June 10, 1958 R. W. BICKMORE 2,838,754

MICROWAVE RADIATOR

Filed April 26, 1955 2 Sheets-Sheet 1

FIG. 1

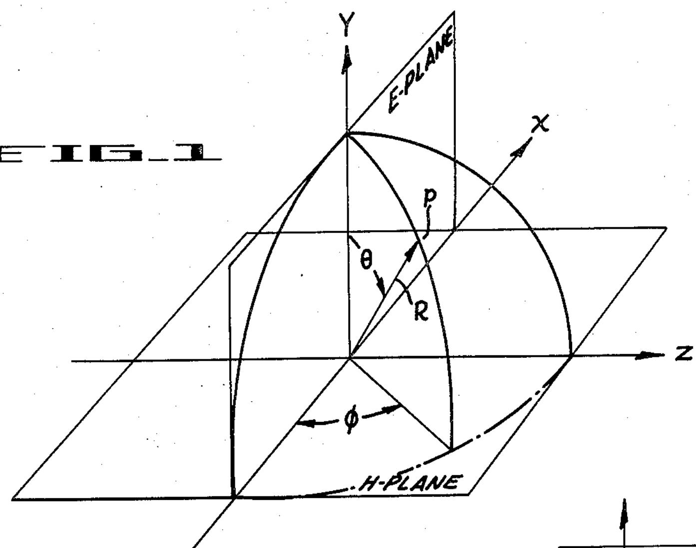
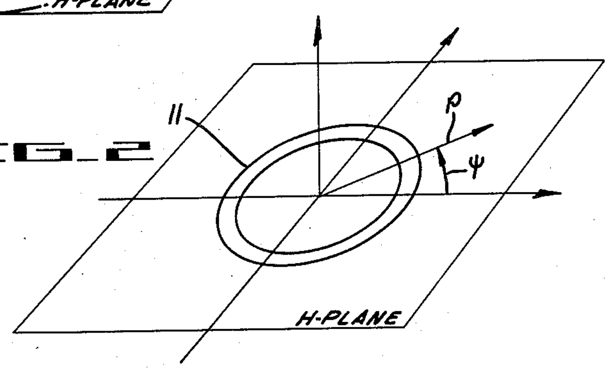


FIG. 2



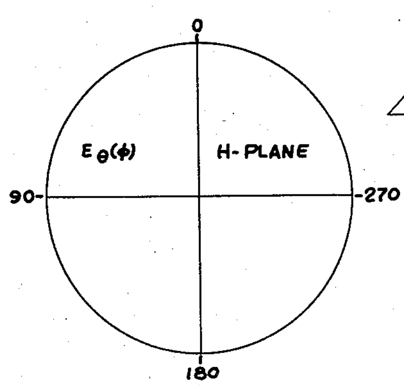
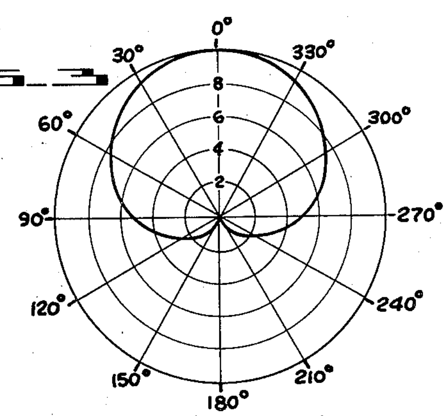


FIG. 4A

FIG. 3



$E_\theta(\phi) \sim 1+\cos\phi$

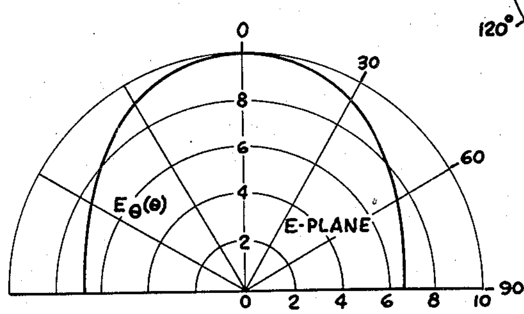


FIG. 4B

ROBERT W. BICKMORE
INVENTOR.

