularly to the reduction of such effects in limited scan applications using large array elements and sub-arrays.

There are many applications requiring a high gain antenna with electronic beam steering over a limited cone of angles near broadside. These include arrays for communication from synchronous satellites, for airport precision approach radars, and for shipboard use. Scanned reflector or lens antenna are most often proposed or used for these applications because of their high gain, their simplicity, and especially because they minimize the array problem. Unfortunately, their scanning capability decreases as the main reflector gain is increased, and seldom exceeds **15** reflector beamwidths. Moreover, these structures usually have low aperture efficiencies and so must be large as compared with an efficiently illuminated aperture. Finally, they suffer the phase shifter and scan loss of the phased array and the pattern degradation of the optical system.

With all of these admitted deficiencies and even in its present state of development, the scanned reflector and lens systems are still the only logical choices for most limited cone scanning systems because the cost, complexity, and weight of a fully steered phased array with the same gain are unreasonable.

Although until now phased arrays have been used to steer reflection antennas they have not been used alone for limited scan because of the large number of elements needed to achieve high gain without excessive grating loss. There currently exists, therefore, the need for apparatus that will provide limited angular scanning with a phased array of a few large elements. The present invention is directed toward achieving this and other ends.

SUMMARY OF THE INVENTION

Grating lobe suppression is achieved by driving each antenna element of an electronically scanned array with both even and odd mode power in each plane of scan. The fundamental even mode power for each antenna element is divided into two sources for each plane of scan. The divided sources are coupled to the antenna element in a manner that provides appropriate even and odd mode power. A ±90° out-of-phase relationship between even and odd mode power at the antenna element aperture is achieved by either feed circuit or antenna element design. The ratio of even mode power to odd mode power is varied as a function of the displacement of the main antenna beam from broadside. This is accomplished by various means including a waveguide power divider, phase shifter and coupling arrangement of the type used in monopulse horn antennas, and alternatively, a passive, reciprocal, linear circuit that utilizes the phase difference between adjacent radiating elements.

It is a principal object of the invention to provide a new and improved method for reducing grating lobes in an electronically scanned antenna array.

It is another object of the invention to provide apparatus capable of providing limited angular scanning with a phased array of a few large antenna elements.

These, together with other objects, advantages and features of the invention, will become more readily apparent from the following detailed description when taken in conjunction with the accompanying drawings in which like elements are given like reference numerals throughout.

DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates a rectangular grid array of rectangular antenna elements;

FIG. **2** is a curve illustrating element pattern shift due to the addition of odd mode aperture distribution;

FIG. **3** illustrates a microwave circuit for exciting LSE_{10} and LSE_{11} modes at input to a flared horn;

FIG. **4** is a basic power divider;

FIG. **5** is a feed circuit that accomplishes odd mode amplitude control with a power divider;

FIG. **6** is a feed circuit that accomplishes odd mode amplitude control using a simplified power divider circuit;

FIG. **7** is a schematic diagram of a circuit for passive odd mode control;

FIG. **8** is a schematic diagram of an alternative circuit for passive odd mode control;

FIG. **9** is a schematic diagram of a circuit for deriving odd mode control signals having good broadside radiation characteristics;

FIG. **10** illustrates a power divider circuit for scanning in two planes;

FIG. **11** illustrates a microwave circuit for scanning in two planes;

FIG. **12** is a circuit for odd mode excitation using waveguide probes;

FIG. **13** is a circuit for odd mode excitation using a hybrid;

FIG. **14** is a curve illustrating E-plane field patterns for LSE_{10} and LSE_{11} waveguide modes;

FIG. **15** is a curve illustrating the H-plane field patterns for LSE_{10} waveguide modes; and

FIG. **16** illustrates H-plane field patterns for LSE_{10} plus LSE_{30} waveguide modes combined for broadside grating lobe suppression and for LSE_{20} waveguide modes.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Phased arrays cannot in general be constructed with elements longer than a wavelength in the direction of either plane of scan because the resulting grating lobes absorb much of the power. Grating lobes can exist either because of an amplitude or phase taper in each element aperture which gives the arrays a scalloped aperture field distribution, or they can come about as the array is scanned because the single mode apertures can only stepwise approximate the linear phase taper which should be achieved for proper scanning of a phased array. Therefore, for elements longer than a wavelength in the scan plane, even if the power loss at abroadside is tolerable, the main beam power decreases much too rapidly with scan for most applications because the grating lobes nearest broadside grow as they move toward the element pattern maximum.

