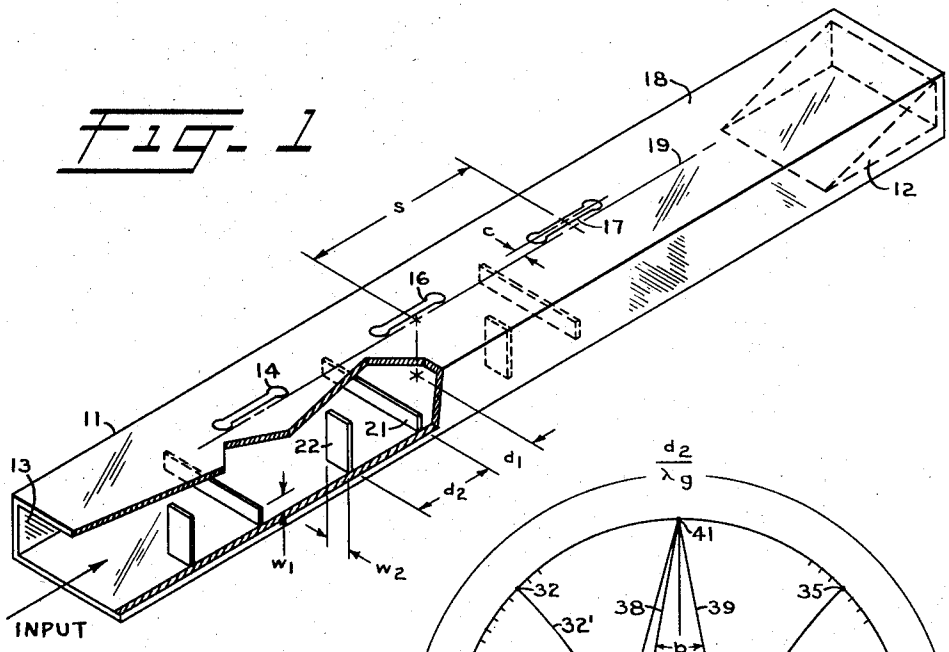
Oct. 13, 1959 H. SALTZMAN 2,908,905

MICROWAVE ANTENNA ARRAY

Filed April 30, 1957

Fig. 1



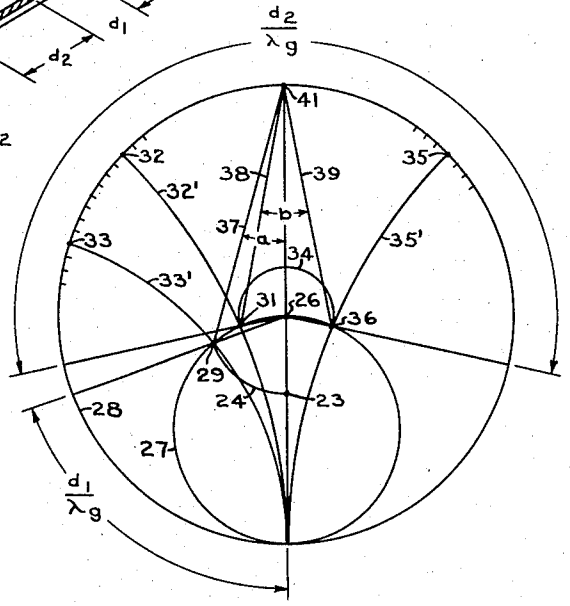


Fig. 2

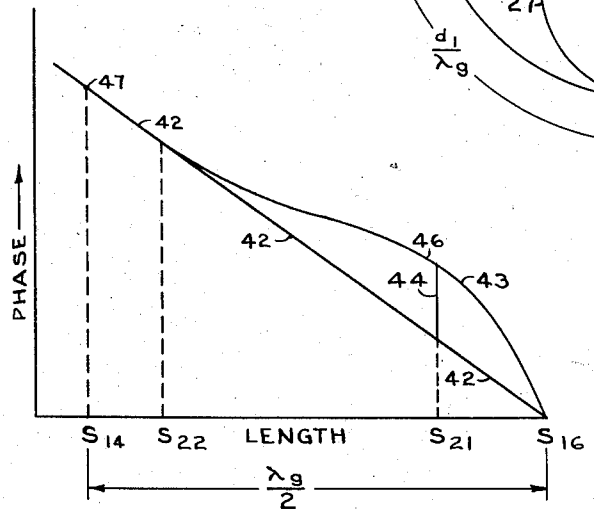


Fig. 3

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MICROWAVE ANTENNA ARRAY

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6 Claims. (Cl. 343—771)

This invention relates to any transmission line network, and provides an improvement in the matching of any discontinuity thereof. This invention is especially applicable to transmission lines for frequencies in the microwave region.

