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[54] **PLANAR RADIAL ARRAY WITH CONTROLLABLE QUASI-OPTICAL LENS**
16 Claims, 16 Drawing Figs.

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343/854, 333/9, 333/84

[51] Int. Cl. **H01q 13/00,**

H01p 5/12

[50] Field of Search **343/753,**

754, 755; 343/778, 854; 333/9, 84 (M)

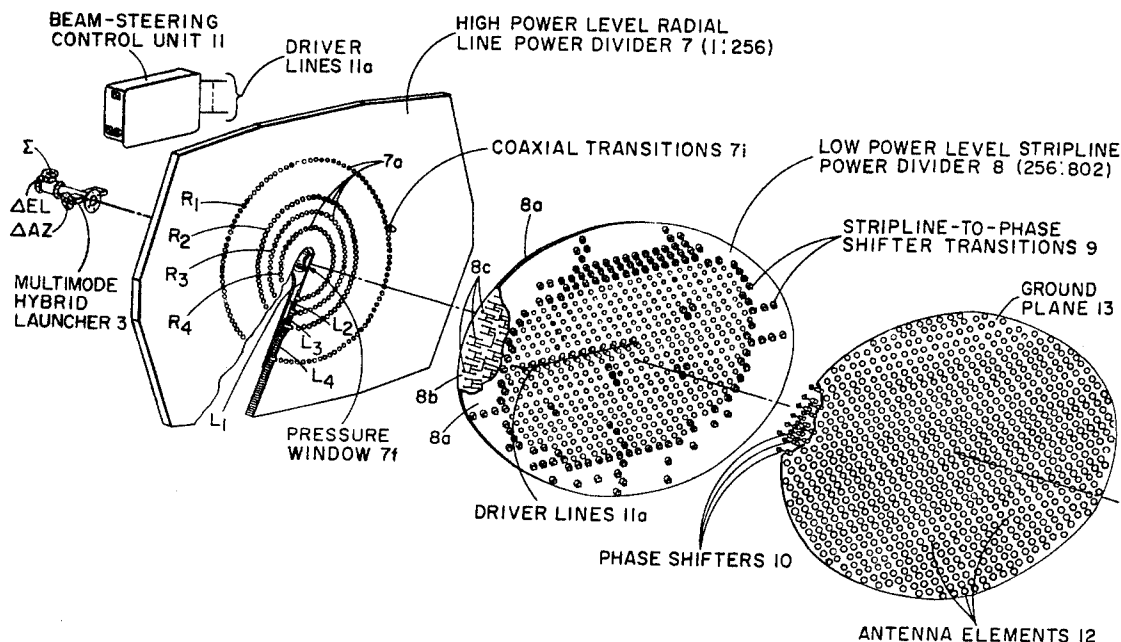
[56] **References Cited**

UNITED STATES PATENTS

3,245,081 4/1966 McFarland **343/754**

3,386,092 5/1968 Hyltin **343/854**

ABSTRACT: Antenna feed apparatus for use in electronically scanned phased-array antenna systems. In a transmit mode of operation, input power to be fed to an array of m antenna elements is applied to a multimode hybrid launcher wherein a sum signal is generated and applied to the input of a high-power level multitier radial line power divider. The sum signal is divided by the radial line power divider into n equivalued output signals of reduced power level. The n signals are then divided into m signals of varying power levels by a low-power level stripline power divider, and applied via m transitions to m phase shifters associated with the array of antenna elements. Each phase shifter operates under the control of a beam-steering control unit to insert a differential phase shift in each antenna element channel whereby a desired phase front is established across the aperture of the antenna array. In a receive mode of operation, monopulse signals received by the antenna array from a target are combined by the power dividers and applied to appropriate sum, elevation difference, and azimuth difference ports of the hybrid launcher.



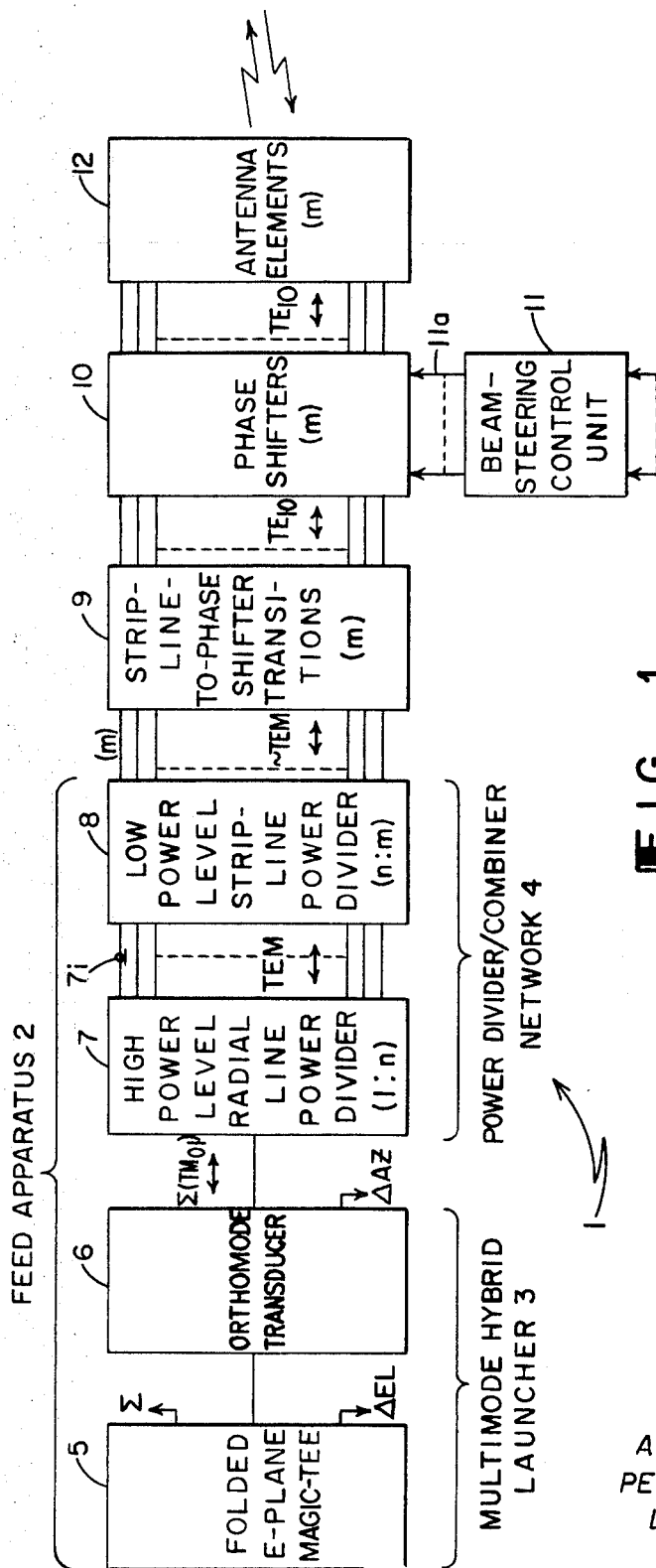


FIG. 1

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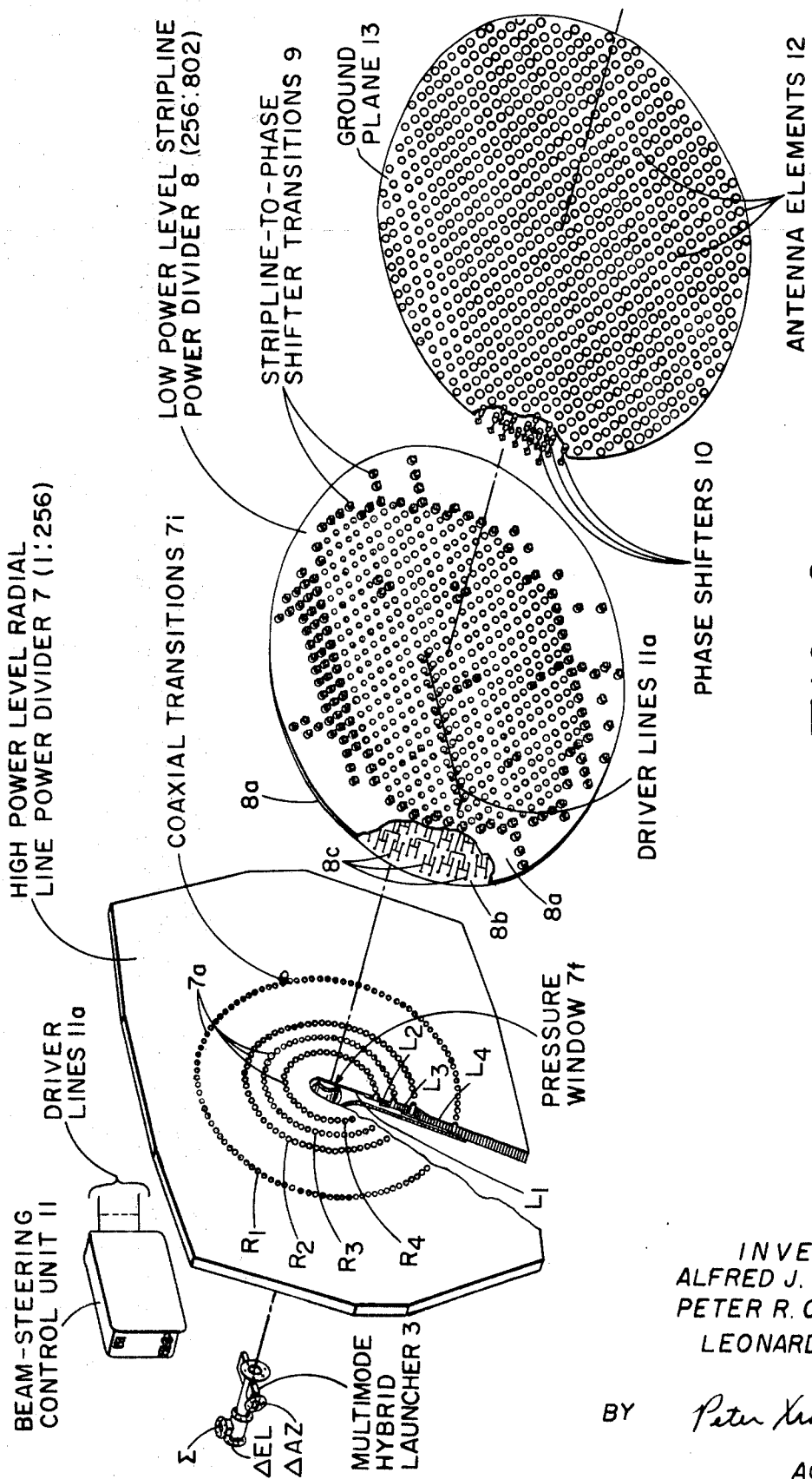