BY Flehr & Swain
ATTORNEYS

MICROWAVE RADIATOR

Filed April 26, 1955 2 Sheets-Sheet 2

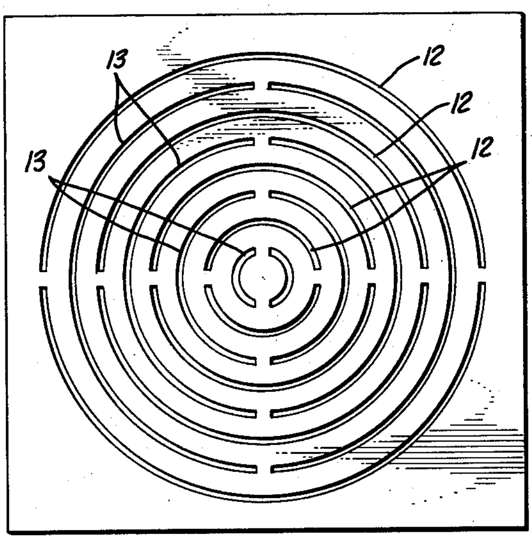


FIG_5

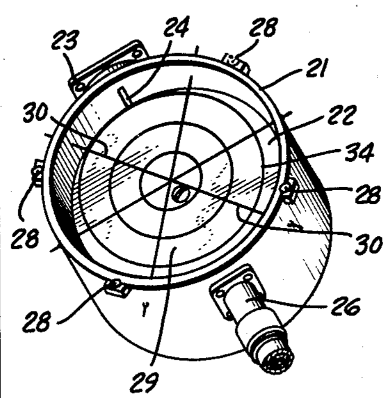


FIG_6

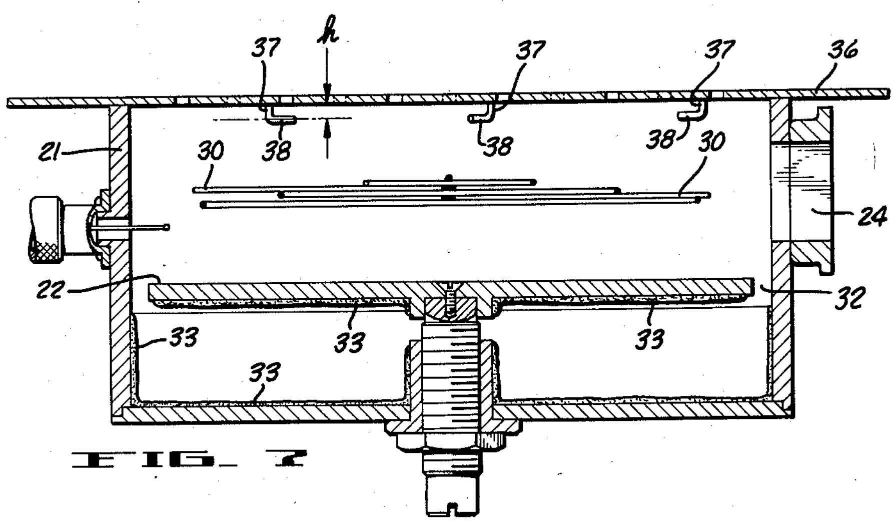


FIG_7

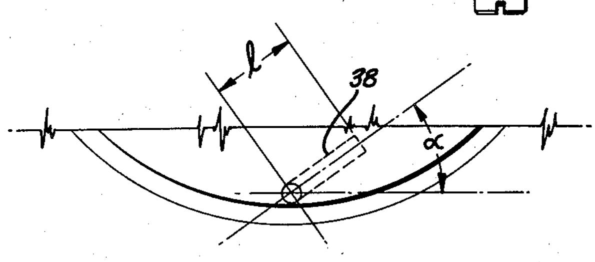


FIG_8

ROBERT W. BICKMORE
INVENTOR.