As an illustration of the employment of this invention, its application to a resonant microwave linear array of radiators is selected. A resonant linear array has its radiators regularly spaced at half-wave intervals. The radiators may be of any type such as, for example, series or shunt slots in rectangular waveguide. Such a resonant array is usually terminated in a short circuit. When the radiator discontinuities are not individually compensated such an array has a very narrow frequency transmission band. As a specific example, if the nominal frequency of the applied microwave energy be ten kilomegacycles per second and departs by 30 mc. p. s. from this nominal value, 11.2% of the energy applied to such an array would be reflected toward the source, corresponding to a voltage standing wave ratio (VSWR) of two to one on the source side of the array. This imposes such a severe limitation on the constancy of frequency of the source as to make use of such an unmatched array difficult.

A reactive matching element such as a post or iris can be placed on the input side of each radiator. This can make the linear array wider band by matching the impedance discontinuities but at the same time introduces phase shift difficulties.

When linear arrays or planar arrays made therefrom are employed to generate a narrow beam or thin cone of microwave radiation, the angle which the beam or cone element makes with the longitudinal axis of the array is usually important. It is often required that this angle be precisely calculated in designing the array and that the measured beam angle of the constructed array be as calculated. It is therefore important that when matching elements are used they do not disturb this beam angle.

When a single matching element is associated with each radiator the beam angle is nearly always changed because each matching element changes the phases of the exciting voltages applied to preceding radiators, and the result is an undesirable beam angle change. This situation is made worse by the fact that illumination of the radiators by the applied energy is usually made to vary along the array in accordance with a chosen function to minimize secondary lobe radiation. The choice of this function is sometimes limited when a single matching element is used.

It has been discovered, however, that if the matching of the impedance discontinuity of each radiator be effected in two steps by two matching elements instead of one, not only is the impedance discontinuity matched just as perfectly as by a single element but also the phases of the exciting voltages applied to preceding radiators are not affected. The result is that the array frequency band is widened without disturbing the beam angle. A further

advantage is the removal of restrictions on the choice of the kind of illumination of the radiators.

As a specific example of this invention a rectangular waveguide linear array having shunt slot radiators at half-wavelength intervals is selected. It is to be understood, however, that the application of this invention, is not confined to any particular type of linear array, to any particular kind of radiator, or to any particular spacing of radiators. This array is chosen because it is in general use and the invention is easily applicable to it. When such an array is terminated in a short circuit and the individual radiators are unmatched, each radiator constitutes an admittance discontinuity and reflects part of the incident microwave energy back toward the source of energy. Since shunt slots may be designed to behave as pure shunt conductances, they are so assumed for purposes of discussion herein. However, this usual case is selected merely for simple illustration and the invention is applicable to any series or shunt radiators having any impedance or admittance phase angle.

It is to be understood that the character of any radiator or matching device is described with equal correctness as impedance or admittance, although in design it is usually more convenient to use one than the other. It is possible to choose the number of radiators and their conductances so that the entire array will, at the design frequency, present characteristic conductance to the source of microwave energy, will not reflect any energy to the source and will have a VSWR of unity at the source end. Reflections and therefore standing waves will exist within the array, the electric vector phase applied to each of the radiators will be the same as it would have been in the absence of reflections, and the band of source frequencies within which the VSWR presented to the source is below, say, 1.6 is very narrow.

Because of the narrow bandwidth of such a linear array its usefulness is limited and common practice is to modify it by terminating it in its characteristic admittance or in an absorbing device, and by applying a matching admittance at each radiator. Each matching admittance is preferably purely susceptive and is positioned on the input side of the radiator at a calculated distance. The magnitude of the susceptance and its positioning can be so chosen as exactly to match the conductance of the radiator. Such an array matches the input source and has a wider bandwidth than the previously-described array. However, each matching susceptance changes the phase of the microwave voltage supplied to the preceding radiator from the phase which this voltage would have in the absence of the matching susceptances. The result is that the angle of the beam of microwave radiation emitted by the array may be modified. This result occurs because the beam angle depends not only on the microwave length in space and in the waveguide, and on the spacing s between radiators, all of which are constant, but also on the input voltage phase at each radiator. Since this phase may be changed by the matching susceptances the beam angle may be changed.

