United States Patent

[11] 3,599,216

[72] Inventors T. O. Paine
Administrator of the National Aeronautics and Space Administration with respect to an invention of;
Arthur F. Seaton, Palos Verdes Estates, Calif.

[21] Appl No 848,810
[22] Filed Aug. 11, 1969
[45] Patented Aug. 10, 1971

[54] VIRTUAL-WALL SLOT CIRCULARLY POLARIZED PLANAR ARRAY ANTENNA
22 Claims, 14 Drawing Figs.

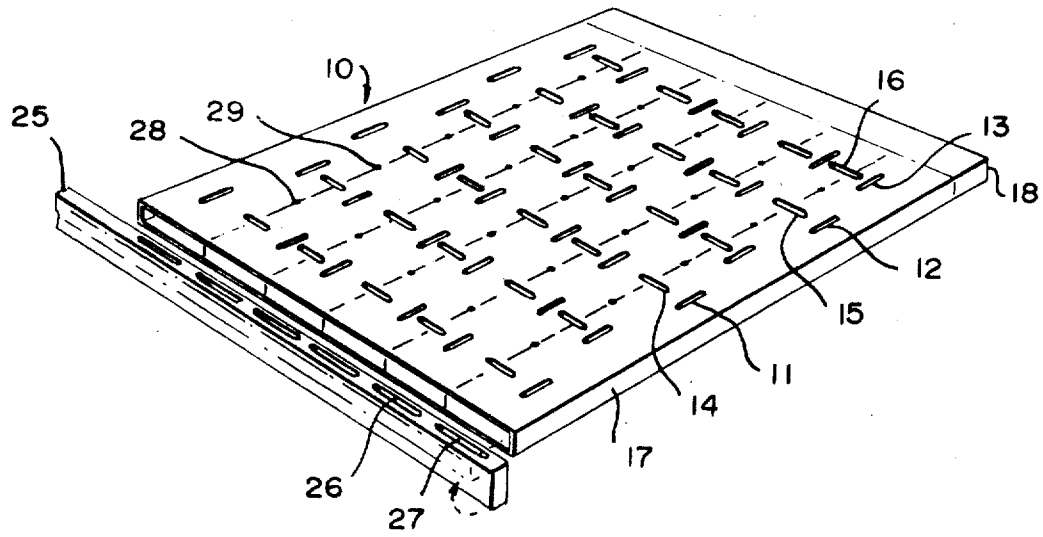
[52] U.S. Cl. 343/771, 343/853
[51] Int. Cl. H01q 13/10
[50] Field of Search 343/770, 771, 853, 854

[56] References Cited
UNITED STATES PATENTS

3,243,818	3/1966	Holtzman	343/771
3,503,073	3/1970	Ajioka	343/771
3,521,287	7/1970	Fee	343/834

Primary Examiner—Eli Lieberman
Attorneys—G. T McCoy, J. H. Warden and Monte F. Mott

ABSTRACT: A circularly polarized planar array antenna is provided by a multimode waveguide with alternately displaced transverse slots over virtual walls for one component, and conventional series or shunt slots between virtual walls for the other component of a circularly polarized beam. Actual walls may be inserted in the place of the virtual walls for unbalanced excitation of the array with a quarter-guide wavelength choke under each wall slot.



PATENTED AUG 10 1971

3,599,216

SHEET 1 OF 4

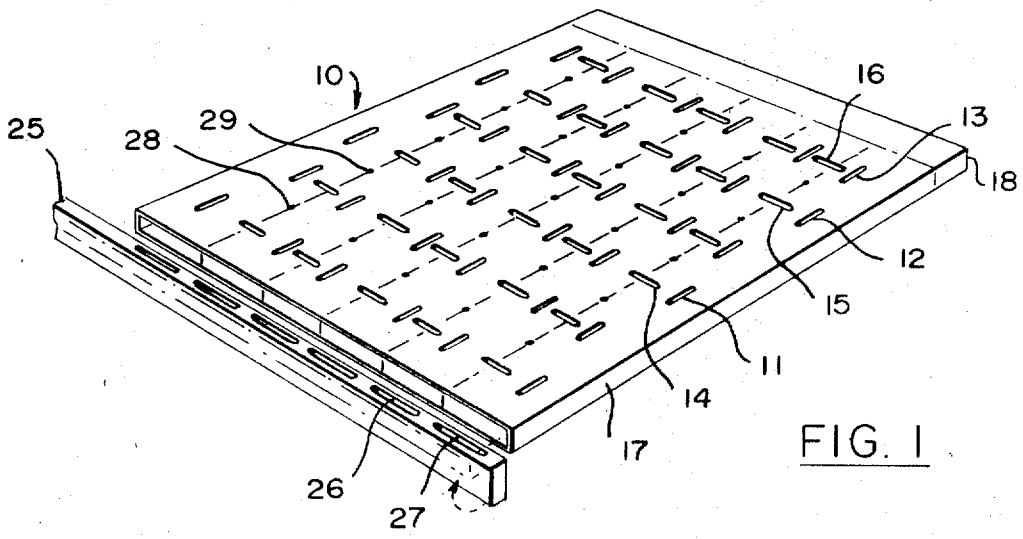


FIG. 1

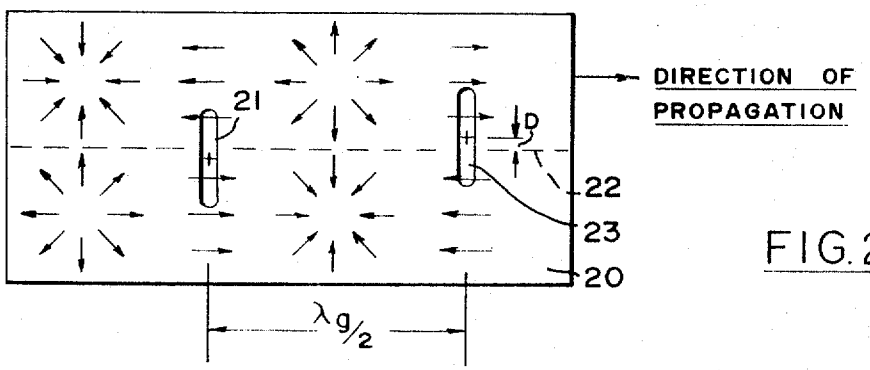


FIG. 2

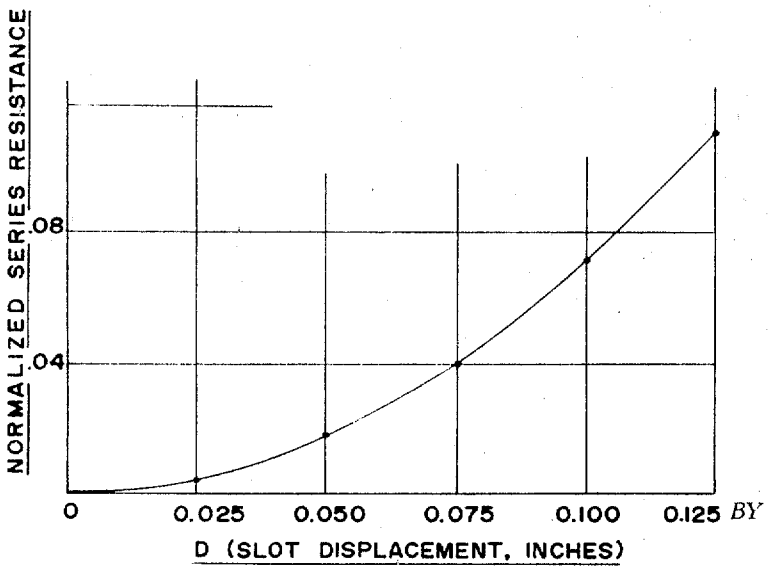


FIG. 3

ARTHUR F. SEATON
INVENTOR.