FIG. 2

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FIG. 3

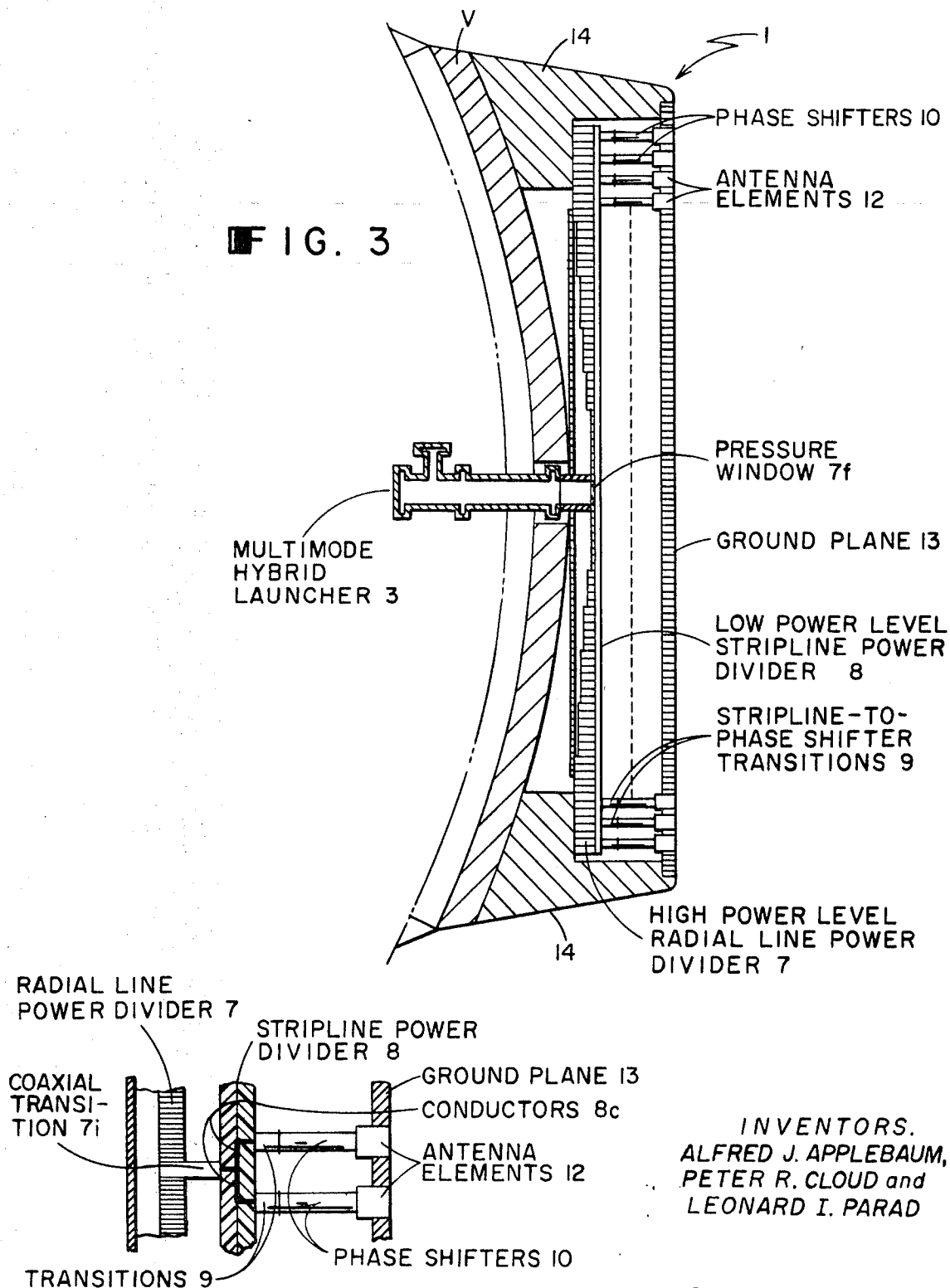
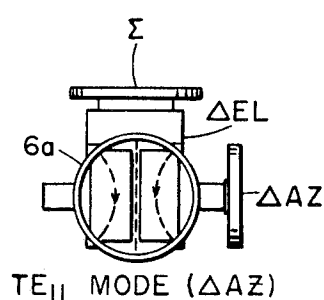
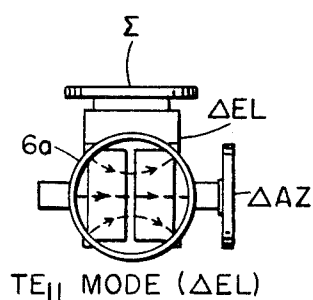
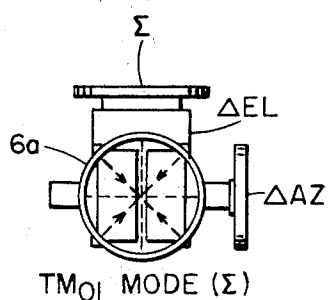
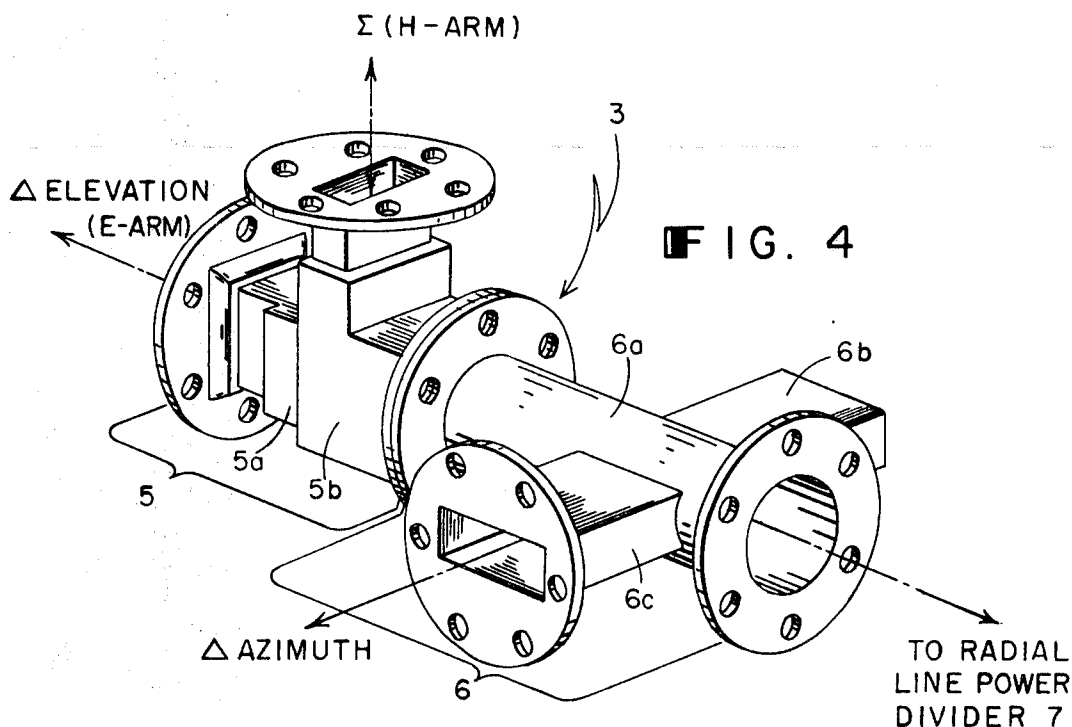


FIG. 3(a)

