APPARATUS AND METHOD OF COMPENSATING A LONG HIGHLY DISPERSIVE TRAVELING WAVE TRANSMISSION LINE

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Filed: Oct. 9, 1969

Appl. No.: 865,044

U.S. Cl. .................................................................................................................. 343/771, 333/31 A

Int. Cl. .................................................................................................................. H01Q 13/10

Field of Search............................................ 343/767, 768, 770, 771, 854; 333/31 A

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ABSTRACT

A method and structure for correcting and linearizing the phase distribution along the waveguide transmission line feed of a long, highly dispersive, slow-wave, N-element antenna array. The method involves the phase probing of the individual radiating elements of a linear array formed by slotting a serpentine waveguide feed. This probing is carried out in predetermined equal increments of Y-elements each.

The measured phase over each of the increments of Y-elements is subtracted from a theoretical or reference phase desired at the predetermined element and the phase error (Δφ) thus determined is divided by Y. Individual dielectric panels are affixed to the serpentine broad internal walls ("a" dimension walls). Enough panels are inserted between the radiators of each adjacent pair to provide a −Δφ/Y phase shift. The process is repeated N/Y times for each linear array. A two-dimensional array can be assembled from M of these linear arrays, with each linear array having equal phase distribution characteristics overall and among its N-elements.

6 Claims, 5 Drawing Figures
1. Field of the Invention

The present invention relates to directive antenna arrays in general and more particularly to means and method for correcting and linearizing the phase distribution among the elements of a long, highly dispersive, slow-wave antenna array.

2. Description of the Prior Art

In the prior art, various Radar systems have been devised to make use of the fact that a slow-wave transmission line feeding a linear array provides a structure for inertialless scanning. The transmission line is often folded into a serpentine as shown in U.S. Pat. No. 3,039,097. Such a configuration is inherently adapted to beam-pointing as a function of frequency of excitation and therefore, inertialless scanning. U.S. Pat. No. 3,438,035 illustrates a system in which a number of serpentine waveguide feed slot arrays are assembled to form a two-dimensional array capable of producing directivity in two coordinates. In this latter prior art patent, the variable frequency excitation produces frequency scanning in one coordinate. The principles describing the operation of such devices as frequency scanners are now well known in this art.

A practical problem arises in connection with a scanner constructed with machined waveguide serpentine as depicted in FIGS. 1 and 4 of U.S. Pat. No. 3,438,035. That is, the required machining is extremely expensive if the degree of phase distribution uniformity necessary for development of desired beam patterns in space is to be achieved. Moreover, the beam-pointing angle for each linear array as a function of frequency of excitation must be the same within a close tolerance. The present invention addresses itself to the aforementioned problems.

SUMMARY

In view of the practical problems presenting themselves in prior art structures of the character described, it may be said that the general object of the present invention was the development of a method and structure for linearizing and making uniform the overall phase distribution of a linear waveguide-fed slow-wave array. A number of such arrays can then properly be assembled into a two-dimensional array having predictable pattern and scanning characteristics. As a corollary to this object, it might be said that it was intended to accomplish the objective with machined (or otherwise fabricated serpentine) waveguide structures built to reasonable manufacturing tolerances.

The showing of U.S. Pat. No. 3,438,035 presumes that the serpentine are machined in halves and assembled mechanically. This particular structure is especially adaptable for use of the present invention, as will be realized as the description proceeds.

The basis of the present invention is the observation that partial loading of rectangular waveguide with a dielectric slab or panel, perpendicular to the E-field, will delay the electromagnetic wave proceeding along the guide. For a dielectric slab or panel extending along the entire broad dimension (a dimension) as an air-filled waveguide, it can be shown that

\[ \lambda_e = \frac{\lambda_0}{\sqrt{1 - \frac{d}{b} \left(1 - \frac{1}{e_i}\right)}} \]

where:
- \( \lambda_e \) = guide wavelength in partially filled guide
- \( \lambda_0 \) = free space wavelength
- \( d \) = thickness of dielectric panel
- \( b \) = narrow dimension of rectangular waveguide
- \( a \) = wide dimension of rectangular waveguide
- \( e_i \) = relative dielectric constant of dielectric panel

Experimental investigation shows that the guide wavelength above described is shorter than the guide wavelength in a corresponding piece of waveguide minus the dielectric panel. Therefore, for equal lengths of identical waveguide, one with dielectric panel and one without, the one with the panel will delay an electromagnetic wave more or cause it to experience more negative phase shift in travel through the length. The so-called dielectric panels of the present invention are actually strips of a dielectric tape selected for its low loss and ease with which it can be installed. The above-described basic principle is that by which the tape strips of the present invention work, i.e., they cause greater delay in the field than a corresponding section of the slow-wave structure not having the strips. It is the ability of the tape strips to disturb the propagation constant that produces the effect. The answer of the tape strips upon the propagation constant can be inferred from the above formula, however, a carefully controlled experimental program has been shown to be a reliable empirical way of ascertaining with accuracy the effect of a given tape strip on the propagation constant.