If the angle of main beam scan is θ_o, and the spacing between elements is D (normalized to wavelength), in the θ-plane, then grating lobes appear at the angles θ_n associated with

$$\sin \theta_n = \sin \theta_o + n/D \quad (1)$$

for any positive or negative integer values of n which define a real angle θ_n. The size of the grating lobes when $\theta_0 = 0$ (broadside) depends upon the amount of amplitude and/or phase scalloping in the basic array elements. If there is no scalloping in one plane, as in the E-plane of an array of thin walled horn apertures, then the field pattern of an element in the array (the array element pattern) will have a null at each n/D point in sin θ space excluding $n = 0$, and all of the grating lobes will have zero amplitude. This is the optimum pattern achievable and it is also the narrowest element pattern achievable without resorting to superdirective apertures. When there is scalloping, as in the E-plane with the normalized aperture width b less than the normlized spacing D, or in the H-plane of horn apertures, the first array element pattern nulls will occur for $\sin \theta > 1/D$ and therefore will be beyond the first grating lobes in|sin|θ space. All such arrays will have non-zero grating lobes at broadside.

The radiation characteristics of a very large array of waveguide apertures **16** is shown in FIG. **1**, and with four incident modes in each aperture (LSE modes **10**, 20, 11, 21) are approximately characterized by the equation given below (which is given in the form for an infinitely large array). The equation neglects mutual coupling and reflections at the element interfaces and is inserted here to illustrate the grating lobe locations and amplitudes. The radiated field strength at a point in generalized direction cosine space is:

$$E(\mu, v)=\sum_m \sum_n e^{-j\hat{k}_{mn}\cdot\hat{r}} [A_{10}F_{10}(\mu, v) + A_{11}F_{11}(\mu, v)+A_{20}F_{20}(\mu, v)+A_{21}F_{21}(\mu, v)] \quad (2)$$

where

$$\hat{r}=|r|(\hat{x}\mu+\hat{y}v+\hat{z}\cos\theta)$$

and

$$k_{mn}=2\pi(\hat{x}\mu_m+\hat{y}v_n+\hat{z}\cos\theta_{mn}).$$

The $F_{pq}(\mu, \nu)$ are element patterns for the mode with subscripts p, q, and the direction cosines μ and v are defined below in general, and for the specific grating lobe positions μ_m, ν_n for a main beam at $\mu_o = \sin \theta_o \cos \phi_o$, $\nu_o = \cos \phi_o \sin \phi_o$

$$\mu = \sin\theta\cos\phi$$

$$\nu = \sin\theta\sin\phi$$

The values m amd n are all integers for which the parameter

$$K_{mn} = 2\pi \sqrt{1 - \mu_m^2 - \nu_n^2} \quad (3)$$

is real, and so the above equation shows the field as made up of a set of plane waves radiating in the direction of the various allowed $\hat{k}mn$ values. The plane wave amplitudes are determined by the excitation coefficients $A\,pq$ of the four incident LSE modes and by their element patterns evaluated at the grating lobe points. Of particular importance is the fact that these element patterns are separable in the direction cosine space, that is:

$$F_{pq}(\mu, V) = g(p, \mu) f(q, v)$$

The lattice spacings are Dx and Dy and the apertures measure a and b in these same coordinates. All parameters are normalized to wavelength.