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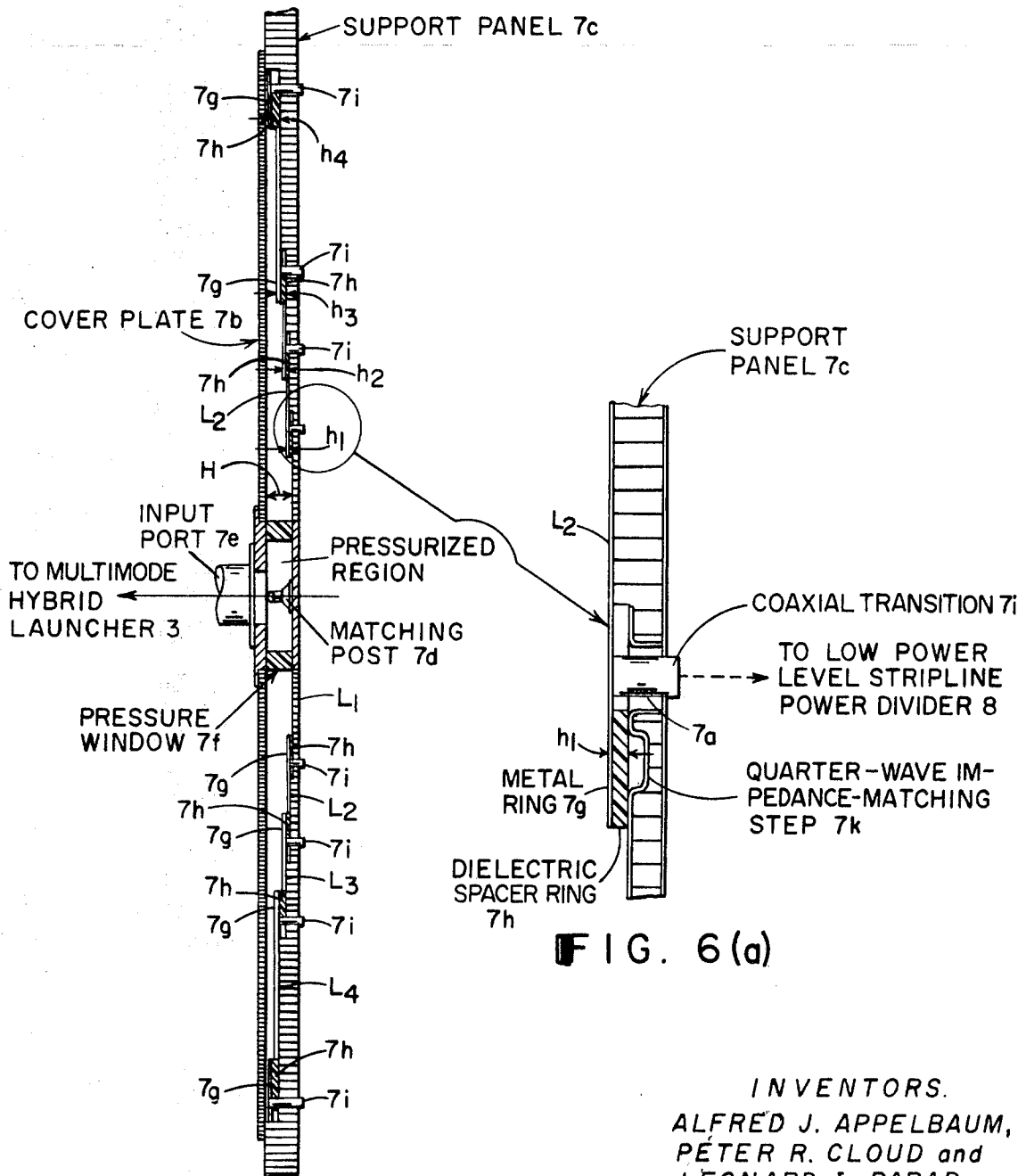


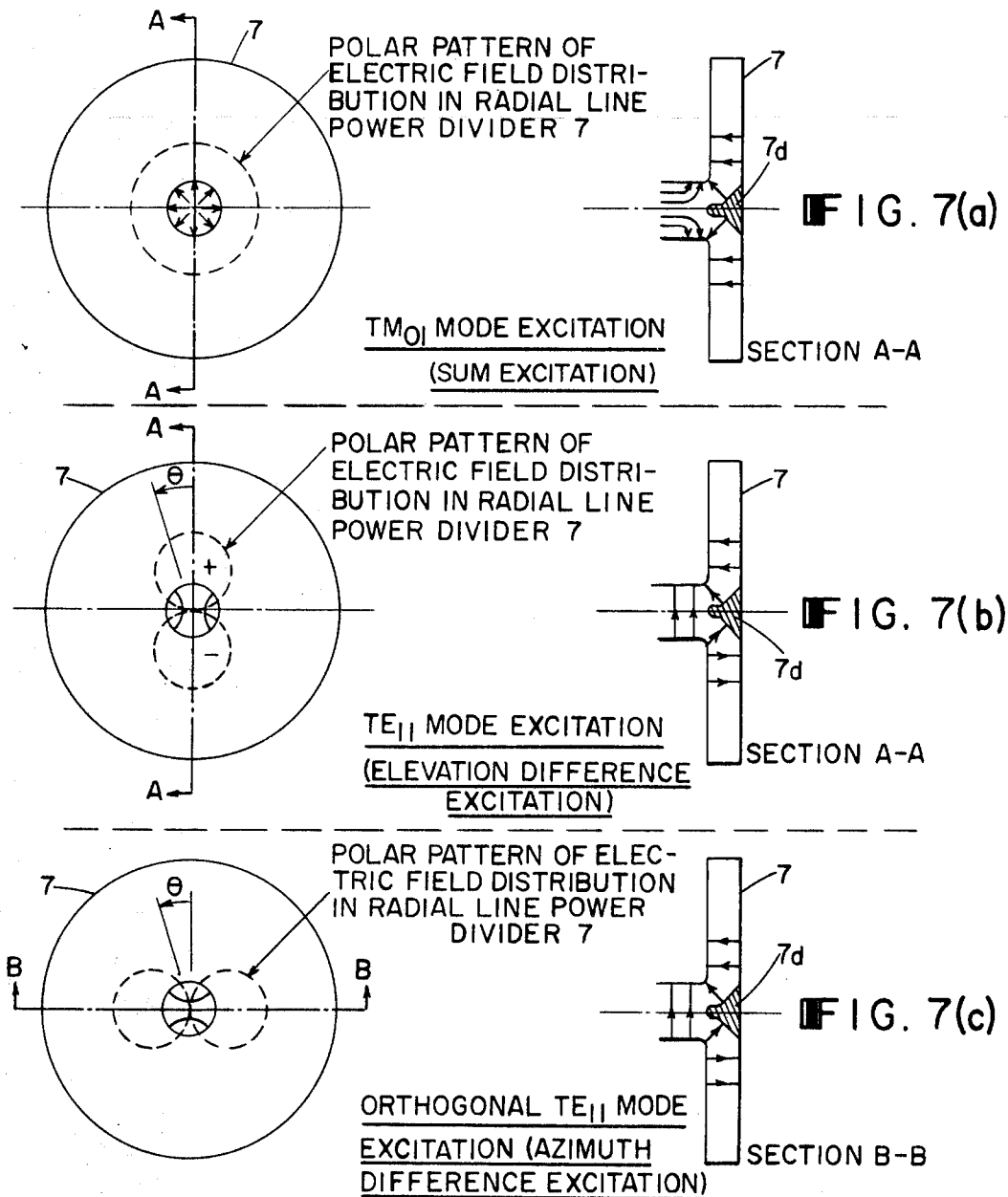
FIG. 6

FIG. 6(a)

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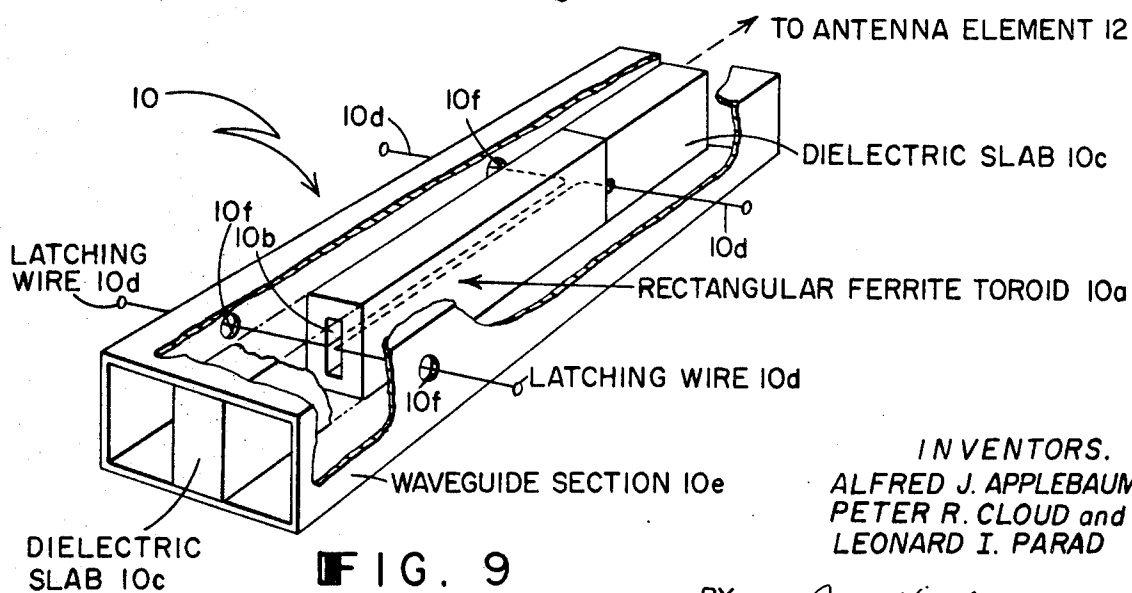
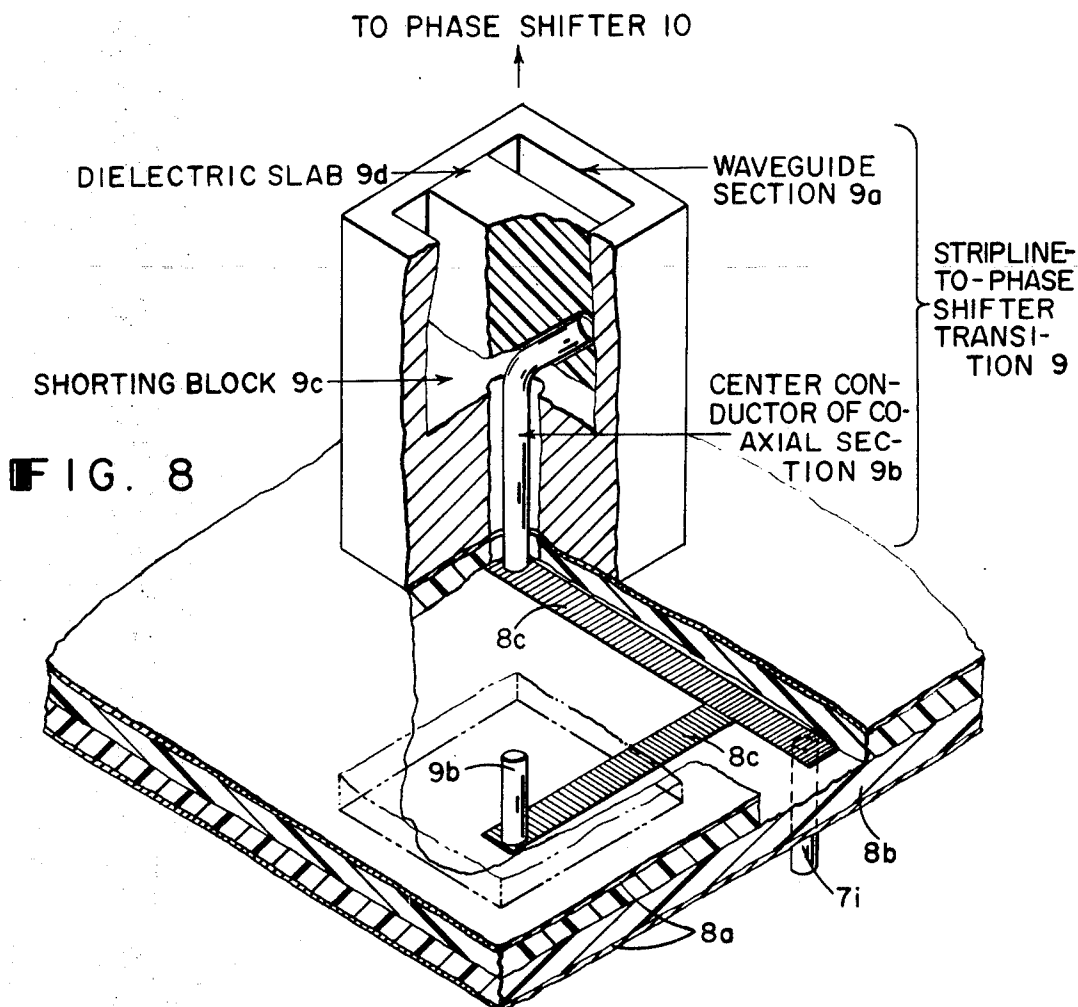
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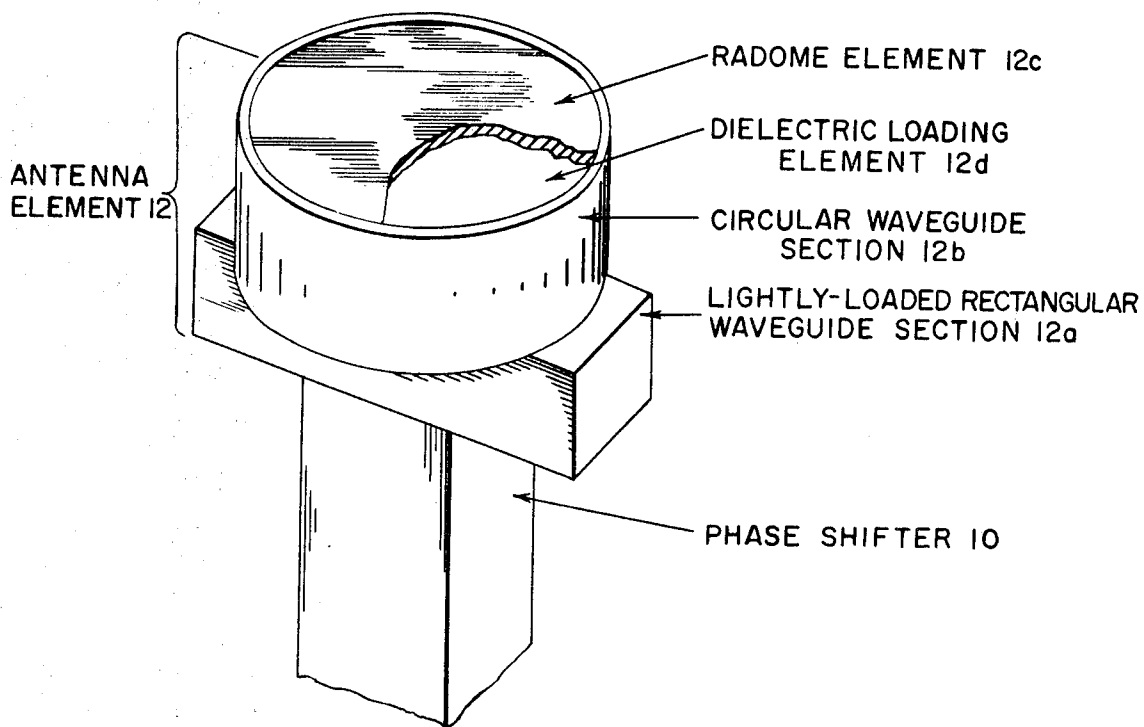