The method involved in applying the dielectric tapes involves first the determination of phase shift experienced by the electric field.

The machined-in-halves serpentine structure referred to is obviously readily adapted to the installation of the tape strips to perform the dielectric panel function, however, as a first step, the serpentine is assembled without the tapes and is phase-probed.

A particular application of the present invention was undertaken in a serpentine built to operate in the vicinity of 9.0 GHz. Phase probing was thus readily accomplished using well-known microwave test equipment.

In phase probing, the phase of energy at predetermined equal increments (\( Y \)-elements each) along the array, is determined with respect to the input of the waveguide. Thus discrete corresponding points on a phase distribution curve are obtained. The required correction (\( \Delta \phi \)) to linearize the curve at these points is then readily determined and converted to a number of discrete dielectric unit strips each of small predetermined phase shifting equivalence. These are then uniformly distributed on the z dimension serpentine interior walls among the paths separating adjacent radiators; \(-\Delta \phi/Y \) phase shift thereby being introduced between adjacent radiators.

Further detail will be added in description taken against the drawings hereinafter.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic of a two dimensional array assembly of M-linear arrays in which the present invention is useful.

FIG. 2 is a schematic of one N-element slotted linear array of the FIG. 1 assembly of M-linear arrays.

FIG. 3 is a phase distribution graph to illustrate correction of two typical serpentine according to the present invention.

FIG. 4 is an isometric partial view of the two halves of a serpentine waveguide structure prior to assembly but having dielectric panels emplaced according to the present invention.

FIG. 5 is a partial lateral view of half of the structure of FIG. 4.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring now to FIG. 1, the two dimensional array depicted schematically could well be that shown in U.S. Pat. No. 3,438,035. This showing is for the purpose of establishing element and linear array identification and relationships, "M" and "N", respectively, for purposes of the description. The feeder network I could readily be the variable waveguide-width phase distributor assembly of that patent, and the typical slot radiator 2 and 3 in the "Mth" linear array in FIG. 1 similarly could be corresponding slots. The line termination or serpentine load 4 is a straight forward expedient, well understood in the art and could be provided by any of various well-known alternatives.
In FIG. 2, the serpentine shown schematically could represent that of any of the linear arrays 1 through M of FIG. 1. The slot element numbers 1 through N also corresponding. The distance \( d \) represents the external or array surface spacing of the elements as contrasted to \( S \), which represents the path length between radiators within the serpentine waveguide. The array normal is represented by a vector \( \mathbf{7} \) and the wave front line \( S \) is that which would correspond to an arbitrary frequency of excitation producing a corresponding phase distribution over the \( 1 \) to \( N \) elements.

The vector \( \mathbf{7} \) points in the direction of radiation (i.e., the normal to the phase field line \( S \)) this vector \( \mathbf{7} \) makes an angle \( \theta \) with the array physical normal \( 7 \).

FIG. 3 depicts the uncompensated phase distributions of two arbitrary selected finish machining serpentines A and B at curves 6 and 7, respectively. Curve 5 is a theoretical or reference phase line constituting the ideal to which A and B serpentines are to be corrected in accordance with the method and structure of the present invention.

Before proceeding with description of the remaining figures, some additional theoretical discussion of the problem and its solution is in order.

In order to focus the array beam at some distant point in space, it is highly desirable that the equiphase contours of the radiated field lie in planes. In order to accomplish these planar phase contours in the far field, it is necessary, as already indicated, that the phase distribution along each of the linear arrays be itself linear. Of course, the phase distribution across the feeder network must also be linear. It is not sufficient that each linear array's distribution have the same slope; the phase distributions along each linear array must, in fact, be equal within a very close tolerance. The so-called serpentine fed linear array with which the present invention is primarily concerned, is broadly classed as a traveling wave array, such arrays being frequency scanable over an angle \( \Theta \) to \( \Theta_{p} \), as the frequency is changed from \( f_{1} \) to \( f_{2} \). In most applications, it is desirable to scan the beam over a relatively wide range of angles using only a moderate frequency range. Ordinarily this dispersion is accomplished by utilizing a slow-wave structure, the geometry of which is depicted in FIG. 2.

Although the present invention is being described as though the individual radiators in the broadwall of the serpentine waveguide are slots, it is, nevertheless, possible for them to be individual dipoles or some other type of radiating element.

In a serpentine waveguide per se, the waveguide is alternately folded back on itself as shown in the referred prior art, in order that the mechanical distance between radiators measured along the waveguide is substantially greater than the straight line distance between radiators along the array surface.