BY

ATTORNEYS

United States Patent Office

2,838,754

Patented June 10, 1958

2,838,754

MICROWAVE RADIATOR

Robert W. Bickmore, Santa Monica, Calif., assignor to The Regents of the University of California, Berkeley, Calif., a corporation of California

Application April 26, 1955, Serial No. 503,926

12 Claims. (Cl. 343—769)

This invention relates generally to high frequency radiating devices and more particularly to radiators of the type which include radiating apertures.

In general, radiating apertures transform a guided wave into a free space wave. In the past, the waves have been introduced into the aperture by various means. For example, apertures have been excited by connecting the conductors of a coaxial cable to opposite sides of the aperture. The apertures have been made the termination of a transmission line or have been cut in the surface of the transmission line in such positions that they become excited by the electromagnetic waves travelling within the transmission line. Apertures have also been excited by probes which extend into the transmission line. All of these methods have the disadvantage that it is difficult to control the distribution, amplitude and phase of the field in the aperture. Only limited control of the radiation pattern is afforded.

In the past, linear arrays of apertures or slots have been used to radiate energy in a specified pattern. This is achieved by properly spacing the apertures and controlling their excitation. Such arrays may be used to transmit energy in a directive pattern, in much the same manner as arrays of dipole antennas may be used to radiate a directive pattern. Arrays which employ linear slots or apertures have the disadvantage that they are large in at least one dimension. It is also difficult to excite the slots or apertures in the proper phase and with the proper amplitude.

An advantage of slotted antennas is that the energy may be supplied to the slot or aperture from below. Consequently, there are no protrusions in the surface. The aperture may be covered with dielectric material to give a competent surface. Such antennas may be flush mounted. For example, they may be mounted on an aircraft without interrupting the aerofoil surface.

It is an object of the present invention to provide a novel microwave radiator.

It is a further object of the present invention to provide a microwave radiator which is small in size.

It is a further object of this invention to provide a microwave radiator which employs annular apertures.

It is a further object of the present invention to provide novel means for exciting an aperture with a field of predetermined distribution, phase and amplitude.

It is another object of the present invention to provide novel means for exciting large arrays of apertures with fields of predetermined distribution, phase and amplitude.

It is a further object of this invention to provide a microwave antenna which comprises a plurality of annular apertures backed by a cavity and which includes means for exciting the apertures with a field of the proper distribution, phase and magnitude.

It is a further object of this invention to provide means for exciting arrays of annular apertures with fields of predetermined distribution, phase and amplitude and which is adaptable to be used for a number of different antenna systems.

It is still a further object of this invention to provide means whereby large arrays of apertures may be excited with fields of proper amplitude and phase and in which mutual coupling between slots may be easily controlled.

Other objects of the invention will be apparent from the following description of the preferred embodiments of the invention as illustrated in the accompanying drawings.

Referring to the drawings:

Figure 1 illustrates the field geometry which will be used in describing the invention;

Figure 2 shows the geometry of the annular aperture;

Figure 3 illustrates the H-plane radiation pattern for an annular aperture excited with a particular field;

Figures 4A, 4B illustrate H-plane and E-plane patterns for another annular slot which is excited with another field;

Figure 5 shows a four element and an eight element annular aperture pencil beam array;

Figure 6 shows a perspective view of a particular excitation device which makes use of mode conversion;

Figure 7 is an elevational view in section of the device of Figure 6; and

Figure 8 is a top view of a portion of the top plate of the device of Figures 6 and 7 showing a portion of an annular aperture and associated probe.

Figure 1 shows a spherical coordinate system in which any point P may be defined in terms of the angles of ϕ, θ, and the radius R. The plane which includes the x and z axis is referred to as the H-plane. A plane which includes the y axis is referred to as an E-plane. In Figure 2, I have shown an annular aperture **11** which has the radius ρ. Any point on the aperture is determined by the radius ρ and the angle ψ.

Any desired θ component pattern in the principal H-plane may be approximated to any desired degree by a single annular aperture **11**, which is excited with a field having a proper distribution, phase and amplitude. The radius of the element is not uniquely determined and limited control of the E-plane pattern is possible. For any plane which is parallel to the principal H-plane, any desired θ or ϕ component pattern may be approximated to any desired degree with a single annular element which is properly excited. Again, the radius of the element is not uniquely determined and limited control of the E-plane pattern and the unspecified component is possible.