The assumption of four incident modes is necessary because the basic concept of the invention is to use these higher order modes to cancel the dominant unwanted grating lobes by placing nulls in the combined four mode element pattern. Only two incident modes (LSE10 and 11) are required for scanning in the E-plane ($\mu = 0$, $\nu = \sin\theta$), and in principle only two are required for scanning in the H-plane (LSE10 and 20). In practice some H-plane pattern shaping is also necessary, as will be described later. The dominant grating lobes cancelled with this invention are those nearest broadsides [$(m, n) = (-1, 0), (-1, 01)$] for general scan angles. Other choices of odd mode amplitude can be made which offer other advantages, for example, minimizing the total power in the sum of all grating lobes, but these possibilities follow directly from the basic concept of using odd modes for cancellation, as would be obvious to one skilled in the art.

One choice of modal amplitudes is made by designing the array element for each principle plane of scan. The grating lobe at $n = 1$, $m - 0$ with a given ν_o and with $\mu = 0$ (E-plane scan) can be eliminated by choosing A_{20} and A_{21} equal to zero, and selecting A_{11} so that

$$A_{11} = -[A_{10} F_{10}(\mu_o, \nu_{-1})]/F_{11}(\mu_o, \nu_{-1}) \quad (5)$$

Similarly, the grating lobe of importance (m=−1) for for H-plane (ν_o = O, $\mu_o = \sin\theta_o$) scan is eliminated by choosing A_{11} and A_{21} equal to zero, and selecting A_{20} so that: $A_{20} = [-A_{10} F_{10}(\mu_{-1}, \nu_o)]/F_{20}(\mu_{-1}, \nu_o)$ (6)

Both of these choices imply that the odd mode amplitudes be ± 90° out of phase with the even mode amplitude and that the A_{11} and A_{20} amplitudes vary with scan. When scanning in a skew plane, these two grating lobes must still be cancelled, and the equations above remain the same. In addition, the grating lobe at $(m-, n) = (-1, -1)$ must also be cancelled, and because of the separability condition one can obtain the required A_{21} value from the relation.

$$A_{21} = A_{20} A_{11} / A_{10} \quad (7)$$

With this choice, the bracketed term of equation (2) is:

$$A_{10}[f(0, \nu) + (A_{11}/A_{10}) f(1, \nu)] \cdot [g(1,\mu) + (A_{20}/A_{10}) g(2,\mu)] = A_{10} F(\nu) G(\mu) \quad (8)$$

This equation shows the separable nature of the combined four mode element pattern, and indicates the modal choice that can provide simultaneous cancellation of the three nearest grating lobes.

In the case of E-plane scan with thin walls, E-plane and intercardinal plane grating lobes are null when an array with $b = D_y$ is phased at broadside. Only the H-plane grating lobes remain. As the array is scanned in the E-plane the grating lobes move out of the element pattern nulls, but if the A_{11} mode amplitude and phase is chosen as noted above, then not only is the $n = -1$, $m = 0$ mode cancelled, but in fact all of the E-plane and intercardinal plane grating lobes are very substantially reduced. This is because, to a first approximation, the entire set of element pattern nulls moves so as to align with the grating lobes points of the new scan angle.

FIG. **2** shows a comparison of several element patterns, curve **17** illustrating a single LSE_{10} mode, and curve **18** illustrating an element using odd mode LSE_{11} signals with an amplitude given by Equation (7) in addition to the even mode signal. The total transmitted power is kept constant. With the A_{11} mode amplitude and phase chosen as noted above, not only is the $n=-1$, $m=0$ mode cancelled, but in fact all of the E-plane grating lobes are very substantially reduced. This is because, to a first approximation the entire set of element pattern nulls moves so as to align with the grating lobe points of the new scan angle. The main feature of the technique is to laterally displace the entire element pattern in $\sin \theta$ space.

In the case of the H-plane scan, if the aperture is excited by waveguide horns with width greater than a wavelength, grating lobes exist even for the main beam at broadside because the element pattern nulls occur beyond the grating lobe points. An odd mode amplitude can still be chosen to cancel the $m=-1$ lobe even when the array is at broadside, but it will in general increase the size of the $m=+1$ grating lobe.