BY

ATTORNEYS

FIG. 4

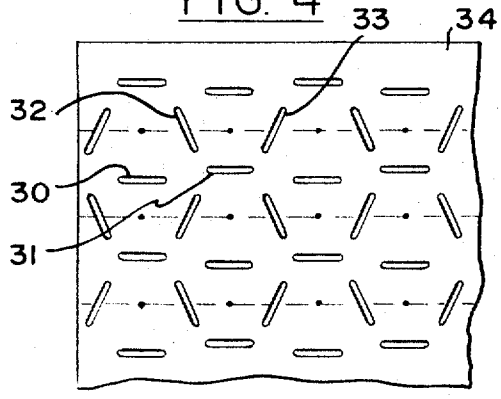


FIG. 5

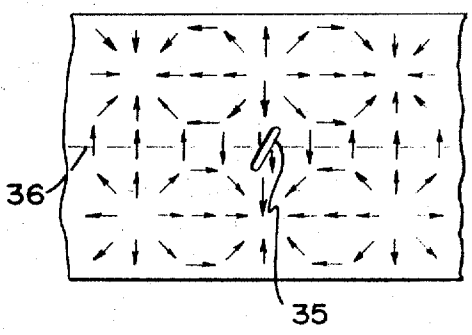


FIG. 6

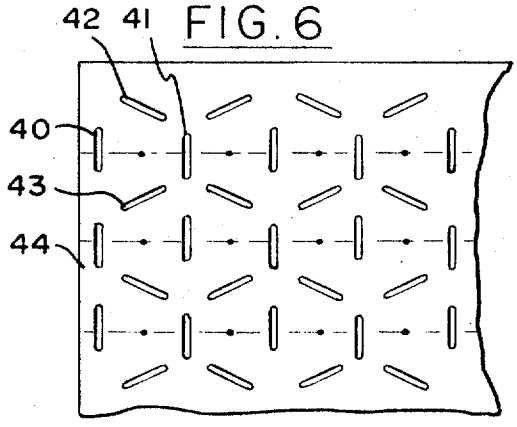


FIG. 7

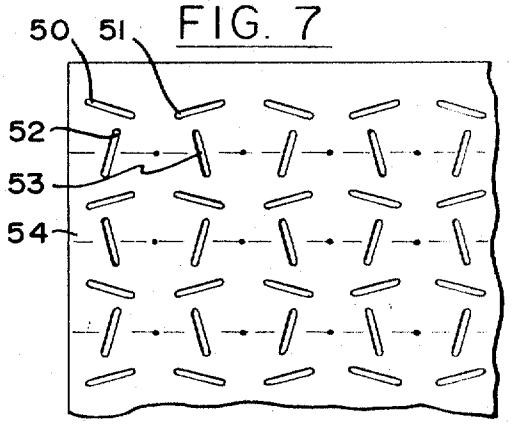
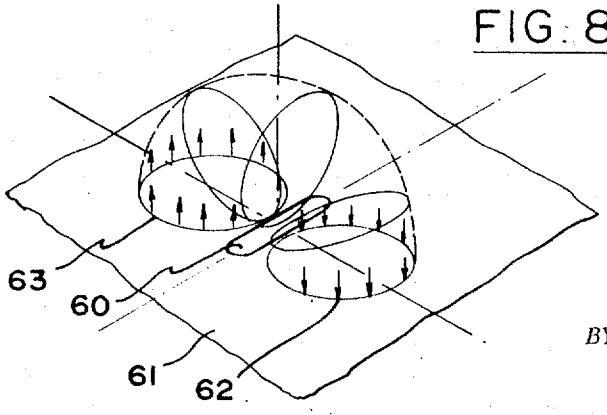


FIG. 8

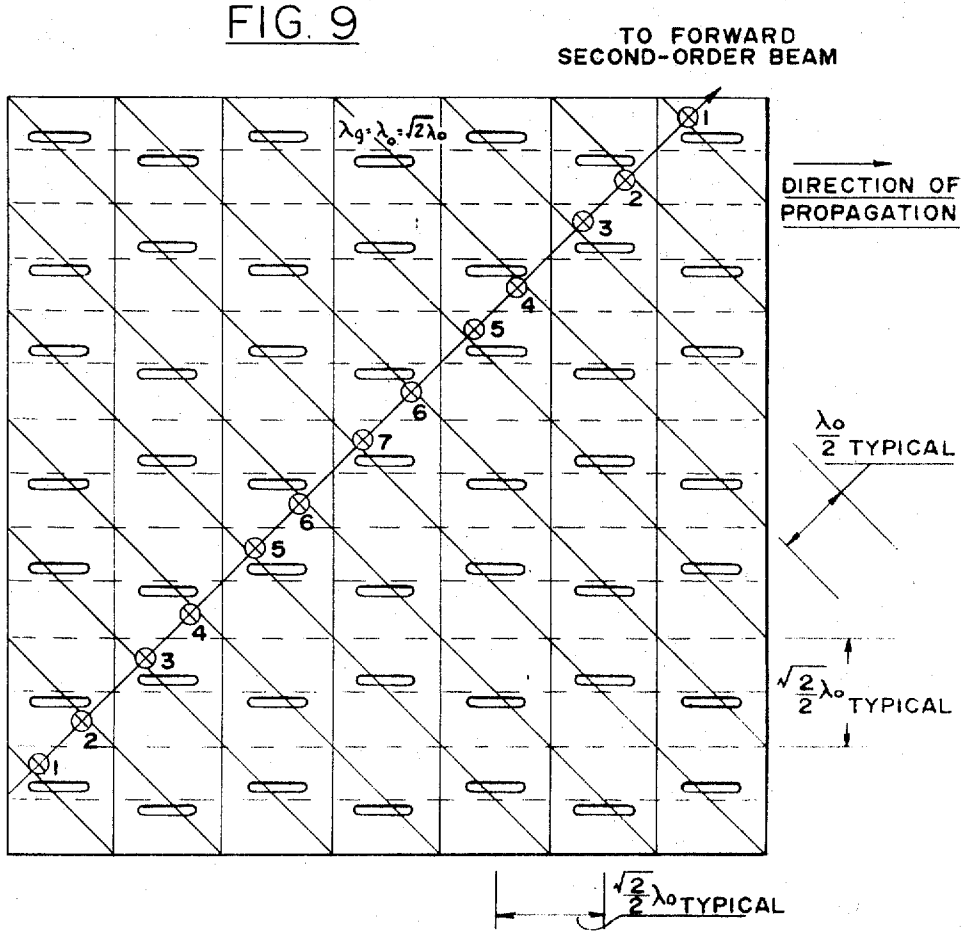


ARTHUR F. SEATON
INVENTOR.