For example, if a microwave radiator is placed near a reflecting obstacle of limited height, it is desirable to limit reflections from the object. A pattern of the type shown in Figure 3 in which

$$E_\theta(\phi) \sim (1+\cos\phi)$$

will prevent radiant energy from striking the object. It can be shown that if the normalized excitation for the annular aperture is

$$E_\theta = E_0(1+j\sin\phi)$$

the desired radiation pattern results.

Any desired θ or ϕ component in a given E-plane may be approximated to any desired degree by a single annular element which is properly excited. The radius of the element is not uniquely determined and limited control of the unspecified component as well as the H-plane pattern is possible. Also, any omni-directional H-plane pattern, with the E-plane pattern variable within limits by suitable choice of the radius ρ and the mode of excitation η_0, may be obtained by properly exciting the aperture.

An example here might be an antenna designed for missile use where it is desired to have the relative time phase of radiation vary with the azimuth angle of the antenna, and where it is desirable to have the amplitude of the radiation be as close to isotropic as possible in the hemisphere of radiation. This requires a θ component pattern which is omni-directional in the principal H-plane and which has a relative phase equal to the azimuth angle. If the slot excitation is given by the equation

$$E\rho = E_0 e^{j\psi}$$

a pattern of the type shown in Figures 4A, 4B can be obtained.

Thus far, apertures made up of a single annular element have been considered. In every case mentioned there are limitations upon the type of radiation pattern which can be obtained. Such antennas might be termed "mode synthesis" antennas since pattern control is afforded mainly by control of the excitation of the aperture.

Any desired spatial pattern completely specified in magnitude, spatial phase, and time phase can be approximated to any desired degree by an array of concentric annular elements which are excited in such a manner that the field of the aperture has the proper distribution, amplitude and phase.

The best example of array synthesis is perhaps that of the production of a pencil beam radiation pattern of circular cross-section perpendicular to the plane of the aperture. In Figure 5, I have shown a four element array **12** in which the excitation coefficients are selected to fall along a predetermined curve. This array produces a linearly polarized radiation field with an X polarization, according to the geometry shown in Figure 1.

The same array can be made to produce a circular polarized pencil beam by interposing concentrically an identical four element array **13** oriented 90° in the ψ direction with respect to the first array, and excited 90° out of time of phase.

Thus it is seen that any desired spatial radiation pattern may be obtained by properly exciting a single annular aperture or an array of annular apertures. As previously described, arrays of this type may be excited by placing the annular apertures at the end of a transmission line. Thus the apertures might be excited by placing them at the termination of circular waveguides, coaxial waveguides, as well as circular cylindrical cavities. In order to excite a given mode in an aperture or apertures, the corresponding TEM, TE or TM mode must appear in the waveguide at least in the vicinity of the aperture. In such a system, it is necessary to have all of the desired modes propagate down the guide in a proper amplitude and phase, which requires a large complex system.

It is, therefore, desirable to provide a system for exciting the aperture or apertures (to be referred to as apertures throughout the remainder of the specification) wherein a simple waveguide system is used to transmit energy to the radiating apertures and in which means are provided for exciting the apertures with a field having the proper distribution, phase and amplitude.

A novel system for exciting the apertures is one in which the energy is supplied to a cavity. One wall of the cavity has the apertures formed therein. All modes within the cavity which give rise to currents on the wall transverse to the apertures are filtered out by suitable means. Thus, only modes which do not give rise to currents which excite the apertures remain within the cavity. Means are then provided for selectively coupling the energy from the remaining modes to the apertures. The orientation of the coupling means controls the amplitude and phase of the coupled energy. The spacing of said coupling means gives the desired distribution. Thus the apertures are excited with fields having the desired distribution, phase and amplitude for a given spatial radiation pattern.

In Figures 6–8, I have shown a novel mode conversion excitation system which allows one basic mode to be propagated in a waveguide and which converts this mode to the necessary modes in the vicinity of the apertures. Means are provided for coupling the modes to the apertures to thereby give the desired field distribution, phase and amplitude in the apertures.