When instead of one matching admittance preceding each radiator two are employed, with proper magnitudes and spacings, the effect is the same as described in the preceding single matching susceptance case except that the feed voltage phase at the preceding radiator is not disturbed and therefore the beam angle is not changed from its value in the unmatched array case. In a special case the two matching admittances are purely susceptive and when

$$s=\frac{\lambda_g}{2}$$

in which λ_g is the wavelength of the energy in the waveguide, the two susceptances must be of opposite signs,

In general, however, the two admittances may be complex and may have the same or different signs.

The general purpose of this invention is to provide a microwave linear array containing two matching elements between each two radiators, these elements being so constructed and positioned as to prevent energy reflected to the source while at the same time providing broadband operation and having no effect on the beam angle of the design frequency.

Further understanding of this invention may be secured from the detailed description and associated drawings, in which;

Figure 1 depicts a rectangular microwave guide linear array embodying the invention.

Figure 2 is a portion of a Smith chart illustrating a method of designing the array of Fig. 1.

Figure 3 is a rectangular coordinate graph illustrating the operation of the array of Fig. 1.

Referring now to Fig. 1, a rectangular hollow waveguide **11** is provided at one end with an absorbing termination **12** consisting of a carbon wedge. The other end **13** of the waveguide is designed to be connected to a source of microwave energy. Three shunt slots **14**, **16** and **17** are positioned along one broad face **18** of the waveguide parallel to the center line **19** thereof. These slots are broadly resonant, being effectively one-half wavelength long. They are spaced from the center line **19** by distances *c* determining the slot couplings. These couplings may be the same or different in accordance with the illumination function selected. The slots are spaced along the length of the waveguide at equal intervals *s*. Although only three slots are shown for simplicity, normally an antenna array has ten or more radiators and may have any number. The array also may be combined with other linear arrays to form a planar array.

The admittance of each slot is matched by two elements placed near it in the waveguide and between the slot and the power source. The first element is a septum **21** placed within the waveguide on the interior surface of the broad waveguide face opposite to the face pierced by the slots. This septum forms an iris opening at a distance d_1 from the center of the succeeding radiator **16**. Such an iris, if the septum be thin, constitutes a nearly pure capacitive susceptance. The second element is a septum **22** placed within the waveguide on one of the narrow faces. This septum, if thin, forms a nearly pure inductive susceptance iris opening at a distance d_2 from the septum **21**. The magnitudes of the susceptances B_1 and B_2 formed by irises **21** and **22** respectively are determined by their dimensions W_1 and W_2.

Although it has been stated that the matching admittances are pure susceptances in the example, in the general case susceptances B_1 and B_2 need not be pure susceptances, but may instead be complex admittances Y_1 and Y_2. In this general case the four parameters Y_1, Y_2, d_1 and d_2 are interdependent and there is an infinitely large number of combinations which will match a given shunt slot and provide the described improved results.

The simple form of the invention described and depicted in Fig. 1 may be used as an example in describing the design method. Preferably a Smith chart is employed, such as described by P. H. Smith in Electronics for January 1939. In Fig. 2, representing a portion of such a chart, the point **23** represents on the vertical diametral scale the sum of the conductance G_{16} of slot **16**, Fig. 1, and of the line termination. For the present purpose it is sufficiently accurate to consider the slot shunt admittance as entirely conductive. The upper end **41**, Fig. 2, of this vertical diametral scale is the zero conductance point of the scale. A circle **24** is now drawn through point **23** about the unit conductance point **26** as a center until it intersects the circle **27** which represents a normalized conductance of unity. Progression clockwise on circle **24** represents progression in waveguide **11**, Fig. 1, from the center of slot **16** toward the waveguide input end **13**, and the amount of progression in fractions of λ_g is measured on a scale on the periphery **28**, Fig. 2, by drawing the radius from center **26** through the point of intersection **29**. The scale distance

$$\frac{d_1}{\lambda_g}$$

Fig. 2, then represents the waveguide distance d_1, Fig. 1. A point **31** is now selected on circle **27** approximately half way between points **26** and **29**. The distance **29–31** represents the susceptance B_1 and its magnitude is ascertained on a second peripheral scale by subtracting the value at point **32** intersected by curve **32'** from that at point **33** intersected by curve **33'**. This matching susceptance B_1 is positive, that is, it is capacitive. A circle **34** is now drawn through point **31** clockwise about center **26** until it meets the unity circle **27** at point **36**. Progression along circle **34** from point **31** to point **36** is measured by extending radii through points **31** and **36** to the first peripheral scale, and is termed