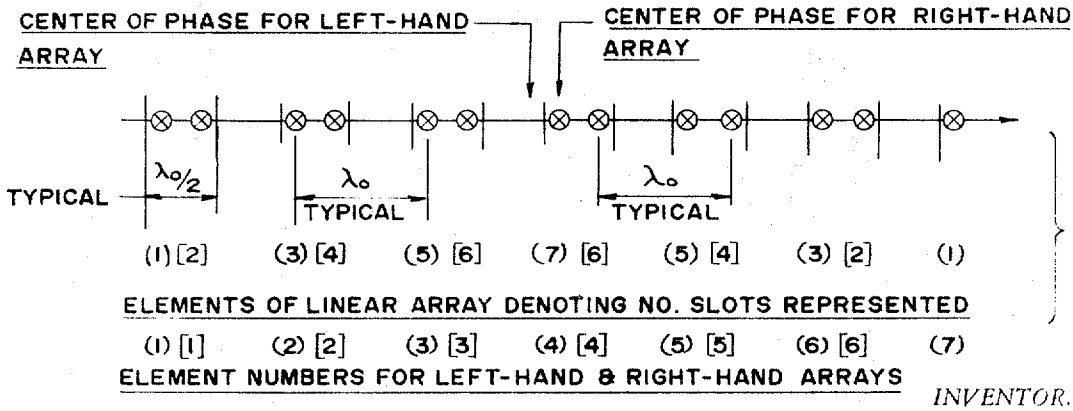
BY

ATTORNEYS

FIG. 9



$\otimes_n$ = ELEMENTS OF LINEAR ARRAY DENOTING NO. SLOTS REPRESENTED



( ) RIGHT-HAND ARRAY
[ ] LEFT-HAND ARRAY

FIG. 10

INVENTOR.
ARTHUR F. SEATON

BY J. H. Warren & Co

ATTORNEYS

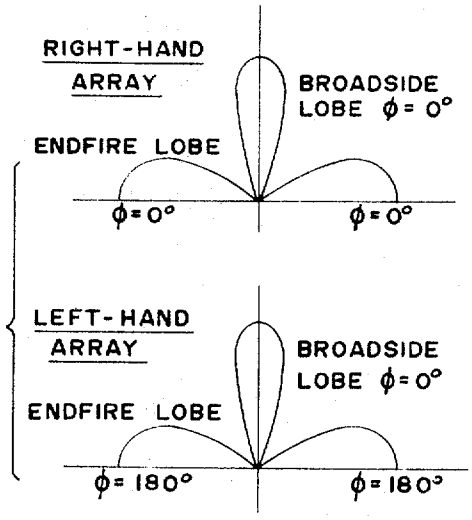


FIG. 11

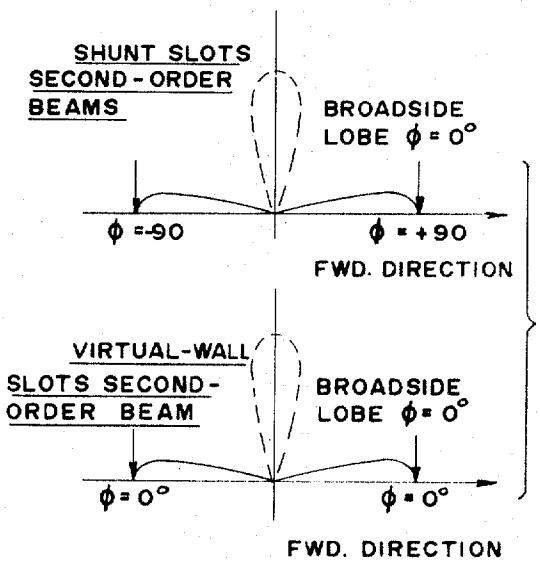


FIG. 13

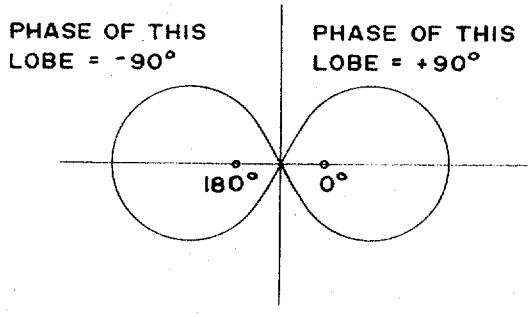
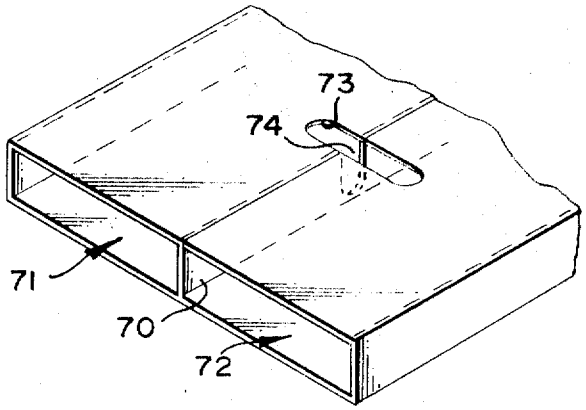


FIG. 12

FIG. 14



INVENTOR.
ARTHUR F. SEATON

BY

ATTORNEYS

VIRTUAL-WALL SLOT CIRCULARLY POLARIZED PLANAR ARRAY ANTENNA

ORIGIN OF THE INVENTION

The invention described herein was made in the performance of work under a NASA contract and is subject to the provisions of Section 305 of the National Aeronautics and Space Act of 1958, Public Law 85–568 (72 Stat. 435; 42 USC 2457).

BACKGROUND OF THE INVENTION

This invention relates to circularly polarized antennas of the planar array type.

The best known prior art of this type antenna is the planar array used on the Surveyor spacecraft for lunar to earth communications. The planar array occupies the smallest volume of all antennas, it lends itself readily to flush mounting and to structural reinforcements on the back, and it can be easily designed for uniform illumination of the aperture for maximum gain. A further advantage is that tapered illumination functions can be used if desired. A disadvantage of this type of antenna is that special slot patterns must be used to obtain circular polarization, and broadband operation is difficult to achieved.