The mode conversion excitation system shown was designed specifically for an eight element circularly polarized pencil beam antenna. It may also be used for a six element "binomial" H-plane array.

It is to be understood, of course, that the invention is not to be limited by the embodiment shown. Mode conversion may be accomplished by using different numbers and sizes of elements spaced to accomplish the desired results.

If in a circular waveguide or a cavity, a wave of the TE_{om} type is excited, there will result purely circumferential currents on the end plate or plates and thus this mode will not couple to any annular slots or apertures formed therein. The TE_{om} modes merely provide a convenient means for transmitting energy and do not contribute directly to the field in the aperture. It is necessary to eliminate all other modes from the cavity since they tend to excite the annular slots.

Referring particularly to Figure 6, a circular cavity is shown which comprises a cylindrical wall **21** with a movable plunger **22**. The cavity is connected to a waveguide system with the coupling flange **23** and energy is transmitted to the cavity through the slot **24**. The slot is designed so that it does not excite unwanted modes within the cavity. For example, a vertical slot between the waveguide and the cavity may be employed.

Sampling means **26** which may comprise a probe **27** (Figure 7) connected to a coaxial line is provided to sample the energy within the cavity. The top plate which includes the annular aperture array is connected to the cavity by means of the screws **28**. The mode filter grid network **29**, to be presently described in detail, serves to attenuate the unwanted modes which are excited within the cavity.

The diameter of the cavity determines the highest order TE_{om} type mode within the cavity. In the one particular cavity, the highest order TE_{om} mode was the TE_{04} mode. This mode was selected because it was the most versatile for excitation control purposes. The mode filter grid network **29** was employed to filter out (attenuate) the unwanted modes within the cavity. These modes were of the TM types, TE_{nm} types, and also the TE_{01}, TE_{02} and TE_{03} modes. The highest order mode is determined by the size of the cavity. The description which follows is not intended to limit the scope of the invention, but it is given as an example of the design of a particular mode conversion system.

As is well known, the TM and the TE_{nm} type modes all have radial components of electric field. Thus, equally spaced radial wires **30** serve to filter (attenuate) these modes. In addition, the movable plunger **22** (Figure 7) is made noncontacting. The TE_{om} modes will have no currents flowing across this junction **32**. The other modes, however, have a current flow at this point. These currents excite currents in the bottom of the cavity underneath the movable plunger **22**. Suitable means **33** are introduced on the surfaces underneath the plunger (the cavity and plunger) to attenuate these currents. For example, the means **33** may comprise "Aquadag" which is placed on cardboard and cemented to the cavity walls and the plunger.

Attenuation of the TE_{01}, TE_{02} and TE_{03} modes which have only an E ψ component is accomplished by the concentric rings **34**. Their radii in general are chosen to correspond to the natural modes of the TE_{04} mode. It is necessary in most instances to chose their axial position carefully so that they do not fall near a $\lambda_{g/2}$ point for any unwanted mode and thereby act as end plates.

Thus, with the system shown and described, the only mode which remains in the cavity is the TE_{04} mode. This mode gives rise to circumferential currents in the wall

36 which includes the annular apertures and therefore does not excite any electric field within the apertures.

The L-shaped probes 37 (Figures 7 and 8) provide suitable means for coupling the energy in the TE_{04} mode to the apertures to thereby excite them with the proper distribution, phase and amplitude. In order to excite the slot, it is necessary to have current flowing in the probes 37. Therefore, there must be a component 38 of the probe length parallel to the electric field of the basic TE_{04} mode. This portion corresponds to bent segment of the probe which lies parallel to the aperture plane. Secondly, since the E-field of the TE_{04} mode is zero on the end-plate, the pick-up portion of the probes must be spaced from the end plate a sufficient distance. Denoting the dimensions of the two proportions of the probe by "l" and "h," it is easily seen that "l" portion is primarily responsible for picking up the signal from the basic modes, and the "h" portion is primarily responsible for re-radiating the induced field to excite the apertures. If "l" and "h" are both very much smaller than the wavelength λ, then the field induced in the gap near the vicinity of the probe is proportional to

$$lh \cos \alpha$$

The number of probes necessary to approximate the field distribution is determined in the manner described. In general, it is expected to space the probes approximately one-half wavelength around the periphery of any given annular aperture. By turning the probes, it is possible to control the phase and amplitude of the field which is excited in the aperture in the vicinity of the probe. Thus it is seen that by making probes having portions "l" and "h" of proper length and orienting the probes with respect to the modes in the cavity, it is possible to excite a field of given distribution, phase and amplitude in the associated aperture.