Therefore, for the H-plane case with scalloped element patterns (horns) some spatial filter technique may be desirable to suppress the grating lobes at broadside before applying the oddmode scheme described herein. Such techniques do exist and are described in the literature as schemes for increasing horn aperture efficiency and decreasing beamwidth. Typical of these is the boxhorn in which an abrupt discontinuity is used to excite the LSE_{30} mode with proper amplitude and phase to significantly increase the H-plane aperture efficiency.

The salient features of the basic E and H-plane element patterns, as well as those of the H-plane with broadside grating lobe suppression are noted below.

Having reference to the E-plane case, the fundamental mode LSE_{10} radiation pattern, shown by curve **21** in FIG. **15,** has zeros at $b \sin \theta = \pm n$ for $n \neq 0$. It has a maximum at $\sin \theta = 0$, and its half power points are approximately 0.89 apart on the $b \sin \theta$ axis.

The grating lobes occur spaced a distance $D_y \sin \theta = \pm n$ on the $b \sin \theta$ axis, and so if $b = D_y$ these occur at the element pattern nulls when $\sin \theta_o = 0$.

The first odd mode (LSE_{11}) whose radiation pattern is also shown by curve **22** in FIG. **14,** has a null at $\sin \theta = 0$ and has zeros at $b \sin \theta = \pm 5/2$, etc., but not at $\pm 1/2$.

The first maximum of the LSE_{11} mode is at $b \sin \theta = 0.75$, and the odd mode half beamwidth is approximately 0.33 on the $b \sin \theta$ axis. Given these facts, one may conclude that the odd mode radiation can be made to cancel the even mode radiation from $b \sin \theta_o = 0$ until the $n=-1$ grating lobe is at the half power point of the odd mode, that is at

$$D_y \sin \theta_{-1} = -0.75 + 0.33 = -0.42.$$

When $b = D_y$ the main beam is at the angle

$$b \sin \theta_o = 0.58 \quad \sim 0.6 \qquad (9)$$

for this case. This formula gives the limit of practical scan correction using this technique for E-plane scan. FIG. **14** shows a sketch of the E-plane field distributions $f(0,\nu)$ and $f(1,\nu)$ as a function of $b \sin \theta$ over the region $|b \sin \theta| \geq 4$. The amplitude of the odd mode distribution $f(1,\nu)$ is chosen so that the addition of this curve to the $F_{10}(\theta)$ gives a null at $b \sin \theta = 0.75$, and if $b = D_y$, this corresponds to a choice of main beam at $\sin \theta = 0.25$. This curve also points out that the grating lobes at $\sin \theta = 1.75, -2.75, -3.75, 1.25, 2.25$, and 3.25 all tend to cancel. These curves also reveal that if the main beam is scanned out be $b \sin \theta = 1.5$, the odd mode no longer has any influence on each of the grating lobes since the odd mode zeros are there. There are also the points where the LSE_{10} mode has its maxima, so although the $n=-1$ lobe is cancelled, the grating lobes are seen directly at the maximum sidelobes of the LSE_{10} mode. Since the odd mode power is large for $b \sin \theta = 0.5$, the $n = \pm 1$ grating lobe has approximately 3 db less power than the sidelobe at that point (13 db). Furthermore, this 16 db ratio must be multiplied by the cosine of the scan ratio to account for the projection factor of the finite array, and this adds an extra 1 db suppression of the $n=+1$ grating lobe for D_y equal to three or less. Equation (9) therefore provides a practical approximation of the allowable E-plane scan angle for a given aperture size.

Referring now to the H-plane case $\phi=0$, the fundamental mode LSE_{10} radiation pattern, shown by curve **23** in FIG. **15,** has H-plane zeros at a $\sin \phi = 1.5, \pm 2.5$, etc.

The grating lobes occur at $D_x \sin \theta = \pm n$ excluding $n=0$.