FIG. 10

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PLANAR RADIAL ARRAY WITH CONTROLLABLE QUASI-OPTICAL LENS

BACKGROUND OF THE INVENTION

The present invention relates to antenna feed apparatus and, more particularly, to antenna feed apparatus for use in phased-array antenna systems.

Existing antenna feed apparatus may be classified in one of three broad categories, namely, transmission line feeds, space feeds, and combinations of transmission line feeds and space feeds. In the first type of antenna feed apparatus, transmission line feeds, input power is fed to an array of antenna elements by subdividing and transferring the input power to the antenna elements by means of standard transmission line components, for example, high-power waveguide transmission lines. The input power may be transferred to the antenna elements either along multiple parallel paths or by means of both parallel and series paths (so-called "corporate" feeds). While transmission line feeds are satisfactory for many applications, these feeds have several undesirable characteristics when considered for certain applications such as airborne applications. For example, transmission line feeds are complicated in construction, occupy a large volume, have a large weight, are difficult to maintain, and are subject to large line length differentials between the input to the feed and each of the individual antenna elements. The latter characteristic is significant inasmuch as it may have an adverse effect on the frequency sensitivity of the antenna array system in which the antenna feed is used.

In the second type of antenna feed apparatus, space feeds, input power is translated to a plurality of antenna elements by means of one or more primary feeds, typically, multimode horns. For example, in a space feed known as a space "lens" feed, a horn radiates power which is picked up by a first array of antenna elements, passed through phase shifters, and then radiated into space from a second array of antenna elements. In another type of space feed, known as a space "reflector" feed, a horn radiates power onto an approximately paraboloidal reflecting surface, and the power is reflected therefrom onto a first array of antenna elements in an almost planar phase front; the power picked up by the first array of antenna elements is then phase shifted, and radiated into space by a second array of antenna elements. In still another type of space feed, known as a "reflect array" feed, a horn radiates power onto an array of antenna elements; the power therefrom is then passed through phase shifters, reflected from a short circuit, passed through the phase shifters again, and radiated into space from the array of antenna elements.

While space feeds are lightweight, easy to maintain, offer small differential line lengths, and readily provide adequate sum and difference illumination functions, such feeds occupy a very large volume, are inefficient (primarily because of large spillover), and cannot readily provide good sum and difference illumination functions simultaneously without unduly complicating the feed. The capability of a feed to provide good sum and difference illumination functions is important because they yield patterns with low sidelobes, which are frequently desirable for satisfactory system operation. Moreover, antenna arrays fed by space feeds are not readily adapted to density tapering (also known as "thinning") whereby the number of active elements is optimized. Because of the above disadvantages, space feeds often present problems which render them unsatisfactory for use in many airborne systems.

The third type of feed apparatus, transmission line and space feed combinations, which employ both horns and transmission line components, serve to simplify the formation of sum and difference beam illuminations. However, for substantially the same reasons presented hereinabove in connection with the transmission line feeds, these combination feeds are not entirely acceptable for airborne applications.

SUMMARY OF THE INVENTION

The present invention pertains to a power feed apparatus which possesses essentially all of the desirable features of the various prior art feed apparatus discussed hereinabove and essentially none of the undesirable features. Accordingly, a feed apparatus is provided which in operation is efficient, capable of providing good sum and difference illuminations simultaneously, and of providing small line length differentials. Moreover, the feed apparatus is lightweight, of a small volume, easily constructed and maintained, and compatible with density-tapering schemes when used with an array of antenna elements. All of the above-enumerated features, when present in a single feed apparatus, results in an apparatus having significant value and importance in many communications systems applications, particularly airborne systems where such factors as weight, volume, ease of construction, attachability, maintainability, and efficiency of apparatus to be used therewith are of considerable importance.

Briefly, in accordance with the present invention, a power feed apparatus is provided which includes a power-dividing means and a power-distributing means. The power-dividing means includes an input port and n output ports and is operative to receive an input signal of a predetermined power level at the input port and to divide the input signal into n output signals of reduced power level at the n output ports. The power-distributing means is operative to receive the n output signals from the n output ports of the power-dividing means and to provide m output signals of varying power levels at m output connections. When the above-described power-dividing and power-distributing apparatus is employed in a power feed apparatus for a phased-array antenna system, the m output signals of the varying power levels are used to establish the required power levels for the antenna elements of the array whereby a desired beam taper illumination function is achieved across the aperture defined by the array of antenna elements.

In a preferred form of the power feed apparatus of the present invention, the power-dividing means is a radial line power-dividing means. The radial line power-dividing means of the preferred form comprises an input port adapted to receive an input signal of a predetermined power level, and a member spaced from the input port and symmetrical about a central axis. The symmetrical member includes a plurality of portions coaxial with the central axis and each of a predetermined height in the direction of the central axis. Each of the portions further includes a group of substantially equally spaced output ports arranged in the portion in a predetermined pattern, each of the groups of output ports being spaced in the direction of the central axis a predetermined distance from the input port. The predetermined distances determine the amount or percentages of the power of the input signal to be distributed to the various groups of output ports. Each of the ports of each group is spaced from the central axis a different distance than each of the ports of the other groups thereby establishing different positional relationships between the various groups of ports and the input port. The total number of output ports is equal to n .

In the operation of the radial line power-dividing means, the input signal of the predetermined power level applied to the input port is coupled by a signal-coupling means to the various groups of output ports. The input signal is divided by the radial line power-dividing means into n output signals of reduced power level at the n output ports. When the radial line power-dividing means is used in a phased-array antenna system where the number of antenna elements m exceeds the value of n , the n output signals at the n output ports of the radial line power-dividing means are coupled to an $n:m$ stripline power-dividing means which includes a plurality of power-dividing conductor means coupled to the n output ports and operative to receive the n output signals from the n output ports and to provide m output signals of varying power levels at m output connections.