Several slot configurations will yield circular polarization. The Surveyor spacecraft used a combination of cross slots and complex slots in alternate rows, the slots of the crossed slots being oriented at a 45° angle from the axis of wave propagation. The complex slots were provided in pairs, one pair for each crossed slot, each of the complex slots consisting of a slot parallel to one of the crossed slots. This arrangement provided an antenna with a measured gain of 27 db. That represents an overall efficiency of 70 percent. However, the slot configuration alone does not provide adequately small interelement slot spacing in all directions of the aperture to suppress endfire lobes that tend to be generated in the quadrants. That disadvantage can be overcome by the use of dielectric or periodic elements in the waveguide to reduce the guide wavelength, λ_g. In the Surveyor antenna, a corrugated bottom or rear wall was used to reduce λ_g by approximately 25 percent. This reduction proved adequate for the suppression of the endfire beams and did not require an excessively high corrugation. It would be desirable to provide a circularly polarized antenna of the planar array type which does not require dielectric or periodic loading of the guide to reduce the guide wavelength, i.e. without the necessity of using a slow wave structure in the waveguide. This invention provides a solution to that problem.

SUMMARY OF THE INVENTION

A circularly polarized antenna of the planar array-type is provided using a waveguide having a multiple order transverse electric wavemode of operation in one dimension virtually forming a plurality of parallel traveling wave channels and transverse slots astride parallel lines over virtual walls therein. These slots are referred to as virtual wall slots. Successive slots astride a given virtual wall are displaced or rotated in alternate directions by amounts which determine the amplitude of inphase excitation of the slots. They have an interelement spacing of $\lambda g_{/2}$ and can be used to efficiently generate one component of a circularly polarized beam. Shunt or series slots in ordinary configurations are used to generate the second component of the circularly polarized beam. In alternate embodiments, virtual walls are formed with actual walls dividing the waveguide into a plurality of traveling waveguide channels by cutting a section (which may be in the form of a quarter-wavelength choke under each virtual wall slot so that the actual wall will not short out the slot while still maintaining a high degree of isolation between adjacent waveguide channels.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates a first embodiment employing shunt and displaced virtual-wall slots on a multimode waveguide for a circularly polarized planar array antenna.

FIG. 2 illustrates displaced virtual-wall slots coupling to longitudinal wall currents in a $TE_{2,0}$ mode waveguide.

FIG. 3 illustrates a graph of displaced virtual-wall slot coupling as a function of slot displacement in the waveguide of FIG. 2.

FIG. 4 illustrates a second embodiment of the invention employing shunt slots and angled virtual-wall slots.

FIG. 5 illustrates angled virtual-wall slot coupling to transverse wall currents in a $TE_{2,0}$ mode waveguide.

FIG. 6 illustrates still another embodiment of the present invention employing series slots and displaced virtual-wall slots.

FIG. 7 illustrates yet another embodiment employing series slots and angled virtual-wall slots.

FIG. 8 illustrates that, for a planar array slot anywhere in the plane of an aperture plate, polarization is everwhere normal to the plane regardless of its orientation.

FIG. 9 illustrates a "collapsing" process by which the phase of second-order beams can be determined for analysis.

FIG. 10 illustrates a collapsed linear array broken into the separate arrays of elements for analysis.

FIG. 11 illustrates far-field patterns of separate arrays of a "collapsed" linear array.

FIG. 12 illustrates two isotropic element patterns spaced less than $\lambda o_{/2}$ apart and fed 180° out of phase.

FIG. 13 illustrates phase and amplitude characteristics of second-order beams generated by shunt slots and virtual-wall slots in the configuration of FIG. 1.

FIG. 14 illustrates a variant of the present invention comprising a wall slot over an actual conductive wall in the position of a virtual wall in a multimode transverse electric waveguide.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1 illustrates a first embodiment of the present invention for circular polarization in a slot antenna **10** employing shunt slots, such as slots **11**, **12** and **13** and virtual-wall slots, such as slots **14**, **15** and **16** in a multimode waveguide **17** for transverse electric waves. The virtual walls straddled by the virtual-wall slots are indicated by dotted lines which effectively divide the multimode waveguide **17** into six waveguides, all terminated by a suitable load **18** and each having its own group of longitudinally displaced shunt slots. The centers of both the virtual-wall slots and the shunt slots are displaced alternately to opposite sides of the respective virtual walls and center lines of the effective waveguides formed by the virtual walls in order that proper coupling be achieved.

The coupling achieved by the shunt slots for one component of the circularly polarized beam is described in chapter 9 of the "Antenna Engineering Handbook" edited by Jasik, McGraw-Hill (1961). Coupling for the second component is illustrated in FIG. 2 where instantaneous wall currents are shown for a section of $TE_{2,0}$ mode waveguide **20** at the instant of time at which longitudinal currents are tending to excite a virtual-wall slot **21**. It should be noted that currents on opposite sides of a virtual wall **22** tend to excite the slot **21** in phase opposition.

When perfectly centered on the virtual wall **22**, the excitation coupled by the slot **21** is balanced by out-of-phase excitation on each side of the virtual wall **22**. Therefore, no radiation takes place. However, when the center of the slot **21** is displaced to either side of the virtual wall **22**, excitation is coupled by the slot **21** most heavily to the currents in the region toward which it is displaced. In that manner, the phase of excitation for each virtual-wall slot is controlled by displacement. For example, to achieve inphase radiation by the slot **21** with a slot **23**, which are spaced a distance $\lambda g_{/2}$, the displacement of the slot **23** over the virtual wall **22** must be in the opposite direction of the displacement of the slot **21** as shown in the FIG. 2.

Slot coupling data taken on an experimental fixture has shown that the coupling achieved by a virtual-wall slot is a function of the displacement as shown in FIG. 3 where displacement is plotted in inches along the abscissa and normalized series resistance along the ordinate for a $TE_{2,0}$ mode waveguide which is equivalent to adjacent sections of the multimode waveguide of FIG. 1.

The virtual-wall slot operation is very similar to the ordinary shunt slot operation which has long been used for waveguide linear and planar arrays. The major differences are that the virtual-wall slot is oriented at 90° to the usual shunt slot as shown in FIG. 1, and that it couples to the longitudinal component of wall current while the shunt slot couples to the transverse components. These two differences make a combination of the two types of slots ideal for radiating a circularly polarized wave from a planar array. Being orthogonal, each furnishes one component of the circularly polarized wave, and since each couples to only one of the major components of wall current in the waveguide, phase quadrature excitation results.

The multimode waveguide **17** for the array **10** of FIG. **1** is fed by a waveguide **25** folded down and under the waveguide **17** in order to show slots in the waveguide **25** such as slots **26** and **27**, each of which is aligned with one channel of the waveguide **17** formed by the virtual walls. Alternatively, the array **10** may be fed by what is commonly referred to as a "corporate feed" using a plurality of excitation elements, one for each channel of the waveguide **17**, and a coaxial line feeding each element. Adjacent coaxial lines are fed in pairs by separate coaxial lines in a second level. The coaxial lines in the second level are then similarly paired in a third level and so on until only one coaxial line remains for feeding all channels. In that manner, the feedpath for all channels is the same length.