In practice, the distance \( d \) from FIG. 2 will be somewhat less than a free space wavelength, while the distance \( S \) may be many multiples of a half wavelength within the guide. The result is a highly dispersive structure, that is, one in which relative phase between adjacent radiator changes very rapidly as the frequency of excitation varies.

For a typical practical planar array, operating in the 9.0 GHz region, \( "M" \) and \( "N" \) may well both be numbers in excess of 150. In manufacturing, a serpentine slow-wave structure of this type can be produced by d isp and assembly of alternates of static pieces of waveguide to a series of 180° bends. This manufacturing technique is generally thought to be suitable where the resulting bulk is not a limiting disadvantage and the tolerances and repeatable requirements are not stringent, for instance, such a fabrication will be more applicable where only one serpentine structure was required, as for example, in U.S. Pat. No. 3,039,097.

In instances where many highly compact identical slow wave structures are required for the construction of a two dimensional planar array, the total machining technique is more applicable. In this technique the individual slow wave structures are machined out of solid blocks of material, as for example, through the use of a digitally programmable end-milling machine. Each serpentine is milled one-half at a time, the split between one-half structures in the assembled product occurring along the middle of the broadwall for conventional rectangular waveguide transmission line. This is the type of structure and fabrication method resulting in a device, such as shown in U.S. Pat. No. 3,438,035. Only one of the said halves has radiating slots milled into it, the actual location of these slots or other radiators with respect to the center line of the broad waveguide wall to be determined in accordance with the polarization desired and other considerations.

The more critical machining dimension in the totally machined serpentine structure is the depth of cut into the two halves as this dimension controls the width of the waveguide broadwall (a dimension) and consequently determines the phase constant of the waveguide. To examine this phase constant relationship in a rectangular waveguide, which the preferred serpentine structure actually is, in extended and folded form, the following may be written.

\[
B = \frac{2\pi}{\beta} = \frac{2\pi}{\lambda} \left( 1 - \left( \frac{\lambda}{a} \right)^{2} \right)^{1/2}
\]

\( B = \) phase constant in radians per unit length

\( \beta = \) guide wavelength

\( \lambda = \) free space wavelength

\( a = \) waveguide broadwall dimension

Differentiating with respect to \( a \) yields:

\[
\frac{\Delta B}{\Delta a} = \frac{\pi \lambda}{a^{2}} \quad \text{which approximately equals} \quad \frac{\Delta B}{\Delta a}
\]

In the following, the inch is the unit of measurement, and

\( \Delta B = \) phase change per inch,

\( \Delta B = \text{phase change in degrees between elements,} \)

\( \Delta B \cdot \text{S} = \text{phase change in degrees across the M-element structure.} \)

The problem of reproducibility and accuracy being the primary manufacturing problem, the development of a unique method of manufacturing M substantially identical N-element structures insofar as phase distributions are concerned, was one of the most pressing in practical instrumentation of slow-wave structure.

To illustrate further, assume the following parameters:

\( 5.168'' = 2\pi \theta_{p} \)

\( d = 0.870'' \)

\( c = 0.851'' \)

\( N = 156 \)

\( \lambda_{s} = 9.1 \text{ GHz} = 2.010'' \)

\( \Delta B = (90') \left( \frac{\Delta \theta}{\theta_{p}} \right) (\Delta a) = 294 \Delta a \)

A very liberal criterion would be a requirement that the maximum difference in phase between the ends of any two of the M slow-wave structures be less than 90°. If this value is substituted into the expression \( \Delta B \cdot \text{S} \cdot \text{N} \), one finds that \( \Delta a = 0.005 \) inch. In effect, this imposes a tolerance on the \( a \) dimension of the waveguide of \( \pm 0.00025 \) inch. Within the present state of the art, this tolerance is not at all practical, in that its attainment would make the manufacturing process extremely costly.

In respect to the difficulty of the foregoing, the placement of dielectric panels perpendicular to the E-field within the waveguide (serpentine) to effect partial loading, and consequently to introduce phase delay, was conceived.

The phase probing of each slow-wave serpentine structure in order to obtain the data depicted in the A and B curves of FIG. 3 can be carried on with sufficient accuracy well within the capabilities of microwave test instruments (such as RF-phase bridge) currently available, and whereas the required total machining tolerances were not critical to achieve even with the more advanced machining methods. A program of experimentation designed to select a practical material for the aforementioned dielectric panels was conducted. Capabilities of various dielectric materials for produc-
ing the desired phase shift were examined in a test waveguide. Tape, identified commercially as X-774-1, dielectric tape, manufactured by the Schjeldahl Co., was selected. Generi-
cally, this tape is a multilayer-type comprising a “Tedlar” layer as an outside coating supported by a “Dacron” cloth layer and a layer of “Mylar.” A good pressure-sensitive adhesive
surface on this tape contributed also to its selection. The actual choice of material for the dielectric panels is open to
selection among a substantial variety of dielectric materials available. The criteria are not unlike those relating to selec-
tion of capacitor dielectric layers. This is to say, reasonably good dielectric strength and low-loss characteristics, as well as
phase-shifting ability in the application, at the microwave
frequency involved are among the most significant consider-
ations.