$$\frac{d_2}{\lambda_g}$$

This scale distance represents the waveguide distance d_2, Fig. 1. The capacitive (positive) susceptance indicated by point **36**, Fig. 2, is read from the second peripheral scale at the intersection **35** of the arc **35'** through point **36**. The lines **37**, **38** and **39** are now drawn between the zero conductance point **41** and points **29**, **31** and **36**, and the positions of points **31** and **36** are readjusted so that angle *a* equals angle *b*. The arc **36—26** is now traced along the unity circle **27**, repersenting the magnitude of inductive (negative) susceptance B_2 which is to be applied to match the susceptance indicated by point **35**. This susceptance B_2 has a sign opposite to that of susceptance B_1 and is nearly but not exactly equal to it in magnitude in the special case of this example.

The fact that the arc **36—26** terminates at the center or match point of the Smith chart indicates that the admittance of the slot **16**, Fig. 1, has been perfectly matched. That is, the reflected wave set up by the admittance discontinuity of the slot does not persist to the left of septum **22**. Additionally, the fact that the angles *a* and *b*, Fig. 2, are equal indicates that the phase of the voltage applied to the slot **14** has not been disturbed from what it would be in an unobstructed line. This design procedure is to be followed for each slot and this analysis holds true for all, therefore the composite beam angle of the entire linear array is not changed by the matching elements.

The described case is special in that both admittances **21** and **22**, Fig. 1, are pure susceptances, this being demonstrated by the fact that the insertions of B_1 and B_2 causes the admittance to move along constant conductance circles of the Smith chart. In the general case arc **24** is not restricted to termination on the unit circle **27**. If, for example, the arc **24** should terminate before reaching the unit circle **27**, say on the circle having value $G=1.1$, application of a general susceptance in place of iris **21** would be depicted, for example, by clockwise progression along the 1.1 circle toward the vertical diameter to some point. From this point a circle drawn clockwise about center **26** to the unit circle **27** would depict some distance such as

$$\frac{d_2}{\lambda_g}$$

and application of a pure inductive susceptance would move the operating location to the match point **26**. This must be done choosing the proper angles at *b'*.

The operation of this invention is further explained by means of the rectangular coordinate graph of Fig. 3, which applies to the linear array of Fig. 1. In this graph the abscissa scale constitutes waveguide longitudinal distance measured in units of λ_g. Progress along this ab-

scissa scale from the left toward the right represents distance measured along the waveguide from the input end toward the termination. The points S_{14} and S_{16} on the scale represent the locations in Fig. 1 of the slots **14** and **16** respectively. The ordinate scale represents the phase of the microwave voltage at any point in the waveguide relative to the voltage phase at the same instant at location S_{16} of slot **16**.

Consider the effect of microwave energy applied from the left in the absence of radiators and matching elements. The guide is "smooth," that is, it has no discontinuities, and the smooth and continuous variation of phase is represented by the straight line **42**, Fig. 3. Now consider the effect of adding radiators **14** and **16** spaced from each other a distance of one-half wavelength of the energy in the waveguide. Energy is reflected by slot **16** resulting in phase change on the input side of this slot. This is partially represented in Fig. 3 by the curve **43** between locations S_{16} and S_{21}. In the absence of matching devices this curve would continue and cross the straight line **42**, and then would meet it again at the location S_{14} of slot **14**. Standing waves would exist to the left of location S_{16}.

Now suppose the capacitive matching element **21** is to be added. This is represented in Fig. 3 at location S_{21} by a vertical line **44**, and produces a change in the rate of curvature of the line representing phase, with the line **46** now representing phase between locations S_{21} and S_{22}. At the latter location the line **46** becomes tangent to the straight line **42**. A standing wave exists to this point.

At location S_{22} suppose the second matching element **22** be applied. This matches the mismatch existing at location S_{22} in such a manner that between locations S_{22} and S_{14} the phase is represented by the straight line **42**. Between these locations there is no standing wave. That is, there is no reflected wave between iris **22** and slot **14**. The fact that the line passes through point **47**, Fig. 3, means that the phase at this point is the same as the phase of an unobstructed line would be and the same as the phase would be at the point in the case of unmatched radiators

$$\frac{\lambda_g}{2}$$

distance apart.