An experimental model of a circularly polarized planar array with virtual-wall slots and shunt slots was built with mode suppressing pins placed in line with the virtual walls, one pin between every pair of virtual-wall slots, such as pins **28** and **29**. These pins must extend and be connected to opposing walls, but need not pass through the aperture (upper wall as illustrated in FIG. **1**). For some applications and operating conditions, fewer mode suppressing pins may be sufficient, such as every other one of the pins illustrated in FIG. **1**. For larger arrays, these mode suppressing pins will greatly assist in maintaining the proper effective *b*-dimension between the broad walls, particularly at the center of the array.

Data obtained from the experimental model indicate an axial ratio of 1.4 db. and patterns with beam widths very near the expected values. The principal advantage found was the relative simplicity of the slot design which lends itself readily to simple manufacturing techniques since all slots are parallel to one of the principal axes of the array. Coupling coefficients of the slots are readily controlled (to reasonable limits) by linear displacement of the slots from the center lines of the waveguide channels in the case of the shunt slots or from the virtual walls in the case of the virtual-wall slots.

The limit of control by linear displacement of the slots is imposed by the physical interference that exists between the shunt slots and the virtual-wall slots. Accordingly, this interference would limit application of this first embodiment illustrated in FIG. **1** to fairly large arrays which do not require large slot coupling factors. It should be noted that this displacement limitation minimizes second-order beam problems because the magnitude of second-order beams is a function of slot offset.

A disadvantage of this first embodiment illustrated in FIG. **1** is that there will always be one more channel center line than there virtual walls in a multimode waveguide. Consequently, there will be one less row of virtual-wall slots than of shunt slots. This difference would show up as a large beam width in the transverse plane for the component supplied by the virtual-wall slots as compared with the shunt slot component. Heavier coupling for these slots could compensate for the resulting loss of gain, but only at the expense of a loss in net gain for the overall circularly polarized array. However, this disadvantage diminishes with larger arrays. The problem mainly concerns small arrays on the order of two to three wavelengths on a side.

A second embodiment of the present invention will now be described with reference to FIG. **4** which shows displaced shunt slots as in the embodiment of FIG. **1**, such as shunt slots **30** and **31**, and angled virtual-wall slots, such as slots **32** and **33** arranged on an aperture plate **34** of an array which is fed and terminated as in the embodiment of FIG. **1**. In this embodiment, both types of slots couple to the transverse wall currents and quadrature excitation is obtained by spacing virtual-wall slots at $\lambda g_{/2}$ intervals, but shifted down the line from the shunt slots a distance $\lambda g_{/4}$.

FIG. **5** illustrates the coupling of an angled virtual-wall slot **35** to transverse wall currents. If the slot is perfectly centered on the virtual-wall **36**, it can theoretically be made to couple to the transverse currents on the waveguide wall by rotation of the slot **35** about its center. In this respect it is similar to the ordinary series slot which is positioned on a waveguide channel center line and rotated for coupling to the longitudinal wall current. Thus the angled virtual-wall slot can be used in conjunction with the standard shunt slot to generate a circularly polarized beam.

Although heavier coupling can be used in the embodiment of FIG. **4** without physical interference of the slots than in the embodiment of FIG. **1**, quite heavy coupling of the slots cannot be used because of the physical interference of the angled virtual-wall slots rotated about their center and the shunt slots laterally displaced for greater coupling. However, an advantage is that the slots can be placed on the aperture **34** as shown with a column of angled virtual-wall slots at each end of the rows of shunt slots. In that manner, there will always be one column of virtual-wall slots more than there are rows of shunt slots. The additional column of virtual-wall slots helps compensate for the fact that there will always be one less row of virtual-wall slots than there are rows of shunt slots. For a square array of shunt slots, the total number of virtual-wall slots will then be only one less than the total number of shunt slots.

A third embodiment of the present invention illustrated in FIG. **6** employs displaced virtual-wall slots, such as wall slots **40** and **41** similar to the displaced wall slots of the embodiment of FIG. **1**, but used in conjunction with standard series slots, such as slots **42** and **43**, in an aperture plane **44** for a circularly polarized planar array antenna. Both types of slots couple to the longitudinal component of the current. Therefore, in a manner similar to the embodiment of FIG. **4**, the virtual-wall slots spaced $\lambda g_{/2}$ apart are displaced a quarter wavelength ($\lambda g_{/4}$) from the series slots to obtain the quadrature excitation necessary for circular polarization. The primary advantage of this arrangement is that extremely heavy coupling can be used, if needed, without any physical interference of slots. For instance, slots **40** and **41** may be displaced to their extreme while series slots **42** and **43** may be rotated to their extreme without any physical interference. However, if very heavy coupling is used, large second-order beams will be generated. Another advantage is that, as in the embodiment of FIG. **4**, the total number of virtual-wall slots will be more nearly equal to the number of series slots in the aperture plate **44**.

A fourth embodiment illustrated in FIG. **7** employs the series slots of the embodiment of FIG. **6**, such a s slots **50** and **51**, with the angled virtual-wall slots of the embodiment of FIG. **4**, such as the wall slots **52** and **53** in an aperture plate **54**. The two types of slots used together to generate a circularly polarized beam are predominately orthogonal; one type couples to the transverse component of current while the other couples to the longitudinal component. Since the slots lie in the same transverse plane, they will be excited in phase quadrant and the condition for circular polarization is satisfied.

In this embodiment, as in the embodiment of FIG. **6**, very heavy coefficients of coupling can be obtained because each

of the slots of the two types can be rotated about its center as far as is necessary without interferring with rotation of adjacent slots. For light to medium coupling, the slots will not come even close to each other so that no weak spots will be present in the slotted aperture plate **54** which could cause trouble in a high vibration environment. As in the embodiment of FIG. **6**, if very heavy coupling is employed, there is a possible loss of a sizeable amount of power into second order beams. However, since large rotation of the slots is not needed with large arrays, this loss of power would be a problem only with very small arrays.

An analysis of second-order beam generation will now be described with reference to FIGS. **8** to **13**. Most planar array slot configurations lose power through the generation of spurious beams that are commonly called second-order beams. These beams arise because of certain asymmetrics in the geometry of the slot pattern. Once a particular slot configuration is chosen, the slot location is dictated by the phase and amplitude of coupling required by the aperture distribution of the array and the beam pointing angle. Because heavy coupling coefficients can cause an unacceptably large amount of power to be lost in second-order beams, the four embodiments described with reference to FIGS. **1**, **4**, **6** and **7** were analyzed for determination of their second-order beam characteristics.

Destructive interference between second-order beams generated by the two separate types of slots in each configuration is, in theory, at least partially possible because the polarization of any slot in the plane of the array is everywhere normal to that plane regardless of its orientation in the plane as shown in FIG. **8**, which shows a slot **60** on an aperture plate **61**, and the amplitude of the slot radiation pattern in the plane of the array represented by circles **62** and **63** drawn on the plate **61**. The arrows on those circles indicate the polarities of interest. Determination of any suppression of second-order beams by such interference was of particular interest in the analysis.