The odd mode (LSE_{20}) nulls shown by curves **24** and **25** in FIG. **16** are at a $\sin \theta = \pm 2, \pm 3, \ldots$, and the first maximum of the odd mode pattern occurs at approximately a $\sin \theta = \pm 0.77$. This is very close to the position of the E-plane odd mode maximum, and since the H-plane and E-plane odd mode beamwidths are not very different one can expect that if the grating lobes which exist for broadside can be tolerated or removed by pattern shaping, then the formula given for the E-plane limit is also approximately true in the H-plane,

$$a \sin \theta = 0.58.$$

The TE and TM waveguide modes with odd aperture field symmetry in the E-plane also have cross-polarized radiation fields. Proper combinations of the TE_{11} and TM_{11} modes form the linearly polarized LSE_{11} mode, the desired waveguide mode for E-plane control using this technique. The LSE_{20} mode is used for H-plane control. One circuit for exciting the LSE_{11} mode is shown by waveguide **26** and horn **27** of FIG. **3,** an equivalent magic-tee circuit for H-plane control is also simply implemented. Power dividers are required with division ratios variable with scan and which must maintain a $\pm 90°$ phase difference between the odd and even modes. One such circuit is shown in FIG. **4** and comprises input waveguide port **28,** 90° hybrid **29,** and phase shifter **30.** This well known circuit provides signals at its two output terminals which are exactly out of phase, and given by

$$e^{j\eta/2} \sin \eta/2 \text{ and } -e^{j\eta/2} \cos \eta/2$$

apart from a constant phase factor, where n is the delay of the phase shifter shown in the figure. If one of these outputs is used as the source of odd mode signal and one as the source of even mode signal, and these are applied to the circuit of FIG. **3,** then varying η will provide the proper odd mode signal for scanning with a fixed phase relationship between even and odd modes. For example, if $\eta = 180°$ is chosen for broadside, all the power will appear at arm B; choice of η less than 180° will scan the beam in one direction, and more than 180° will scan it in the other. In both cases a ± 90° phase difference must appear at the aperture, and this can be adjusted by proper choice of line lenghts taking into account that the even and odd modes propagate with difference phase velocities. The phase shift η is the same for each horn, and this simplifies the control requirements considerably.

A second circuit for performing the scan function and which can also be implemented using the power divider circuit of FIG. 4 is shown in FIG. 5. This circuit includes the elements of FIG. 4 plus a waveguide power plane converter **31.** In this case the outputs at ports A and B are combined directly at the input of the horn, and so in the E-plane case, form the excitation of the symmetric LSE_{10} and antisymmetric LSE_{11} modes directly with amplitudes given by ($\cos \eta/2 + \sin n/2$) and ($\cos \eta/2 - \sin \eta/2$). The proper selection of η and the proper use of waveguide and horn propagation characteristics allows the ±90° phase relationship to be maintained throughout the scan plane. This circuit differs from the one previously discussed because, though requiring one less hybrid, it does not allow the odd and even modes to be treated (delayed, advanced in phase or attenuated) separately, and since they are not separately accessible it requires a more complicated waveguide design to achieve the 90° relationship.

The simplest circuit of this type, shown in FIG. **6**, is derived by omitting the second hybrid of FIGS. **4** or **5** and merely using the phase shift difference to derive even and odd components for application to the horn as in FIG. **5.** Since the two modes propagate with different phase velocities, it is possible to choose the line lengths to obtain excitations with $e^{j\eta/2} \sin \eta/2$ and $e^{j\eta/2} \cos \eta/2$ dependence upon the inserted phase shift, as required for circuit behavior. The insertion loss of the phase shifter n enters into the scan characteristics of each circuit slightly differently and must be taken into account in the choice of a final design.

The circuits described above all require phase shifters for power division. Their main advantage is that they are low loss power dividers, and their main disadvantage is that one extra phase shifter is needed for a single plane of scan, three are needed for a single plane of scan, and three are needed for scan in two planes. Since all elements require the same power division ratio, the system control circuitry is substantially simplified, but for applications requiring a lightweight antenna this increase in the total number of phase shifters may detract from the attractiveness of this technique.