Referring again to Fig. 1, the coupling distances C will in general be different for the different radiators, resulting in different admittances for the different radiators. This in turn will require different matching admittances, each pair and its distances being calculated for a specific radiator and different from each other pair and its placement distances.

What is claimed is:

1. A wideband microwave linear array comprising, a plurality of radiators each constituting an impedance discontinuity, each radiator being preceded at a selected distance by a first matching element having a first selected impedance, each of said first matching elements being preceded at a second selected distance by a second matching element having a second selected impedance, each of said first and second matching elements shifting the phase of the microwave energy existing in said linear array, said first and second impedance acting together to neutralize said impedance discontinuity while at the same time mutually cancelling the phase shifting effect of each alone.

2. A wideband microwave linear array comprising, a hollow waveguide section having a source of microwave energy coupled to one end thereof, a plurality of radiating elements equally spaced along the linear length of said waveguide section each coupled to the energy contained therein and interrupting the impedance continuity thereof, a plurality of matching elements equal in number to the number of radiating elements each having a selected individual impedance and causing a selected phase shift of said energy, said matching elements being positioned internally of said waveguide section with respective ones thereof spaced from respective ones of said radiating elements at selected distances in the direction towards said source of energy, and a plurality of other matching elements equal in number to the number of radiating elements each having a selected individual impedance and causing a selected phase shift of said energy, said other matching elements being positioned internally of said waveguide section with respective ones thereof spaced from respective ones of said radiating elements at selected distances in the direction towards said source of energy, the impedance of each one of said matching elements combining with the impedance of one of said other matching elements to neutralize the impedance interruption of one of said radiating elements, and the phase shift of each one of said matching elements being of such magnitude in combination with the phase shift of one of said other matching elements forming a pair, that no phase disturbance is caused in said energy between the source thereof and the nearer one of said pair.

3. A wideband microwave linear array comprising, a hollow waveguide section having a source of microwave energy coupled to one end thereof, a plurality of radiating elements equally spaced at distances of one-half wavelength of said energy in waveguide along the length of said section and coupled to the energy therein, the magnitude of coupling being different for different radiating elements whereby the impedance which each presents to said energy is a function of the coupling, first individual matching impeders for each of said radiating elements each positioned in said waveguide at a selected distance preceding the associated radiating element, the impedance and position of each impeder being selected partly to neutralize the impedance mismatch and phase shift of its associated radiating element, second individual matching impeders for each of said radiating elements each positioned in said waveguide at a selected distance preceding individual ones of said first matching impeders, the signs of said first and second matching impeders being different with the impedance of each individual one of said second matching impeders and its positioned distance being selected completely to neutralize the impedance mismatch and phase shift of its associated individual radiating element left unneutralized by the associated one of said first matching impeders.

4. A wideband microwave linear array comprising, a rectangular waveguide section provided with a linear array of slot radiators regularly spaced along the length thereof, a source energizing said waveguide, and a pair of impedance and phase shift matching elements positioned between each pair of radiating elements, each pair of matching elements consisting of a capacitive element and an inductive element affixed to said waveguide section at such selected distances preceding individual slot radiators as to neutralize the impedance discontinuity and phase shift presented by each slot radiator to said energy source.

5. A wideband microwave linear array comprising, a rectangular waveguide section provided with a linear array of slot radiators regularly spaced along the length thereof, a source energizing said linear array, a pair of impedance discontinuity and phase shift correcting elements positioned between each pair of radiating elements, each pair of correcting elements consisting of a capacitive element affixed to said waveguide section at a selected distance preceding an individual slot radiator and an inductive element affixed to said waveguide section at a selected distance preceding its associated capacitive element, said individual capacitive and inductive elements mutually cooperating to neutralize the impedance discontinuity and the phase shift presented to said energy source by the slot radiator they precede.

6. A wideband microwave linear array comprising, a

rectangular waveguide section provided with a linear array of slot radiators regularly spaced along the length thereof, a microwave source energizing said linear array, a pair of impedance discontinuity and phase shift correcting elements positioned between each pair of radiating elements, each pair of correcting elements consisting of a capacitive iris positioned internally of said waveguide section at a selected distance preceding an individual slot radiator and an inductive iris positioned internally of said waveguide section at a selected distance preceding its associated capacitive iris, each of said pair of irises mutually cooperating to neutralize the impedance discontinuity and the phase shift presented to said

microwave energy source by the slot radiator they precede.

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