For analysis, the circularly polarized array is considered as two orthogonal, interlaced, linearly polarized arrays fed in time quadrature. Each of these linearly polarized arrays consists of all the slots of a particular type in the configuration and will have certain second-order beam characteristics as determined by the geometry of the arrangement. In the types of arrays being investigated here, the second-order beams have their peak amplitudes in the plane of the array of 45° off the principal planes. The beam is fan-shaped and extends up towards the main beam a number of degrees depending on the size of the array. Small arrays will have a large fan beam and large arrays will have a small fan beam. The polarization starts to rotate as the point of observation moves up from the plane of the array. The rate of rotation is slow, however; and if the second-order beam could extend up to the main beam, the polarization vector would rotate only far enough to bring it into line with the polarization vector of the main beam of the linearly polarized array. With such a slot rate of rotation of the polarization vector it can be said that, to a first-order approximation at least, the polarization for all second-order beams studied is normal to the plane of the array.

It is necessary that the phase of the second-order beams be established in relationship to some standard. For convenience, the component of the main beam contributed by the ordinary slots (shunt or series, as the case may be) has been chosen as the reference. The phase of the second-order beams is determined by a "collapsing" of all the elements of a linearly polarized planar array onto a line that points in the direction of the maxima of the second-order beam. In illustration of this process, a linearly polarized array consisting of the shunt slots of the embodiment of FIG. **1** is shown in FIG. **9** with the slots collapsed onto a line running diagonally across the array. The linear array thus formed determines the amplitude and phase characteristics of the second-order beams.

Close examination of the "collapsed" linear array (as shown in FIG. **10**) reveals certain symmetries in the apparently asymmetrical distribution. First, all of the element positions that lie to the right side of the $\lambda o/2$ marks form an array with interelement spacing of λo. The amplitude distribution is given by the number of slots which were "collapsed" to each point and is listed in the following Table.

AMPLITUDE DISTRIBUTION OF RIGHT-HAND ARRAY

Element number	1	2	3	4	5	6	7
Relative amplitude	1	3	5	7	5	3	1

Because of the symmetrical nature of this array inspection will show that its phase center will coincide with element No. 4; and further, because of the λo interelement spacing three principal maxima will exist (one in the broadside direction and one each in the endfire directions). The far field pattern of this array can be sketched as in FIG. **11**. It can be shown that an array of seven elements of this type will have endfire lobes that are in phase with the broadside lobe, with five sidelobes of alternating phase between each principal maxima. Since the sidelobes will be very small because of the triangular amplitude distribution on the array, they will be ignored.

The second symmetry to be noted is that all of the element positions lying to the left side of the $\lambda o/2$ marks also form an array with an interelement spacing of λo. The amplitude distribution is given in the following Table.

AMPLITUDE DISTRIBUTION OF LEFT-HAND ARRAY

Element number	1	2	3	4	5	6
Relative amplitude	2	4	6	6	4	2

This array is also symmetrical and the center of phase lies halfway between elements 3 and 4. Again, three principal maxima will exist with sidelobes in-between. Because there are only six elements in this array, the endifre lobes will be 180° out-of-phase with the broadside lobe with four sidelobes in-between. Again the sidelobes will be very small because of the triangular amplitude taper and will be ignored. The farfield pattern of this array is also sketched in FIG. **11**.

The total pattern of all thirteen elements is the sum of the two patterns shown in FIG. **11** when their respective locations are at the centers of phase as noted in FIG. **10**. It can be seen that the two centers of phase are not superimposed; if they were, the endfire lobes would cancel and there would be no second-order beams. It can also be seen that, for this example at least, the centers of phase are less than $\lambda o/2$ apart. A $\lambda o/2$ spacing would result in no suppression of endfire lobes and the second-order beams would have the same magnitude as the main lobe. The broadside lobes add to become the main lobe of the array and in the farfield are unaffected by the positions of the phase centers of the two patterns. For convenience, the broadside lobe can be ignored and the patterns can be considered as being identical except for the fact that one is 180° out-of-phase with the other. The endfire patterns can be effectively added now by an assumption that the source of each is an element with a pattern as shown in FIG. **11**.

The total array of thirteen elements reduces to an array of two identical elements which are fed 180° out-of-phase and are separated by some distance less than $\lambda o/2$. It can be shown that such an array has a pattern with phase and amplitude characteristics as shown in FIG. **12**. The phases are in relation to a broadside lobe which is assumed to be at **O°** phase. The phase center of the pair is half way between the elements. When the element pattern (endfire lobe pattern) is superimposed on this array pattern by the pattern multiplication principle, the resulting pattern yields the second-order beams of the planar array of shunt slots along the diagonal line shown in FIG. **9**. These beams take on the approximate shape and the exact phase shown in FIG. **13**. The center of phase of the second-order beam pattern is the geometric center of the two-dimensional slot configuration when the slots are assumed to have infinitely small displacements.

By a line of reasoning similar to that demonstrated for the shunt slots, it can be shown that the second-order beam pattern generated by the array of displaced virtual-wall slots has the phase and amplitude characteristics also shown in FIG. **13**.

The center of phase for this pattern is the geometric center of the virtual-wall slot configuration. In this example the geometric centers and, hence, the phase centers of the two types of slots coincide.

In the embodiment of FIG. 1 the virtual-wall slot excitation leads that of the shunt slots by 90°; therefore, compared with the main beam of the shunt slot array, the second-order beams of the virtual-wall slot array are at $\Phi=+90°$ for both the forward and backward looking beams. Since the phases of the forward and backward beams of the shunt slot array are at +90° and −90°, respectively, it follows that the forward beam will be reinforced while the backward beam will tend to be cancelled. There would be no change in the power lost into the second-order beams, just a redirection of some of that power.

If one unit of power (with one unit of voltage) is assumed in each of the four second-order beams of each linearly polarized array, a total of eight units of power is lost. When the two arrays are combined into a circularly polarized array, the backward beams will be suppressed while the two forward beams will add. Since the voltages are added, each forward beam has an intensity of two units of voltage. The impedance of space does not change so that this intensity represents four units of power in each beam, for a total of eight (the same amount of power lost by the two linearly polarized arrays considered separately).

Two different sizes of each slot configuration were analyzed in a fashion similar to the qualitative analysis performed for a seven-by-seven array of the embodiment of FIG. 1. The second-order beam characteristics of four of the typical arrays investigated are summarized in the following Table.

					10			11	
1	2	3	4	5	6	7		8	9
FIGURE 1	7 by 7	RH	Shunt DVW	0 +90	+90 +90	Reinforces		−90 +90	Cancels.
FIGURE 7	8 by 8	LH	Series AVW	0 −90	180 180	Reinforces		180 0	Cancels.
FIGURE 4	8 by 8	RH	Shunt AVW	0 +90	−90 +90	Cancels		+90 +90	Reinforces.
FIGURE 6	8 by 8	LH	Series DVW	0 +90	180 180	Reinforces		180 0	Cancels.

Note:
1—Slot configuration.
2—Size of composite array, shunt or series slots.
3—Sense of circular polarization.
4—Type of slots used in component arrays.
5—Phase of slot excitation, degrees.
6—Phase, degrees.
7—Result of summing of two components.
8—Phase, degrees.
9—Result of summing of two components.
10—Forward-looking second-order beams.
11—Rearward looking second-order beams.
RH—Right-hand.
LH—Left-hand.
DVW—Displaced virtual-wall.
AVW—Angled virtual-wall.