Referring now to FIG. 4, the emplacement of the tape strips, constituting the dielectric panels as aforesaid, is illustrated. Two halves of serpentine 8 and 9 are illustrated with the
dielectric tapes installed and ready for assembly. For clarity,
the showing is of only a partial serpentine length since, as
previously indicated, the number of radiating slots in a prac-
tical X-band array might well be on the order of 150 or more.

The radiating slots 10 and 11 are assumed for the sake of
example, to be the N-3 and N-4 elements. The dielectric
panels across the broadwall of the completely assembled
structure are then actually two in number, such as for ex-
ample, 17 and companion 17a, when the final assembly of 8 and 9
is effected. The other panel pairs called out are then 18 and 18a,
19 and 19a, and also 20 and 20a. The inside webs which form the said broadwall, such as 12, 13, 14, 15 and 16 (typi-
cally) are butted against 12a, 13a, 14a, 15a and 16a, as will be
apparent from FIG. 4.

Referring also to FIG. 5, a lateral view looking into 9
is presented, showing dielectric panels 21, 22 and 23 not visible
in FIG. 4. These panels would normally also have companion
panels not visible. The use of these parallel panel pairs makes the
broadwall loading symmetrical and is desirable as far as
possible as an expedient for preventing the appearance of
higher order modes in the serpentine.

From an understanding of the dielectric panel installations,
it follows from FIG. 5 that the path S between adjacent slot
radiators 10 and 11 can include up to eight panels of the rela-
tive size illustrated, i.e., 22, 18, 23, and 19 in serpentine half 9
and their companion panels in 8.

Of course, in a serpentine requiring relatively little cor-
rection, only one or two broadwall pair of panels may be
required between slots, rather than the indicated four pairs.
Each panel contributes its increment of phase delay, whether
in series or parallel with another panel within the guide.

The typical drilled web boss 34 accommodates the bolting
together of 8 and 9. The shape of the internal web boss, such
as at 25, is not a part of the present invention, but is to be
regarded as one of various internal configurations possible in
the making of a machined serpentine. The “dovetail” internal
construction illustrated in U.S. Pat. No. 3,438,035 is one of
these possible variations.

Concerning the practical procedure for sizing the tape strips
to function as dielectric panels, it was experimentally deter-
mined that a suitable tape strip for use in an X-band serpen-
tine of the type illustrated was 1 inch long and 0.375 inch in
width. The effective incremental phase shift per strip was
0.95° at 9.0 GHz. In one practical embodiment, the correction
required over the first 20 elements was determined by phase-
probing at element number 20 to be 140° degrees. Ac-

andently, 147 tapes were required to be distributed uniformly
between the first and twentieth element.

It will be understood that other variations are possible in the
precise method and structure of the present invention, and
these will be apparent to those skilled in this art, once the
present invention is understood.

The invention is, of course, capable of implementation at
frequencies other than the X-band assumed in the description.

What is claimed is:

1. The method of achieving linear phase distribution over the
length of a waveguide transmission line of the slow-wave
type, comprising:

2. A linear antenna array which includes a plurality of
radiating elements fed from successive points along an ex-
tended path rectangular waveguide transmission line for
developing an electromagnetic beam narrow in at least one
polar scan coordinate, said beam being generated at a pointing
angle which is a function of frequency of the excitation energy
within said waveguide, comprising:

3. Apparatus according to claim 2 in which said folded
waveguide structure is defined as a serpentine-shaped array
feedline.

4. The invention set forth in claim 3, further defined in that
said waveguide is fabricated in two parts, said two parts being
such as would be formed by cutting said serpentine lengthwise
bisecting said a dimension internal walls, and said dielectric
panels are mounted substantially symmetrically on said a
dimension wall on both sides of said bisection, thereby to af-
ford installation of said dielectric panels before said serpen-
tine waveguide is fully assembled.

5. The invention set forth in claim 3, further defined in that
said dielectric panels are individually located between ad-
jacent radiating element feed points along substantially un-
curved walls of said serpentine waveguide.

6. The invention set forth in claim 3, further defined in that
said dielectric panels are individually distributed along all sub-
stantially uncurved a dimension internal walls of said
waveguide serpentine.