The m output signals at the m output connections are applied to m phase-shifting means coupled to the stripline power-dividing means, which phase-shifting means are adapted in response to steering command signals from a control means to phase shift each of the signals received thereby by a predetermined amount. An array of m antenna elements is coupled to the phase-shifting means. When the steering command signals are applied to the m phase-shifting means by the control means, the signals received by the phase-shifting means are caused to be shifted by controlled amounts whereby a desired phase front is established across the array of m antenna elements.

DESCRIPTION OF THE DRAWING

FIG. 1 is a diagrammatic block diagram representation of a monopulse electronically scanned planar phased-array antenna employing the antenna feed apparatus of the present invention;

FIG. 2 is an exploded view in perspective of the phased-array antenna of FIG. 1, portions thereof being broken away to illustrate internal details of some of the elements comprising the phased-array antenna;

FIG. 3 is a vertical cross-sectional view of the phased-array antenna of FIG. 2, illustrating the manner in which the component elements thereof are integrated into a single, compact, flat assembly, and the assembly secured to an airborne vehicle;

FIG. 3(a) is an enlarged view, partly in schematic form and in cross section, of the elements in a typical path extending through the phased-array antenna of FIG. 2;

FIG. 4 is an enlarged pictorial view, showing in greater detail and more clearly than in FIG. 2, a multimode hybrid launcher employed in the antenna feed apparatus of the invention;

FIGS. 5(a) through 5(c) are diagrammatic representations, useful in understanding the present invention, of the various electromagnetic field distributions produced in the multimode hybrid launcher of FIG. 4;

FIG. 6 is an enlarged vertical cross-sectional view of a high-power level radial line power divider included in the feed apparatus of the invention;

FIG. 6(a) shows a blown-up vertical cross-sectional view of a typical output section of the radial line power divider of FIG. 6;

FIGS. 7(a) through 7(c) are diagrammatic representations, useful in understanding the present invention, of the various electromagnetic field distributions produced in the radial line power divider;

FIG. 8 is an enlarged view in perspective of a stripline to phase shifter transition employed in the present invention, a portion being broken away to illustrate internal details;

FIG. 9 is an enlarged view in perspective of a latching ferrite phase shifter employed in the present invention, a portion being broken away to illustrate internal details; and

FIG. 10 is an enlarged view in perspective of an antenna element employed in the present invention, a portion being broken away to illustrate internal details.

DESCRIPTION OF THE PREFERRED EMBODIMENT OF THE INVENTION

Planar Phased-Array Antenna—FIG. 1

Referring to FIG. 1, there is shown in a generalized block diagram form a planar phased-array antenna 1 including an antenna feed apparatus 2 in accordance with the present invention. For illustrative purposes, a monopulse antenna system will be described. However, it is to be understood that the feed apparatus 2 may also be used in nonmonopulse types of antenna systems. As shown in FIG. 1, the feed apparatus 2 comprises a multimode hybrid launcher 3 including a folded E-plane magic-tee 5 coupled to an orthomode transducer 6, and a power divider/combiner network 4 including a $1:n$ high-

power level radial line power divider 7 connected to an $n:m$ low-power level stripline power divider 8 by means of a plurality of n coaxial transitions or probes 7*i*. The feed apparatus 2 is coupled to a plurality of m antenna elements 12 arranged in an array by means of a corresponding plurality of m stripline-to-phase shifter transitions 9 and a corresponding plurality of m phase shifters 10. The phase shifters 10 are controlled by means of a beam-steering control unit 11 coupled thereto by a plurality of driver lines 11*a*.

The feed apparatus 2 performs two basic operations. First, the feed apparatus 2, in response to input energy from an RF source (not shown), generates and distributes m signals having appropriate power levels to the corresponding m transitions 9, phase shifters 10, and antenna elements 12 in such a manner that a desired beam taper illumination function is achieved across the aperture defined by the array of antenna elements 12 ("transmit" mode of operation). Second, the feed apparatus 2 receives and forms monopulse azimuth and elevation error signals as well as a sum signal from the energy returned to the array of antenna elements 12 from a given target ("receive" mode of operation). The specific manner in which the feed apparatus 2 functions in the planar phased-array antenna 1 of FIG. 1 may best be understood from the following discussion of the operation of the phased-array antenna 1 of FIG. 1.

Operation of Monopulse Planar Phased-Array Antenna—FIG. 1

In the transmit mode of operation, RF input energy of a high-power level is applied from the RF input source (not shown) to the multimode hybrid launcher 3. The launcher 3 is constructed so as to produce a high-order mode, typically a TM_{01} sum distribution or pattern, in the orthomode transducer 6, and to apply the TM_{01} energy to the high-power level $1:n$ radial line power divider 7. Because of the particular construction of the radial line power divider 7, to be described in greater detail hereinafter, a cylindrically symmetric TEM distribution is excited therein by the TM_{01} sum distribution from the output of the orthomode transducer 6. The high-power TEM energy present in the radial line power divider 7 is subdivided thereby into n output signals of equal power value, the power level of each output signal, however, being considerably less than the power level of the input signal applied thereto. The particular value of n is selected in accordance with the particular number (m) of antenna elements 12 required for a given application, that is, the size of the antenna array.

The output signals from the outputs of the radial line power divider 7 are coupled by the corresponding coaxial transitions 7*i* to corresponding inputs of the low-power level $n:m$ stripline power divider 8. The field distribution or mode present in each of the coaxial transitions 7*i* is the TEM mode. The $n:m$ stripline power divider 8 is adapted to further subdivide the n input signals applied thereto to m output signals of varying power levels, and to route or distribute the m output signals to the corresponding transitions 9, the phase shifters 10, and the antenna elements 12 so as to establish the desired beam taper illumination function across the aperture defined by the array of antenna elements 12. The field distribution or mode present in the stripline power divider 8 is similar to the TEM distribution common to coaxial lines.

As will be more fully apparent hereinafter from a detailed description of the stripline-to-phase shifter transitions 9, each transition 9 includes a waveguide section of a construction whereby a higher order mode, typically a TE_{10} distribution, is excited therein by the essentially TEM distribution from the corresponding output connection of the stripline power divider 8. The TE_{10} distribution is applied by the output of the waveguide section to the corresponding phase shifter 10. Each of the phase shifters 10 is driven by a signal from the beam-steering control unit 11 on one of the driver lines 11*a* so as to appropriately establish the phase length of the corresponding

antenna element channel at the value required to point the transmitting beam in the desired direction. More particularly, the beam-steering control unit 11 applies a steering command signal to each of the m phase shifters 10 to cause a controlled amount of phase differential to be inserted by each of the phase shifters 10 in each associated antenna element channel whereby a phase front having a plane perpendicular to the desired beam-pointing direction is established.

In the receive mode of operation, signals returned from the target are received by the antenna elements 12 and directed to the phase shifters 10 which are controlled by the beam-steering control unit 11. The control unit 11 sets the phase shifters 10 so that a sum beam and two tracking beams will be formed by the feed apparatus 2 in the approximate direction of the target. More particularly, m —signals of the essentially TEM mode are applied to the stripline power divider 8 by the transitions 9 and combined to n signals. The n signals are then applied to the radial line power divider 7 and combined therein so as to produce and apply to the multimode hybrid launcher 3 the TM_{01} distribution as well as the orthogonal TE_{11} difference azimuth and difference elevation distributions, the various amplitudes of which depend upon the target angle from the antenna-pointing direction. The various distributions are then applied by the hybrid launcher 3 to a three-channel monopulse receiver (not shown) and further processed so as to determine the new direction in which the transmit beam is to be pointed by the beam-steering control unit 11.

Planar Phased-Array Antenna—FIG. 2, FIG. 3, FIG. 3(a)

The planar phased-array antenna 1 of FIG. 1 is shown in an exploded view in perspective in FIG. 2. FIG. 3 illustrates in a vertical cross-sectional view the general manner in which the major component elements of the phased-array antenna 1 are integrated into a single, compact, flat assembly and the assembly attached via conventional fairings 14 to a vehicle V such as an aircraft. FIG. 3(a) illustrates the elements present in a typical path extending through the antenna array 1 and the manner in which a simple power division operation is accomplished. In order to gain a full understanding and appreciation of the present invention, the various components of the phased-array antenna 1, shown in greater detail in FIGS. 4, 6, 8, 9, and 10, will now be more fully described in conjunction with FIGS. 2, 3, and 3(a).

Multimode Hybrid Launcher—FIG. 4

The multimode hybrid launcher 3 of FIG. 2 is shown in an enlarged perspective view in FIG. 4. The function of the launcher 3 is to produce a sum illumination distribution in the transmit mode of operation, and sum and difference illumination distributions in the receive mode of operation. The sum and difference patterns are developed by the briefly aforementioned component parts of the launcher, namely, the folded E-plane magic-tee 5 and the orthomode transducer 6. The first component part, the folded E-plane magic-tee 5, comprises an elevation difference (ΔEL) arm or port (also referred to as the E-arm), and a sum (Σ) arm or port (also referred to as the H-arm). The ΔEL and Σ ports are interconnected by standard rectangular waveguide sections, typically of cast aluminum, such as shown at 5a and 5b in FIG. 4. Although not shown in FIG. 4, the impedance of the folded E-plane magic-tee 5 is matched to the impedance of the orthomode transducer 6 by means of a conventional impedance-matching transformer.

The orthomode transducer 6 comprises a circular waveguide section 6a coupled to an output port of the magic-tee 5, a shunt rectangular waveguide section 6b, and a rectangular waveguide section 6c. As indicated by FIG. 4, the waveguide section 6c is the azimuth difference (ΔAZ) arm or port of the launcher 3. The purpose of the shunt waveguide section 6b is to prevent cross-coupling between the modes excited at the ΔEL and Σ ports. For example, as shown in FIG. 5(a), the TM_{01} mode, for reasons of symmetry, will couple to

the Σ port only. On the other hand, a TE_{11} mode will couple either to the ΔEL port or to the ΔAZ port, or both, according to the particular orientation of the TE_{11} mode, as shown in FIGS. 5(b) and 5(c). It may be noted from FIGS. 5(a) through 5(c) that any asymmetry in the launcher 3 will couple the TM_{01} and TE_{11} modes together. In order to prevent this asymmetry, the short-circuited waveguide section 6b is inserted in the circular waveguide section 6a. Moreover, the length of the waveguide section 6b is selected such that the section appears to be almost infinitely long to the modes excited at the ΔEL and Σ ports which are cut off in the ΔAZ port. Hence, the junction of the ΔAZ port and the circular waveguide section 6a appears symmetrical.