It can be seen from this table that cancellation of both forward and backward beams never takes place simultaneously, but that one of them is always reinforced. This occurrence is apparently in line with the conservation of energy in the second-order beams as noted above.

A limitation to this analysis results from the implicit assumption that the second-order beams along both diagonals of the array behave identically. This behavior is not necessarily so. There is some reason to believe that one or more of the component beams may suffer a 180° phase reversal because of the different orientation. This reversal could cause the resultant second-order beams to appear to one side of the array instead of both forward or both backward.

A series of pattern measurements were made on the circularly polarized planar array of the embodiment of FIG. 1. These results confirmed the prediction that the forward looking second-order beam would be reinforced and the rearward looking beam suppressed. In this particular case the two beams that are reinforced are always the two pointing forward compared to the direction of travel within the guide.

A limitation of the slot configurations disclosed derives from the dependency of each on a higher order mode of propagation. This dependency implies that within each virtual waveguide an equal amount of power must flow, and satisfactory symmetry can be maintained in the structure only by the use of a uniform illumination of the aperture in a plane perpendicular to the direction of power flow. It may be desirable to design a circularly polarized planar array with an amplitude taper in both principle planes, but that is not possible that virtual walls. Instead, actual walls must be provided. That may be accomplished as shown in the variant of the present invention illustrated in FIG. 14 which shows a solid wall 70 in place of a virtual wall in a $TE_{n,0}$ mode waveguide to provide isolated channels, such as channels 71 and 72. A slot 73 is provided with a quarter-wavelength choke 74 cut in the wall 70 that separates the two channels 71 and 72. The power in the two channels may then be set 180° out-of-phase. When equal power is sent into each channel, the slot 73 is operated on by essentially the same field structure as described with reference to FIG. 2. The only difference is the presence of the wall 70 with the choke 74 under the slot 73. Control over coupling of the slot 73 may be effected by displacement of the slot on one side of the actual wall 70 or the other, in the same manner and to the same approximate magnitude as with the structure of FIG. 2. Alternatively, the slot 73 may be rotated for coupling as described with reference to FIG. 5.

If the power levels in the two channels 71 and 72 are then deliberately unbalanced by various amounts, the choke 74 will keep the slot 73 from being shorted and at the same time provide a high degree of isolation between the two channels 71 and 72 while the slot 73 is coupled to the two channels. With different power levels in channels 71 and 72, the coupling established by the displacement of the slot 73 is effected. For example, assuming the slot is adjusted for a null position with equal power in the two channels 71 and 72, then when the power levels in the two are deliberately unbalanced, the slot 73 would no longer be in a null position and hence would radiate. However, it could always be brought to a new null position by displacement of its center into the region of the guide carrying the smallest amount of power. Thereafter, control of the slot coupling is achieved by displacement of the center of the slot to either side of this new null position, or rotation about this point, the phase being determined by the direction of displacement or rotation and the magnitude being controlled by the amount of displacement or rotation.

From the foregoing description of FIG. 14, it may be readily seen that if all of the virtual walls of the four different embodiments described hereinbefore are replaced by actual walls, each with chokes cut under wall slots, design of circularly polarized planar arrays with any desired amplitude taper in both principal planes is possible by control of power coupled to each of the resulting isolated channels. Such a design would retain the simplicity of construction inherent in the virtual-

wall designs, and require no slow-wave structures such as were used in the prior art. Accordingly, inasmuch as a virtual wall can be replaced by an actual wall, unless otherwise indicated, the term "wall slot" in the appended claims is intended to refer to a slot over an actual wall with a quarter-wavelength choke cut under the slot in the wall as well as a slot over a virtual wall. Other modifications and variations falling within the spirit of the invention will occur to those skilled in the art. Therefore, it is not intended that the scope of the invention be determined by the disclosed exemplary embodiments, but rather should be determined by the breadth of the appended claims.

What we claim is:

1. A circularly polarized beam antenna of the planar array type comprising:

a rectangular waveguide having a multiple order transverse electric wavemode of operation in one dimension virtually forming a plurality of parallel traveling wave channels therein;

means for coupling a high frequency signal to all channels of said waveguide in parallel for operation in said mode;

virtual-wall slots in one broad wall of said waveguide astride virtual walls between said channels, said virtual-wall slots being of a type selected from a group of two types, a first type being one in which the longitudinal axis of each slot is rotated from a position perpendicular to a virtual wall to interrupt transverse current for radiation, and a second type being one in which the longitudinal axis of each slot is perpendicular to a virtual wall and in which the center of the slot is displaced from a position over the virtual wall to interrupt longitudinal currents for radiation, and

conventional slots in said one broad wall, said conventional slots being of a type selected from a group consisting of series slots and shunt slots, said conventional slots being disposed in every one of said wave channels.

2. An antenna as defined in claim 1 wherein said virtual walls are formed with actual walls dividing said waveguide channels, said actual walls having a section cut out under each virtual wall slot.

3. An antenna as defined in claim 1 wherein said virtual-wall slots are selected to be of the second type and said virtual-wall slots astride a given virtual wall have their centers alternately displaced from a null position over said given virtual wall by a predetermined amount which establishes the amplitude of inphase excitation of said wall slots desired for one component of a circularly polarized beam.

4. An antenna as defined in claim 3 wherein a second component of said beam is provided by conventional slots selected to be of the shunt-type, one centered on each end of each of said virtual-wall slots.

5. An antenna as defined in claim 3 wherein a second component of said beam is provided by conventional slots selected to be of the series-type, one on each side of every pair of adjacent virtual-wall slots along a given virtual wall, and the centers of said series slots are displaced from said virtual-wall slots a quarter-guide wavelength in the direction of wave travel through said channels, where said quarter-guide wavelength is measured for a given series slot along a line perpendicular to a row of virtual-wall slots perpendicular to said virtual walls.

6. An antenna as defined in claim 1 wherein each slot of said virtual-wall slots is centered over a virtual wall and alternate ones along a direction parallel to said virtual walls and also along a direction perpendicular to said virtual walls are rotated through a given angle from a position perpendicular to said virtual walls to determine the amplitude of inphase excitation of said slots desired for one component of a circularly polarized beam.

7. An antenna as defined in claim 6 wherein a second component of said beam is provided by conventional slots selected to be of the series-type, one of each end of each of said virtual-wall slots, and the centers of said virtual-wall slots are in line with the centers of said series slots.

8. An antenna as defined in claim 6 wherein a second component of said beam is provided by conventional slots selected to be of the shunt-type, one on each side of every pair of adjacent wall slots along a given virtual wall, and said shunt slots are displaced from said virtual-wall slots a quarter-guide wavelength in the direction of wave travel through said channels, where said quarter-guide wavelength is measured for a given shunt slot along a line perpendicular to a row of virtual-wall slots perpendicular to said virtual walls.