Alternatively, power divider circuits based upon the use of switches and hybrids or directional couplers can also provide lossless power division, and may in some cases be lighter or more compact.

A third possibility is the use of passive, reciprocal, linear circuits to perform the power division. One class of such circuits uses the phase differenc between adjacent radiators to derive odd and even mode signals. FIG. 7 comprising the network of pulse divider **32** and hybrid **33** shows the simplest of these, in which adjacent signals are split in half, added and subtracted. The sum and difference signals are:

Sum: $e^{j\eta/2} \cos \eta/2$

Difference: $je^{j\eta/2} \sin \eta/2$ The ratio of the difference signal to the sum signal changes sign on either side of broadside as determined by the relative phase difference N at the input. The ratio is infinity at $n = \pi = (d \sin \theta)2\pi$, but the null formed by this choice of signal distribution is much further out in angle than the beam which is being formed. In any case, even if the odd mode is attenuated, an absolute scanning maximum is between $D \sin \theta = 0.45$ and 0.5. Instead of deriving these signals separately, it is only necessary to combine the signals $e^{jn}/\sqrt{2}$ and $1/\sqrt{2}$ in one oversize waveguide, (in the manner of FIG. **5**), and that the even and odd modes thus excited will have the same variation within as indicated above. The circuit described above does not provide a particularly optimum choice for scanning out ot the $D \sin \theta = 0.5$ point because the even mode signal gets small so quickly that the element pattern null is always at an angle much further out than the array scan angle. One way around that problem is to derive an odd mode signal by sampling the incident signals, forming the sum (even) and difference (odd) parts of these samples, and simply throwing away the even part. The circuit of FIG. **8** comprises the network of Tee **35,** magic Tee **37** and load **36** and shows one means of achieving this end. If about one half of the power is taken out of the basic circuit, and combined with the adjacent signal in a difference hybrid and the result of this combined again with each adjacent signal in a difference hybrid, the resulting signals will be proportional to $\sin^2 \eta/2$ and will be at the proper phase angle for reintroduction into the odd mode arm. If exactly one half of the power is used, the ratio of odd to even power at $D \sin \theta = 0.5$ will be unity, and this is only slightly greater than that required for this scan position. In addition, the $\sin^2\eta/2$ behavior near $\eta = 0$ makes the scanning more nearly correct for those angles. This circuit has two disadvantages: (1) its behavior is an even function of N, and so does not introduce the required 180° shift when scanning across, broadside; and (2) more important, approximately one-half of the power is lost at broadside when scanning out to the $D \sin \theta_{max} = 0.5$ limit is desired. The first of these is easily remedied by introducing a 180° switching operation, but the power loss at broadside can be avoided either by not introducing any off mode signal until the main beam is scanned a given amount off broadside, or by re-using the power that would otherwise be lost at broadside. The first solution is impractical because it allows scan only out to approximately $D \sin \theta = 0.1$ (for 20 db grating lobe suppression) before the odd mode signal is required, and at this point most of the signal is still lost once it is switched into the network. The second alternative is shown by the network of Tee **35,** magic Tee **37,** loads **36** and short circuits **38** of FIG. **9** and consists of re-using some of the power at the sum terminals of the magic tee. At broadside, the line lengths are adjusted to provide an apparent short circuit at the waveguide-tee and all of the incident power is properly distributed to the even mode port. At $D \sin \theta = 0.5$, the ratio of odd mode to even mode power is two, corresponding to an element pattern null beyond the 0.5 point. (this is also the occasion of a 25 percent power reflection in the main line.) A further increase in $\sin \theta$ decreases the ratio of odd mode to even mode power until a crossover point is reached where the element pattern null is exactly where it should be for the given array pattern. This alternative does not change relative power ratios, because when these signals are recombined with the line signal at the hybrid summing network and this network is lossy whenever the signals are not equal. This loss accounts for one quarter of the power at D sin $\theta = 0.5$. In either case, this circuit and the one of FIGS. **7** and **8** must be used with a 180° phase reversal to scan to either side of broadside.