In the operation of the multimode hybrid launcher 3 in the transmit mode, high-level input energy of the order of magnitude of several megawatts peak, tens of kilowatts ave. (for example, 5 megawatts peak, 50 kilowatts ave.) is applied to the Σ port of the magic-tee 5 whereby the previously described TM_{01} field distribution, such as shown in FIG. 5(a), is produced in the circular waveguide section 6a of the orthomode transducer 6 and applied to the input of the radial line power divider 7.

In the operation of the launcher in the receive mode, the field distribution produced in the radial line power divider 7 excites the TM_{01} distribution (FIG. 5(a)) and the orthogonal TE_{11} distributions (FIGS. 5(b) and 5(c) in the circular waveguide section 6a. These distributions are appropriately coupled to the Σ , ΔAZ , and ΔEL ports of the launcher 3 (acting as output ports in the receive mode) and then to the three-channel monopulse receiver (not shown) for further processing.

High-Power Level Radial Line Power Divider—FIGS. 6 and 6(a)

The high-power level radial line power divider 7 is shown generally in FIG. 2, and in greater detail in the vertical cross-sectional views of FIGS. 6 and 6(a). As shown in FIG. 2, the radial line power divider 7 is provided with a plurality of output ports 7a arranged in a plurality of rings $R_1 \dots R_4$, each ring being coaxial with the central axis of the divider 7 and appearing at a different one of a plurality of portions of plateaus $L_1 \dots L_4$ of varying heights in the direction of the central axis. The spacing between each adjacent pair of output ports 7a is adapted to be the same for each of the rings $R_1 \dots R_4$. Although a total of four rings $R_1 \dots R_4$ are illustrated in FIG. 2, both the number of rings R and the radii of the rings are determined in accordance with the particular application. For example, the particular number of rings R required in a given application (and therefore the number of output ports 7a) is generally determined in accordance with the number of antenna elements 12 required for the application and, to a lesser extent, also on the amount of power-division and signal-distribution capability that can be built into the low-power level stripline power divider 8 while maintaining a reasonable size therefor. The radii of the rings R are those which most effectively locate the output ports of the rings in the vicinity of the antenna elements 12 to which the output ports are to be ultimately coupled.

By way of a particular example, an antenna operating at a frequency of 3.15 GHz. (± 5 percent) with 802 active antenna elements 12 ($m=802$) may be considered. If these antenna elements are arranged in a general pattern such as illustrated in FIG. 2, the ring R_1 may have a radius of 25 inches and include 104 output ports 7a spaced apart from each other by approximately 1.5 inches, the ring R_2 may have a radius of 16 inches and includes 68 output ports 7a, the ring R_3 may have a radius of 12 inches and include 50 output ports, and the ring R_4 may have a radius of 8 inches and include 34 output ports.

The physical arrangement and construction of the radial line power divider 7 is shown in greater detail in FIGS. 6 and 6(a). As shown therein, the power divider 7 structurally comprises: a cover plate 7b and a support member or panel 7c ar-

ranged to enclose a space through which input power is distributed to the output ports 7a, both the cover plate 7b and member 7c being typically of a high-strength, lightweight, aluminum honeycomb construction; a conventional aluminum matching post 7d located adjacent to an input port 7e of the power divider 7; a cylindrical, electrically transparent, low-loss quartz pressure window 7f located near the center of the power divider 7; a plurality of aluminum annular rings 7g each coaxial with the central axis of the divider 7, one ring for each of the portions or plateaus L₁...L₄ and supporting a plurality (or ring) of the coaxial probes or transitions 7i; and a plurality of annular dielectric spacer rings 7h, typically of "tellite" (ε=2.3) located at the plateaus L₁...L₄ of the power divider 7 and flush therewith and spacing the metal rings 7g from the support panel 7c.

The purpose of the matching post 7d is to impedance-match the output of the multimode hybrid launcher 3 (FIG. 4) to the power divider 7. Although not shown in FIG. 6, but shown in FIG. 6(a), conventional quarter-wave impedance-matching steps 7k are also provided to match the coaxial transitions 7i to the associated plateaus L₁...L₄. As indicated in FIG. 6, the region of the radial line power divider 7 enclosed by the pressure window 7f is maintained under pressure, for example, 15 p.s.i.g. The purpose of the pressurization is to prevent electrical breakdown from occurring in the output regions of the power divider due to high-power levels, for example, the megawatt peak level. Inasmuch as the window 7f is electrically transparent to the input energy applied to the input port 7e of the power divider 7, the input energy is satisfactorily coupled through the window 7f to the output ports 7a. The pressure level in the output regions of the power divider 7 is substantially at one atmosphere. For lower-power levels, for example, 2 Mw. peak, the pressure window 7f may be eliminated in which event the pressure in all regions of the power divider 7 is at one atmosphere.

It may be noted from FIG. 6 that the metal rings 7g are located at different distances h₁...h₄ from the corresponding power divider plateaus L₁...L₄. The ratios of each of these distances h₁...h₄ to the maximum distance H between the cover plate 7b and the support panel 7c determine the extent of power division to take place between the input port 7e of the power divider 7 and each of the individual rings R₁...R₄, the power density decreasing proportionately with the inverse of distance from the point of excitation. In the present invention, the heights of the plateaus L₁...L₄ and the distances h₁...h₄ corresponding thereto are selected so as to allow the same value of power to be coupled out of each of the output ports 7a of the power divider 7 to each of the associated coaxial transitions 7i. In so doing, the design of the stripline power divider 8 is simplified since the stripline power divider need not take into account a variety of input power levels in performing further power division. It is to be understood, however, that the radial line power divider 7 may be modified in its construction such that signals of different power levels are produced at the various output ports 7a, the different power levels in this case being compensated for by the stripline power divider 8.

The particular values of the distances h₁...h₄ can be determined from the general expression

$$h_k = \frac{N_k}{N} H$$

where h_k is the distance of a kth metal ring 7g from its associated plateau, N_k is the number of output ports (7a) in the kth ring, N is the total number of output ports, and H is the maximum inside dimension of the radial line power divider 7. From the particular values set forth above for each of the rings R₁...R₄ and the spacing of the output ports 7a, and assuming a typical value of 1.5 inches for H, the values for h₁...h₄ may be calculated to be approximately 0.20 inches, 0.28 inches, 0.41 inches, and 0.61 inches, respectively. Further, for these values of h₁...h₄, the percentage of the input power coupled to each of the rings R₁...R₄ is approximately 40.6%, 27.4%,

18.6 percent, and 13.4 percent, respectively, and the value of the power coupled out of each of the output ports 7a to each of the coaxial transitions 7i for the 5Mw input signal is 20kw peak, which level is tolerable in stripline of the type employed by the present invention.

The various electric field distributions or modes which are present in the radial line power divider 7 during the transmit and receive modes of operation are illustrated pictorially in FIGS. 7(a) through 7(c). FIG. 7(a) illustrates the circularly symmetric nature of the TM₀₁ mode distribution (sum excitation) present in the power divider 7 between the cover plate 7b and each of the portions L₁...L₄ during the receive mode of operation. FIGS. 7(b) and 7(c) illustrate the particular nature of the orthogonal TE₁₁ modes (elevation difference and azimuth difference excitations) present in the radial power divider 7 during the receive mode of operation, the electric field shown in FIG. 7(b) having a cosine θ dependence, and the electric field shown in FIG. 7(c) having a sine θ dependence. During the receive mode of operation, both of the orthogonal TE₁₁ distributions are present in the radial line power divider 7 simultaneous with the TM₀₁ sum distribution.

Low-Power Level Stripline Power Divider—FIG. 2, FIG. 8

While the radial line power divider 7 effectively serves its purpose of high-power subdivision, it does not lend itself to the more sophisticated design tradeoffs of peripheral thinning and aperture synthesis. In the present invention, this additional flexibility of peripheral thinning and aperture synthesis is achieved from the use of the low-power level stripline power divider 8. The stripline power divider 8 is shown in detail in FIGS. 2 and 8.

As shown in FIGS. 2 and 8, the stripline power divider 8 comprises a pair of electrically independent ground planes 8a with a bonded dielectric slab 8b disposed therebetween, the dielectric slab 8b containing therein a plurality of conductors 8c formed by an etching process and interconnected to form a plurality of power dividers capable of providing varying amounts of input-power division (noting also FIG. 3(a)). Typically, the stripline power divider 8 is constructed by using a "bonded stripline" process which provides a thin, flat, lightweight, low-loss structure. By way of example, the ground planes 8a may be of copper, the dielectric slab 8b of polyethylene (ε=2.3), and the conductors 8c of copper.

In the transmit mode of operation, the stripline power divider 8 performs two basic functions. First, the stripline power divider interconnects each of the TEM electric field distributions traversing each of the coaxial transitions 7i with the associated phase shifter 10 and antenna element 12 and, second, feeds each of the phase shifters 10 with a specific power level so as to obtain a desired beam taper illumination function across the antenna array. By way of example, the stripline power divider may be adapted to subdivide the 256, 20 kw. (peak) input signals applied thereto into 802 output signals, the 802 output signals varying in power value from 20 kw. peak at the center of the divider (1:1 power division) to 2 kw. peak at the edges.

In the receive mode of operation, the stripline power divider 8 serves to combine the m signals traversing the phase shifters 10 and to apply these signals to the radial line power divider 7 for further combining as previously described.