At any point where it is desired that the excitation be zero, a metal strap is preferably placed across the gap. This aids in securing the correct field distribution. Jumper straps are particularly important in the case of six element binomial arrays where each slot mode has its own slot. The straps prevent the lower order modes in the small slots from coupling to the progressively larger slots and since the small slots offer a very high impedance to the higher order modes, mutual coupling virtually is non-existent. This, of course, is one of the advantages of the array of heterogeneous elements over the conventional linear arrays used in prior art devices.

Mutual coupling in the pencil beam arrays occurs between elements of the same group, but can be quite useful in exciting tapered distributions. For instance, only one ring of probes can be used for each four-element array of apertures in the radiator shown in Figure 5. Directly exciting the largest slot provides inverse tapered illumination, and direct excitation of the smallest slot provides the tapered illumination. Coupling between the two four element groups is virtually zero due to the orthogonality of the orientations.

Apparatus of the type described was constructed to provide pencil beam radiation. The annular array was of the type shown in Figure 5 and the diameter of the outer annular aperture was 4.3 wavelengths. The inside diameter of the cylindrical portion 21 of the cavity was 6 inches. The movable plunger had a diameter of 5¾ inches. The three annular filter wires employed had a radius of .865, 1.579 and 2.291 inches, respectively. Six equally spaced radial wires were employed. All of the wires of the mode filter were made of 1⁄16 inch copper. The associated waveguide system was coupled to the cavity through a vertical slot which was .900 inches in height and .010 inch in width. The lower surface of the plunger and of the cavity was coated with cardboard which had been impregnated with "Aquadag." The probe employed had a length of h of .300 inch and a length l of .375 inch. The various probes were spaced to give the desired pencil beam pattern, and a pencil beam pattern was obtained.

It is to be understood of course that the figures and drawings merely show a particular mode conversion excitation system. It may be desirable to employ modes other than the TE_{04} for the transmission of energy. It may also be desirable to form a larger or smaller cavity and to provide a greater or smaller number of wires in the grid network which serve to filter out the unwanted modes. As can be seen, these are merely variations in construction.

Thus, it is seen that a versatile method for controllably exciting apertures is disclosed. This method is adaptable for use in all cases where excitation may not be readily secured by one of the well known means. The apertures may be easily excited with a field having distribution, amplitude and phase to give a prescribed spatial radiation pattern. Although the excitation system described lends itself most readily to annular apertures, it may be modified for use in conjunction with linear array of apertures. It is also seen that I have provided a novel microwave radiator which employs an annular apertures array and which affords complete control of the radiation in magnitude, spatial phase and time phase, and which may, for example, be flush mounted on aircraft without disturbing the aerofoil surface.

I claim:

1. A microwave radiator comprising a plurality of concentric annular apertures formed in a conducting plate, a cavity associated with said plate, means for supplying electromagnetic energy to said cavity, filter means associated with said cavity to filter out undesired modes, and means for selectively coupling the energy within said cavity to the said apertures to thereby excite the apertures with fields of predetermined distribution, phase and amplitude, whereby a desired spatial pattern completely specified in magnitude, spatial phase and time phase may be obtained.

2. A microwave radiator comprising a plurality of concentric annular apertures formed in a conducting end plate, a cylindrical cavity associated with said plate, means for supplying energy to said cavity, filter means associated with said cavity, a tuning plunger forming one end wall of said cavity and thereby providing means for tuning the cavity, and means for selectively coupling energy from said cavity to said apertures to thereby excite the apertures with fields of predetermined distribution, phase and amplitude.