FIGS. **7** and **9** are shown using a second magic tee to derive an odd mode signal at each Nth port with phase progression $N\mu/\pi$, where $\eta = 2\pi D \sin\theta$. This second tee was necessary because the odd mode output of the first tee was in phase with $N\eta/\pi$, and so could not be adjusted to provide a constant 90° phase difference from the even mode signals at phase $N\eta$. Alternatively, this hybrid can be omitted, and the odd mode signal at $N\eta$ can be applied directly to the odd mode port. If this signal is added so that it would be in-phase with the even mode signal $D \sin\theta = 0$, then at $D \sin\theta = 0.5$ this signal would have the required 90° phase difference from the even mode. Though the phase difference is not correct for small angles of scan, the odd mode amplitude is small then, and reasonable scanning properties can be obtained. The advantage of this process is the elimination of one hybrid. A 180° switch is still required to go from a positive to a negative scan sector.

The waveguide circuits of FIGS. **12** and **13** show schemes for implementing the sin $\eta/2$ structure of **7.** These are shown in waveguide and use either probe **40** (FIG. **12**) or a magic tee coupler **41** (FIG. **13**) to form the proper odd mode signal. The dimension L provides a ¼ λ short and $S_1 - S_2 = ½\ \lambda$ so signals will subtract and go to the horn. The geometry shown is for E-plane scan, but it is obvious that an H-plane version could also be designed using the folded hydbrid of FIG. **3.**

The principle of using an odd mode to cancel at least the first grating lobe of a phased array scanning in a plane leads to the requirement of a separable distribution for scanning of either principal plane.

This distribution can be achieved using a minimum number of power divider circuits if it is done sequentially as shown in FIG. **10.** In this case, three power dividers are required for each horn element to scan in two planes. The horn element can be like the one shown in FIG. **11** with separate input ports **40** for each mode, and in this case each power divider functions like that of FIG. **4** to completely serparate the even and odd modes. Alternatively, the horn element can be like that of the one plane geometry shown in FIG. **5** in which even and odd modes are combined in the appropriate ratios. In this second case, great care must be taken to maintain the desired phase relationships between the modes which all propagate with different phase velocities in the horns. The odd mode concept for two planes of scan requires $3N^2$ power dividers, where N^2 is the number of elements in the square array. If phase shifters are used in the power dividers, then a total of $4N^2$ phase shifters are required to steer the beam and suppress the grating lobes.

The operation of the circuit shown in FIG. **10** is explained as follows, for the special case of use with the feed of FIG. **11.** This circuit consists of three conventional variable power dividers, the first one controlled by the inserted phase shift η_E for E-plane/control, and the second two controlled by the identical inserted phase shifts for H-plane control. The output ports AA, AB of the first power divider have signals

$$\begin{aligned} &\text{at A A ; } j\ e\ j\ \eta_E/2 \sin \eta_E/2 \\ &\text{at A B ; } j\ e\ j\ \eta_E/2 \cos \eta_E/2 \end{aligned} \qquad (10)$$

These are the input signals for the other two power dividers, which operate in the same manner as the first to give at the output ports (suppressing the $e\ {-j}\ \eta_E/2\ e\ {-j}\ \eta_E/2$):

$$\begin{aligned} &\text{at C A ; } \sin \eta_E/2 \sin \eta_H/2 \\ &\text{at C B ; } \sin \eta_E/2 \cos \eta_H/2 \\ &\text{at D A ; } \cos \eta_E/2 \sin \eta_H/2 \\ &\text{at D B ; } \cos \eta_E/2 \cos \eta_H/2 \end{aligned} \qquad (11)$$

These signals are used to excite the $LSE_{21,\ 11,\ 20\ and\ 10}$ modes respectively in the throat of the horn using a microwave circuit like that shown in FIG. **11.** The horn structure itself is designed to provide H-plane control and to collimate the beam in the E-plane as previously described, and has separable radiation patterns in the E and H-planes for each of the incident modes. In direction cosine space these patterns have symmetry as denoted by the subscripts (e = even) (o = odd)