Stripline-to-Phase Shifter Transition—FIG. 8

Each of the output signals from the low-power level stripline power divider 8 is coupled to a phase shifter 10 by means of a short-length transition 9 such as shown in FIG. 8. The transition 9 comprises an aluminum waveguide section 9a adapted to provide a TE₁₀ distribution when excited, a copper center conductor of a coaxial section 9b, a solid aluminum shorting block 9c, and a dielectric slab 9d loading the waveguide section 9a. The dielectric slab 9d, typically of magnesium titanate (ε=15), has a dielectric constant of a value to match the transition 9 to a corresponding phase shifter 10. Also, the

characteristic impedance of the center conductor of the coaxial section 9b is made to match the phase shifter to the stripline.

The transition 9 of FIG. 8 provides two electrical transitions, namely, a transition between one of the conductors 8c of the stripline power divider 8 and the center conductor of the coaxial section 9b, and a transition between the center conductor of the coaxial section 9b and the dielectrically loaded waveguide section 9a. Thus, the transition 9 provides an RF path perpendicular to the stripline power divider 8, and an end-on transition into a corresponding phase shifter 10. In the operation of the transition 9 in the transmit mode, the center conductor of the coaxial section 9b carries an essentially TEM distribution from the stripline power divider 8 and, because of the particular construction of the waveguide section 9a, causes a TE₁₀ mode to be generated by the waveguide section 9a and to be applied to a corresponding phase shifter 10. In the receive mode of operation, the reverse operation of that described hereinabove takes place.

Phase Shifter—FIG. 9

A phase shifter 10 is shown in enlarged detail in FIG. 9. In the preferred embodiment, the phase shifter 10 is of a latching, analog, nonreciprocal type. However, other types of phase shifters of known construction and operation may also be used. As shown in FIG. 9, the phase shifter 10 of the preferred embodiment includes a single extruded ferrite toroid 10a which is typically a holmium-doped garnet toroid rectangular in shape with a rectangular-shaped opening 10b running therethrough. The phase shifter 10 further includes a pair of dielectric spacers or slabs 10c of magnesium titanate ($\epsilon=15$) entering one end of the opening 10b and exiting from the opposite end, and an aluminum rectangular waveguide section 10e. Four exit holes 10f are provided in the waveguide section 10e for the latching wires 10d.

In the operation of the phase shifters 10 in the transmit mode, command signals are applied by the beam-steering control unit 11 (FIGS. 1 and 2) to one of the latching wires 10d associated with each of the phase shifters 10 so that the appropriate direction in space in which the transmit beam is to be pointed is established. Although the beam-steering control unit 11 is not shown in detail in the drawing, this unit in one typical configuration may comprise a central radar control computer, a steering processor, and suitable control logic and driver apparatus. Briefly, in operation, the computation of steering commands for the individual phase shifters 10 is initiated by means of multibit coded input words defining the system-operating frequency and the direction in space in which the beam is to be pointed. The coded words are applied by the central radar control computer to the steering processor which then computes 802 *m* digital steering words, one word for each of the phase shifters 10, and applies the steering words to the associated control logic and driver apparatus. Path length differences between the multimode hybrid launcher 3 and each of the antenna elements 12 are also compensated for in the steering processor.

The control logic and driver apparatus then applies constant-amplitude pulses of varying widths to corresponding ones of the 802 pairs of latching wires 10d associated with the 802 ferrite toroids 10a (via the driver lines 11a) to cause the ferrite toroids to be latched in a specific state of magnetization. The amount of phase differential to be inserted in each antenna element channel is determined by the width of the pulse applied to the phase shifter disposed in the channel. The TE₁₀ distributions from the transitions 9 are then propagated by the waveguide sections 10e of the phase shifters 10 to the corresponding antenna elements 12 whereby the proper illumination beam is established and transmitted to a target.

In the receive mode of operation, steering command control signals are applied by the beam-steering control unit 11 to each of the other ones of the 802 pairs of latching wires 10d

associated with each of the ferrite toroids 10a so as to set each ferrite toroid 10a with the proper setting so that received signals from a target will form sum and difference beams in the same direction as the transmitted beam. The steering control unit 11 further operates to generate and distribute new steering commands which may reflect a beam position change only, a beam position and frequency change, or a frequency change only.

Antenna Element—FIG. 10

FIG. 10 illustrates at 12 an antenna element employed in the present invention. The antenna element 12 of FIG. 10 comprises: an aluminum waveguide section 12a lightly loaded with a small amount of dielectric; a circular waveguide section 12b; a protective radome element 12c in intimate contact with a portion of the inside wall of the circular waveguide section 12b; and a dielectric loading element 12d. All these components serve to match the phase shifter 10 to free space.

Typically, the waveguide section 12b may be of cast aluminum, the radome element 12c of alumina ceramic ($\epsilon=8.5$), and the dielectric loading element 12d of magnesium titanate ($\epsilon=15$). Although not shown in FIG. 10, the radome element 12c is fused to the portion of the inside wall of the circular waveguide section 12b by a low-expansion alloy, for example, nickel-iron.

As may be noted from FIG. 2 and FIG. 3(a), each of the antenna elements 12 is disposed in a ground plane 13 such that the top surface of each antenna element is substantially flush with the top surface of the ground plane. The ground plane 13 acts as a weather seal and thermal insulator for the system and is typically constructed from a lightweight, high-strength, honeycomb aluminum material. Although the use of 802 active radiating antenna elements 12 has been previously described, it is to be understood that additional "dummy" antenna elements may be incorporated in the ground plane 13 and rendered passive in a conventional manner in accordance with a desired peripheral thinning scheme. By way of example, for the 3.15 Ghz. operating frequency previously stated, a total of 1,004 antenna elements 12 may comprise the array of antenna elements, with 202 of these, mainly peripheral antenna elements, being passive.

The above-described integrated radome antenna element arrangement offers several advantages over conventional nonintegrated arrangements most commonly used heretofore. It has been a common practice, for example, to employ a single radome of fiberglass as a protective shield for an array of antenna elements. However, experience has shown that both antenna performance and system performance has had to be sacrificed when radomes required for aerodynamic and structural reasons have been used. More particularly, it has been discovered that conventional radomes absorb energy and contribute to the degradation of sidelobes, both individual sidelobes and average sidelobes.

As described previously, each of the antenna element 12 (including the radome elements 12c) is disposed in and supported by the ground plane 13. Because of this arrangement, the problems of reflection and absorption are effectively minimized thereby providing an improved electrical performance and transmission efficiency. Additionally, no external support structures are required and, accordingly, the size and weight of the radome-antenna arrangement are reduced and installation on an aircraft or other mobile vehicle is readily accomplished.

It will now be apparent that a novel antenna feed apparatus and a phased-array antenna apparatus have been disclosed in such full, clear, concise, and exact terms so as to enable any person skilled in the art to which such apparatus pertain to construct and use the same. It will also be apparent that various changes and modifications may be made in form and detail by those skilled in the art without departing from the spirit and scope of the invention. Therefore, it is intended that the invention should not be limited except as by the appended claims.

We claim:

1. A power-dividing apparatus including:
 - a radial line power-dividing means including an input port and n output ports, said radial line power-dividing means being operative to divide an input signal of a predetermined power level applied to the input port into n output signals of reduced power level at the n output ports; and
 - a stripline power-dividing means including n input connections directly coupled to the n output ports of the radial line power-dividing means, m output connections, m being greater than n , and a plurality of individual power-dividing conductor arrangements connected between the n input connections and the m output connections, each of said power-dividing conductor arrangements including a first conductor connected to one of the n input connections and a number of additional conductors connected to the first conductor and to a corresponding number of the m output connections, the number of additional conductors in each of the individual power-dividing conductor arrangements having a value of one or greater, the total number of additional conductors for the plurality of power-dividing conductor arrangements being equal to m , each of the m output connections having one of the total number of additional conductors connected thereto, whereby m output signals of varying power levels are provided at the m output connections in response to the n output signals from the n output ports of the radial line power-dividing means being received at the n input connections.
2. A power feed apparatus including the power-dividing apparatus of claim 1 and further including:
 - a signal source adapted to apply an input signal of a predetermined power level to the input port of the radial line power-dividing means.
3. A power feed apparatus comprising:
 - a signal source for providing an input signal of a predetermined power level;
 - a radial line power-dividing means including:
 - a. an input port coupled to the signal source and adapted to receive the input signal of the predetermined power level;
 - b. a member spaced from the input port and symmetrical about a central axis, said member including a plurality of portions coaxial with the central axis and each of a predetermined height in the direction of the central axis, each of said portions having a group of substantially equally spaced output ports provided therein in accordance with a predetermined pattern, the total number of output ports being equal to n , each of the groups of output ports being spaced in the direction of the central axis a predetermined distance from the input port and each of the ports of each group being spaced from the central axis a different distance than each of the ports of the other groups; and
 - c. means for coupling the input signal from the input port to the groups of output ports whereby the input signal is divided into n output signals of reduced power level at the n output ports, the percentage of the power of the input signal distributed to each group of output ports being established by the predetermined distance in the direction of the central axis of the groups of output ports from the input port; and
 - a stripline power-dividing means including a plurality of power-dividing conductor means coupled to the n output ports of the radial line power-dividing means and operative to receive the n output signals from the n output ports and to provide m output signals of varying power levels at m output connections, m being greater than n .
4. A power feed apparatus in accordance with claim 3 wherein the heights of the portions of the member are selected such that a different percentage of the power of the input signal is distributed to each group of output ports.
5. A power feed apparatus in accordance with claim 3 wherein the number of groups of output ports and the pattern

of each group of output ports, the number and spacing of the output ports of each group, and the heights of the portions of the member are selected such that the power of the input signal is divided into n signal portions of equal value at the n output ports.

6. A power feed apparatus in accordance with claim 3 wherein the radial line power-dividing means further comprises:

a plurality of spacer means each of a predetermined thickness and coaxial with the central axis, each of said spacer means being secured to the surface of a corresponding one of the plurality of portions in a region adjacent to the group of output ports provided in the portion, the thickness of each spacer means being selected such that an upper surface thereof is flush with the surface of the adjacent portion;

a plurality of contact plate means each coaxial with the central axis and each secured both to the upper surface of a corresponding one of the plurality of spacer means and to the surface of the portion adjacent to and flush with the spacer means, each of said contact plate means being adapted to receive power from the input port;

m probe means disposed within the n output ports and in direct contact with the plurality of contact plate means and operable in response to the contact plate means receiving power from the input port to sense the power received by the contact plate means and to couple out n signals from the n output ports.