3. Apparatus as in claim 2 wherein the said tuning plunger adapted to fit within the cylindrical cavity is spaced therefrom to thereby cause radial components of current in said plunger to excite modes below the plunger, and means associated with the cavity formed below the plunger for attenuating the said modes.

4. A microwave radiator comprising a plurality of concentric annular apertures, said apertures formed in a conducting end plate, a cylindrical cavity, said end plate forming one wall of said cavity, a tunable plunger forming the other end wall of said cavity and spaced from the walls thereof, filter means placed within said cavity between said end plate and plunger, said filter means comprising a plurality of radial wires and a plurality of annular wires, said wires having a predetermined spacing to thereby attenuate undesired modes within said cavity, and means associated with said end plate for coupling energy to the apertures to thereby excite the said apertures with fields of predetermined distribution, phase and amplitude.

5. Apparatus as in claim 4 wherein said means for coupling the energy to said apertures comprises L-shaped probes which extend into said cavity.

6. Apparatus as in claim 4 wherein said means for coupling energy from said cavity to said annular apertures comprises a plurality of spaced L-shaped probes having a portion which is parallel to the end plate and a por-

tion perpendicular thereto, the parallel portion rotatable to control the amplitude and phase of the coupled energy.

7. A microwave radiator comprising a plurality of concentric annular apertures formed in a conducting end plate, a cylindrical cavity backing said end plate, a movable plunger having its plane parallel to the end plate and adapted to be moved within the said cavity and spaced from the walls thereof, filter means placed within the said cavity and located between said end plate and said plunger, said filter means comprising a plurality of radial wires and a plurality of annular wires having a predetermined spacing to thereby attenuate undesired modes propagated within said cavity, and coupling means for coupling said cavity to said annular apertures, said coupling means comprising L-shaped probes having portions which extend parallel to the end plate and portions perpendicular thereto, the parallel portions being rotatable to control the amplitude and phase of the energy coupled to the probes, and the perpendicular portion serving to transmit the coupled energy to the apertures.

8. Apparatus as in claim 7, together with shorting means for shorting across the said annular apertures to thereby assure that the intensity of the aperture field at the shorting means is zero.

9. In a microwave system, a plurality of radiating apertures, a mode conversion system for exciting said radiating apertures with fields of predetermined distribution, phase and amplitude comprising a cavity, filter means associated with said cavity for filtering undesired modes which propagate within the cavity, and means for selectively coupling the energy within said cavity to the associated apertures.

10. In a microwave system, a plurality of radiating apertures, a mode conversion system for exciting said radiating apertures with fields of predetermined distribution, amplitude and phase comprising a cylindrical cavity, filter means placed within said cavity and comprising a plurality of radial wires and a plurality of annular wires, said wires having a predetermined spacing to thereby attenuate undesired modes within the cavity, and means associated with said cavity for coupling energy to the associated apertures.

11. In a microwave radiating system, a plurality of radiating apertures, a mode conversion system for exciting radiating apertures with fields of predetermined distribution, amplitude and phase, comprising a cylindrical cavity having an end wall, a tunable plunger contained within said cavity and spaced from the cylindrical wall, said plunger being movable to tune the cavity, filter means comprising a plurality of radial wires and a plurality of annular wires, said wires having a predetermined spacing to thereby attenuate undesired modes within the cavity, and means for selectively coupling the energy within said cavity with the associated apertures.

12. Apparatus as in claim 11 wherein said means for coupling energy from said cavity to said apertures comprises a plurality of spaced L-shaped probes having a portion which is parallel to the end plate and a portion perpendicular thereto, the parallel portion being rotatable to control the amplitude and phase of the energy coupled to said apertures.

References Cited in the file of this patent

UNITED STATES PATENTS

2,508,085	Alford	May 16, 1950
2,605,459	Cook	July 29, 1952

FOREIGN PATENTS

529,539	Great Britain	Nov. 22, 1940

OTHER REFERENCES

"Theory of the Concentric-Slot Antenna," T. Morita, condensed version of a technical paper presented at the 1951 IRE national convention, pages 14-1 to 14-3.