LSE mode incident	Radiation Pattern (μ, ν)
10	$f_e(\nu)\ g_e(\mu)$
20	$f_e(\nu)\ g_o(\mu)$
11	$f_o(\nu)\ g_e(\mu)$
21	$f_o(\nu)\ g_o(\mu)$

Exciting each of these radiation patterns with the output of the circuit of FIG. **10** (Equation 11) gives the result:

$$\text{Field } (\mu, \nu) = (\cos \eta_E\ f_e(\nu) + \sin \eta_E\ f_o(\nu).\ \cos \eta_H\ g_e(\mu) + \sin \eta_H\ g_o(\mu) = F(\nu)\ G(\mu) \qquad (13)$$

This pattern exhibits the separable distribution as shown in Equation **8.** Since the grating lobe positions μ_m and ν_n are independent of one another, then one can chose η_E to give nulls at the grating lobe positions in the E-plane ($\mu = 0$) and the separable character of the product above shows that the circuit of FIG. **10** will position the nulls properly for generalized scan angles.

If one of the passive linear circuits of FIGS. **7, 8,** or **9** is used to provide odd mode control, then only (N-**2**) odd mode outputs are available per column and so the total number of antennas with full odd mode control is $(N\text{-}2)^2$. The antennas at the extreme outer ring can have no odd mode control, but a fixed level of even modes power with proper phase can be selected for these outer antennas and provide good sidelobe and grating lobe characteristics without loss of gain. The system therefore should control the N^2 array, even though only the central $(N\text{-}2)^2$ elements have odd mode signals.

While it has been shown and described what is considered at present to be preferred embodiments of the invention, modification thereto will readily occur to those skilled in the art. In particular, although horn apertures were used as the waveguide elements, it should be obvious that the basic techniques of the invention apply equally well when the array element is itself a sub-array of dipoles or horn elements. In this case the distributions need not be trigonometric in nature but may be tailored to provide optimum coverage. Therefore an odd linear field amplitude distribution or even one with an inverse taper in the odd mode might well be preferred for selected scan geometries. It is not therefor desired that the invention be limited to the specific arrangement shown and described and it intended to cover in the appended claims all such modification that fall within the true spirit and scope of the invention.

What is claimed is:

1. The method of suppressing grating lobes in an electronically scanned antenna array comprising the steps of

dividing the fundamental even mode power for each radiating element of the array into two power sources for each plane of scan

converting the power of one power source for each plane of scan to odd mode power,

varying the ratio of even mode power to odd mode power as a function of beam position, and

maintaining a 90° out of phase relationship between even mode power and odd mode power at each radiating element aperture.

2. In an antenna system having an array of radiating elements, circuits for feeding fundamental mode electromagnetic wave power to each radiating element, and means for electronically scanning the main beam radiating from the array of radiating elements, the improvement comprising grating lobe suppression apparatus, said grating lobe suppression apparatus including

means for dividing the fundamental mode power feed circuit for each radiating element into two feed channels for each plane of scan,

means adapted to feed each radiating element through said feed channels to provide one even mode and one odd mode power source for each plane of scan,

means associated with each radiating element for varying the ratio of even mode power to odd mode power as a function of main beam position, and

means for providing, at each radiating element aperture, a 90° out of phase relationship between odd mode and even mode power.

3. Grating lobe suppression apparatus as defined in claim **2** wherein each said means for varying the ratio of even mode power to odd mode power effects and maintains a null in its associated radiation element radiation pattern at one principal grating lobe position.

4. Grating lobe suppression apparatus as defined in claim **3** wherein said means for providing 90° out of phase relationship between odd mode and even mode power effects, for each plane of scan, a +90° out of phase relationship when the main beam is scanned to one side of broadside and a −90° out of phase relationship when the main beam is scanned to the opposite side of broadside.

5. Grating lobe suppression apparatus as defined in claim **4** wherein said array of radiating elements is a rectangular array of rectangular horn antennas and said fundamental mode electromagnetic wave power is LSE_{10} mode power.

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