9. In a circularly polarized beam antenna of the planar array type having a waveguide operating in a $TE_{n,o}$ mode, where n is an arbitrary integer greater than one to provide a plurality of traveling wave channels separated by virtual walls, the combination comprising:

means for coupling a high frequency signal to each channel of said waveguide;

a plurality of virtual-wall slots in one broad wall of said waveguide, said virtual-wall slots being astride said virtual walls between said channels, with virtual-wall slots along a given virtual wall spaced half a guide wavelength apart and oriented for inphase coupling of radiation with a desired magnitude for one component of a circularly polarized beam; and

a plurality of standard slots in said channels on each side of each of said virtual walls, said standard slots being oriented for inphase coupling of radiation with a desired magnitude for a second component of said circularly polarized beam.

10. In a circularly polarized beam antenna of the planar array type having a waveguide operating in a $TE_{n,o}$ mode, where n is an arbitrary integer greater than one to provide a plurality of traveling wave channels separated by virtual walls, the combination comprising:

means for coupling a high frequency signal to all channels of said waveguide;

a plurality of virtual-wall slots in one broad wall of said waveguide, said virtual-wall slots being astride said virtual walls between said channels, with virtual-wall slots along a given virtual wall spaced half a guide wavelength apart, all of said virtual-wall slots being orthogonal to said given virtual wall, and alternate ones of said slots along said given virtual wall being alternately offset from a centered position over said given virtual wall by a predetermined amount which establishes the amplitude of inphase excitation of said virtual-wall slots desired for one component of a circularly polarized beam; and

a plurality of shunt slots, one centered on each end of each of said virtual-wall slots, said shunt slots disposed in a given channel of said multimode waveguide being alternately offset from a center line of said given channel by a predetermined amount which establishes the amplitude of inphase excitation of said shunt slots for a second component of said circularly polarized beam.

11. In a circularly polarized beam antenna of the planar array type as defined in claim 10 including mode suppressing pins in line with said virtual walls, one pin between a given pair of virtual-wall slots.

12. In a circularly polarized beam antenna of the planar array type as defined in claim 11 wherein a mode suppressing pin is placed between every pair of said virtual-wall slots.

13. In a circularly polarized beam antenna of the planar array type having a waveguide operating in a $TE_{n,o}$ mode, where n is an arbitrary integer greater than one to provide a plurality of traveling wave channels separated by virtual walls, the combination comprising:

means for coupling a high frequency signal to all channels of said waveguide;

a plurality of virtual-wall slots in one broad wall of said waveguide, said virtual-wall slots being astride said virtual walls between said channels, with virtual-wall slots along a given dividing line spaced half a guide wavelength apart, all of said virtual-wall slots being centered over said given virtual wall, an alternate ones of said virtual-wall slots

along said given virtual wall being alternately rotated from an orthogonal position over said given virtual wall by a predetermined amount which establishes the amplitude of inphase excitation of said virtual-wall slots desired for one component of a circularly polarized beam; and

a plurality of shunt slots, one centered on each end of each of said wall slots, said shunt slots disposed in a given channel of said multimode waveguide being alternately offset from a center line of said given channel by a predetermined amount which establishes the amplitude of inphase excitation of said shunt slots for a second component of said circularly polarized beam.

14. In a circularly polarized beam antenna of the planar array type as defined in claim **13** including mode suppressing pins in line with said virtual walls, one pin between a given pair of virtual-wall slots.

15. In a circularly polarized beam antenna of the planar array type as defined in claim **14** wherein a mode suppressing pin is placed between every pair of said virtual-wall slots.

16. In a circularly polarized beam antenna of the planar array type having a waveguide operating in a $TE_{n,o}$ mode, where n is an arbitrary integer greater than one to provide a plurality of traveling wave channels separated by virtual walls, the combination comprising:

means for coupling a high frequency signal to all channels of said waveguide;

a plurality of virtual-wall slots in one broad wall of said waveguide, said virtual-wall slots being astride virtual walls between said channels, said virtual-wall slots along a given virtual wall spaced half a guide wavelength apart, all of virtual-wall slots being orthogonal to said given virtual walls and alternate ones of said virtual-wall slots along said given virtual wall being alternately offset from a centered position over said given virtual wall by a predetermined amount which establishes the amplitude of inphase excitation of said virtual-wall slots desired for one component of a circularly polarized beam; and

a plurality of series slots one on each side of a pair of adjacent virtual-wall slots and centered on a line orthogonal to said given dividing line at a midpoint between virtual-wall slots, said series slots disposed in a given channel of said multimode waveguide being centered on a center line of said given channel and rotated from a longitudinal position through an angle which establishes the amplitude of inphase excitation of said series slots for a second component of said circularly polarized beam.

17. In a circularly polarized beam antenna of the planar array type as defined in claim **16** including mode suppressing pins in line with said virtual walls, one pin between a given pair of virtual-wall slots.

18 In a circularly polarized beam antenna of the planar array type as defined in claim **17** wherein a mode suppressing pin is placed between every pair of said virtual-wall slots.

19 In a circularly polarized beam antenna of the planar array type having a waveguide operating in a $TE_{n,o}$ mode, where n is an arbitrary integer greater than one to provide a plurality of traveling wave channels separated by virtual walls, the combination comprising:

means for coupling a high frequency signal to all channels of said waveguide;

a plurality of virtual-wall slots in one broad wall of said waveguide, said virtual-wall slots being astride virtual walls between said channels, with virtual-wall slots along a given virtual wall spaced half a guide wavelength apart, all of said virtual-wall slots being centered over said given virtual wall and alternately rotated from an orthogonal position over said given virtual wall by a predetermined amount which establishes the amplitude of inphase excitation of said virtual-wall slots desired for one component of a circularly polarized beam; and

a plurality of series slots one centered on each side of the center of each of said virtual-wall slots and rotated from a longitudinal position along the center of the channel in which disposed through an angle which establishes the amplitude of inphase excitation of said series slots for a second component of said circularly polarized beam.

20. In a circularly polarized beam antenna of the planar array type as defined in claim **19** including mode suppressing pins in line with said virtual walls, one pin between a given pair of virtual-wall slots.

21. In a circularly polarized beam antenna of the planar array type as defined in claim **20** where a mode suppressing pin is placed between every pair of said virtual-wall slots.

22. In a circularly polarized beam antenna of the planar array type having a multichannel waveguide, each channel isolated from other channels by internal conductive walls:

means for coupling a high frequency signal to each channel of said waveguide;

a plurality of wall slots in one broad wall of said waveguide, said wall slots being astride said internal conductive walls, with wall slots along a given internal conductive wall spaced half a guide wavelength apart and oriented for inphase coupling of radiation with a desired magnitude for one component of circularly polarized beam;

a plurality of quarter-wavelength chokes in said internal conductive walls, one under each of said wall slots; and

a plurality of standard slots in said channels on each side of each of said internal conductive walls, said standard slots being oriented for inphase coupling of radiation with a desired magnitude for a second component of said circularly polarized beam.