7. A radial line power divider including:

an input port adapted to receive an input signal of a predetermined power level;

a member spaced from the input port and symmetrical about a central axis, said member including:

a. a plurality of portions coaxial with the central axis and each of a predetermined height in the direction of the central axis, each of said portions having a group of substantially equally spaced output ports provided therein in accordance with a predetermined pattern, the total number of output ports being equal to n , each of the groups of output ports being spaced in the direction of the central axis a predetermined distance from the input port and each of the ports of each group being spaced from the central axis a different distance than each of the ports of the other groups; and

b. means for coupling the input signal from the input port to the groups of output ports whereby the input signal is divided into n output signals of reduced power level at the n output ports, the percentage of the power of the input signal distributed to each group of output ports being established by the predetermined distance in the direction of the central axis of the groups of output ports from the input port.

8. A radial line power divider in accordance with claim 7 wherein the heights of the portions of the member are selected such that a different percentage of the power of the input signal is distributed to each group of output ports.

9. A radial line power divider in accordance with claim 7 wherein the number of groups of output ports and the pattern of each group of output ports, the number and spacing of the output ports of each group, and the heights of the portions of the member are selected such that the power of the input signal is divided into n signal portions of equal value at the n output ports.

10. A radial line power divider in accordance with claim 7 wherein the radial line power-dividing means further comprises:

a plurality of spacer means each of a predetermined thickness and coaxial with the central axis, each of said spacer means being secured to the surface of a corresponding one of the plurality of portions in a region adjacent to the group of output ports provided in the portion, the thickness of each spacer means being selected such that an upper surface thereof is flush with the surface of the adjacent portion;

- a plurality of contact plate means coaxial with the central axis and each secured both to the upper surface of a corresponding one of the plurality of spacer means and to the surface of the portion adjacent to and flush with the spacer means, each of said contact plate means being adapted to receive power from the input port; and
- n probe means disposed within the n output ports and in direct contact with the plurality of contact plate means and operable in response to the contact plate means receiving power from the input port to sense the power received by the contact plate means and to couple out n signals from the n output ports.
11. A phased-array antenna system comprising:
- a signal source for providing an input signal of a predetermined power level;
- a radial line power-dividing means including an input port coupled to the signal source and n output ports, said radial line power-dividing means being operative to divide the input signal from the signal source into n output signals of reduced power level at the n output ports;
- a stripline power-dividing means including n input connections directly coupled to the n output ports of the radial line power-dividing means, m output connections, m being greater than n , and a plurality of individual power-dividing conductor arrangements connected between the n input connections and the m output connections, each of said power-dividing conductor arrangements including a first conductor connected to one of the n input connections and a number of additional conductors connected to the first conductor and to a corresponding number of the m output connections, the number of additional conductors in each of the individual power-dividing conductor arrangements having a value of one or greater, the total number of additional conductors for the plurality of power-dividing conductor arrangements being equal to m , each of the m output connections having one of the total number of additional conductors connected thereto, whereby m output signals of varying power levels are provided at the m output connections in response to the n output signals from the n output ports of the radial line power-dividing means being received at the n input connections;
- m phase-shifting means coupled to the m output connections of the stripline power-dividing means and adapted to receive the m output signals of varying power levels from the m connections and in response to steering command signals from a control means to phase shift each of the signals received thereby by a predetermined amount;
- an array of m antenna elements coupled to the m phase-shifting means; and
- a control means adapted to apply steering command signals to the m phase-shifting means to cause the signals received thereby to be shifted by controlled amounts whereby a desired phase front is established across the antenna array.
12. A phased-array antenna system comprising:
- a signal source for providing an input signal of a predetermined power level;
- a radial line power-dividing means including:
- a. an input port coupled to the signal source and adapted to receive the input signal of the predetermined power level;
- b. a member spaced from the input port and symmetrical about a central axis, said member including a plurality of portions coaxial with the central axis and each of a predetermined height in the direction of the central axis, each of said portions having a group of substantially equally spaced output ports provided therein in accordance with a predetermined pattern, the total number of output ports being equal to n , each of the groups of output ports being spaced in the direction of the central axis a predetermined distance from the input port and each of the ports of each group being spaced from the central axis a different distance than each of the ports of the other groups; and

- c. means for coupling the input signal from the input port to the groups of output ports whereby the input signal is divided into n output signals of reduced power level at the n output ports, the percentage of the power of the input signal distributed to each group of output ports being established by the predetermined distance in the direction of the central axis of the groups of output ports from the input port; and
- a stripline power-dividing means including a plurality of individual power dividers coupled to the n output ports of the radial line power-dividing means and capable of providing different amounts of power division, said individual power dividers being operative to receive the n output signals from the n output ports of the radial line power-dividing means and to provide m output signals of varying power levels at m output connections, m being greater than n ;
- m phase-shifting means coupled to the m output connections of the stripline power-dividing means and adapted to receive the m output signals of varying power levels from the m output connections and in response to steering command signals from a control means to phase shift each of the signals received thereby by a predetermined amount;
- an array of m antenna elements coupled to the m phase-shifting means; and
- a control means adapted to apply steering command signals to the m phase-shifting means to cause the signals received thereby to be shifted by controlled amounts whereby a desired phase front is established across the antenna array.
13. A phased-array antenna system in accordance with claim 12 wherein the heights of the portions of the member are selected such that a different percentage of the power of the input signal is distributed to each group of output ports.
14. A phased-array antenna system in accordance with claim 12 wherein the number of groups of output ports and the pattern of each group of output ports, the number and spacing of the output ports of each group, and the heights of the portions of the member are selected such that the power of the input signal is divided into n signal portions of equal value at the n output ports.
15. A phased-array antenna system in accordance with claim 12 wherein the radial line power-dividing means further comprises:
- a plurality of spacer means each of a predetermined thickness and coaxial with the central axis, each of said spacer means being secured to the surface of a corresponding one of the plurality of portions in a region adjacent to the group of output ports provided in the portion, the thickness of each spacer means being selected such that an upper surface thereof is flush with the surface of the adjacent portion;
- a plurality of contact plate means each coaxial with the central axis and each secured both to the upper surface of a corresponding one of the plurality of spacer means and to the surface of the portion adjacent to and flush with the spacer means, each of said contact plate means being adapted to receive power from the input port; and
- n probe means disposed within the n output ports and in direct contact with the plurality of contact plate means and operable in response to the contact plate means receiving power from the input port to sense the power received by the contact plate means and to couple out n signals from the n output ports.
16. A monopulse phased-array antenna system comprising:
- a multimode hybrid launcher comprising:
- a. a folded E-plane magic-tee including a sum port, an elevation difference port, and an output port; and
- b. an orthomode transducer coupled to the output port of the folded E-plane magic-tee and including an azimuth difference port and an output port;
- said multimode hybrid launcher being operative in a transmit mode of operation to transfer a signal of a predetermined

mined power level applied to the sum port of the folded E-plane magic-tee to the output port of the orthomode transducer;

a radial line power divider including:

- c. an input port adapted to receive the signal provided at the output port of the orthomode transducer; 5
 - d. a member spaced from the input port and symmetrical about a central axis, said member including:
 - e. a plurality of flat circular portions coaxial with the central axis and each of a predetermined height in the direction of the central axis, each of said portions having a group of substantially equally spaced output ports provided therein in accordance with a ring pattern, the radii of the rings of output ports being different, the total number of output ports being equal to n , each of the groups of output ports being spaced in the direction of the central axis a different distance from the input port; 10
 - f. a plurality of flat spacer rings coaxial with the central axis and each of a different thickness, each of said spacer rings being secured to the surface of a corresponding one of the plurality of portions in a region adjacent to the ring of output ports provided in the portion, the thicknesses of the spacer rings increasing with increasing radii of the rings of output ports, an upper surface of each spacer ring being flush with the surface of the adjacent portion; 15
 - g. a plurality of flat contact rings each coaxial with the central axis and each secured both to the upper surface of a corresponding one of the plurality of spacer rings and to the surface of the portion adjacent to and flush with the spacer ring, each of the contact rings being adapted to receive power from the input port; 20
 - h. n probes disposed within the n output ports and in direct contact with the plurality of contact rings and operable in response to the contact rings receiving power from the input port to sense the power received by the contact rings and to couple out n signals from the n output ports; and 25
 - i. means for coupling the input signal from the input port to the rings of output ports; 30
- the number of rings of output ports and the number and spacing of the output ports of each ring being selected 35

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whereby in the transmit mode of operation the input signal is divided into n output signals of reduced power level at the n output ports, the percentage of the power of the input signal distributed to each ring of output ports increasing with increasing radii of the rings of output ports;

a stripline power divider including a plurality of individual power dividers coupled to the n probes and capable of providing different amounts of power division, said individual power dividers being operative in the transmit mode of operation to receive the n output signals from the n output ports of the radial line power divider and to provide m output signals of varying power levels at m output connections, m being greater than n ;

m transitions connected to the m output connections of the stripline power divider for transferring the m output signals of varying power level from the m output connections;

m latching, analog, nonreciprocal phase shifters connected to the m transitions and adapted to receive the m output signals of varying power levels from the m output connections and in response to steering command signals from an electronic beam-steering control unit to phase shift each of the signals received thereby by a predetermined amount;

an array of m antenna elements coupled to the m phase shifters; and

an electronic beam-steering control unit operative in the transmit mode of operation to apply individual steering command signals to the phase shifters to cause the signals received thereby to be shifted by controlled amounts whereby a desired phase front is established across the antenna array;

said array of m antenna elements being operative in a receive mode of operation to receive monopulse signals from a target, said signals being combined by the stripline power divider and the radial line power divider to form a sum signal, an elevation difference signal, and an azimuth difference signal at the output port of the orthomode transducer, said sum signal, elevation difference signal, and azimuth difference signal being applied by the orthomode transducer to the sum port, elevation difference port, and azimuth difference port, respectively, of the multimode hybrid launcher.