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MICROWAVE DIGITAL PHASE-SHIFTER

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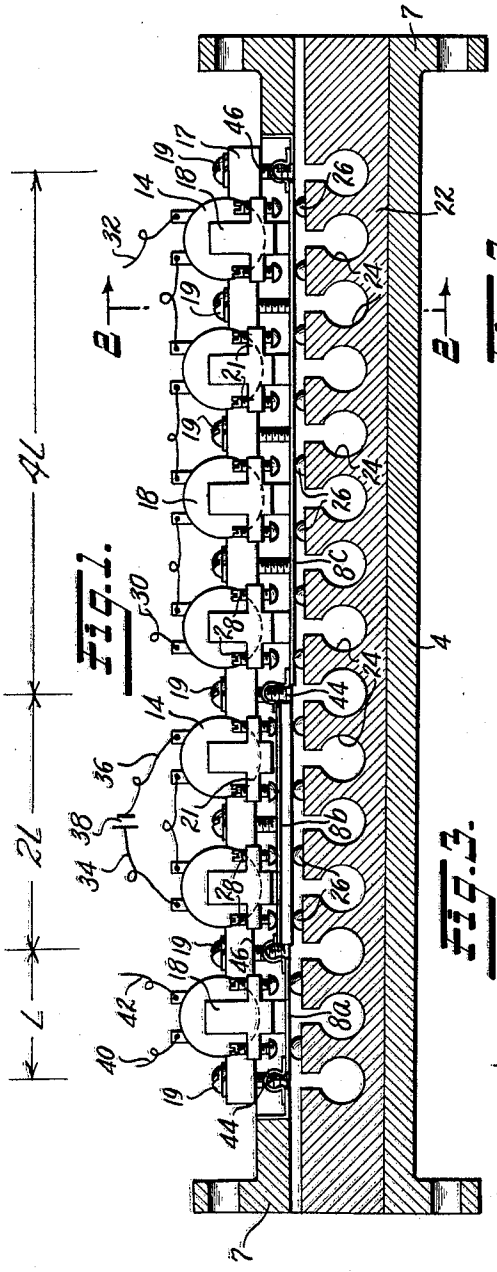


FIG. 1.

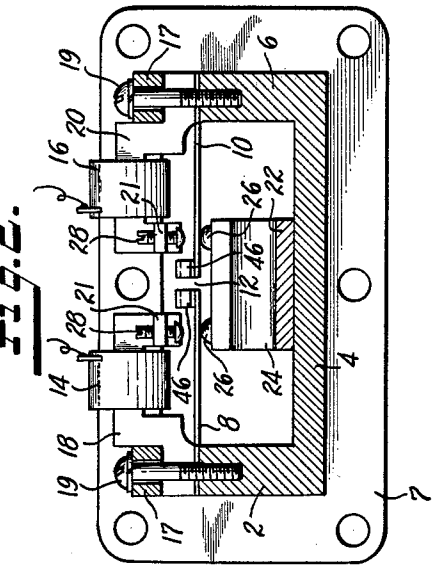


FIG. 2.

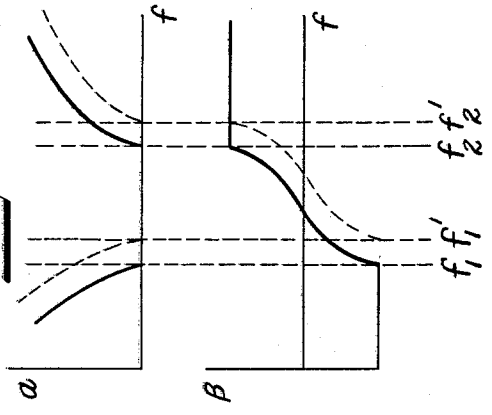


FIG. 3.

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MICROWAVE DIGITAL PHASE-SHIFTER

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This invention relates to the transmission of radio frequency or microwave energy in waveguides, and more specifically to the rapid control of the phase of the field associated with such energy.

It is sometimes desirable, in microwave systems, to be able to change the RF phase of the energy in a waveguide, in response to a control signal, without causing appreciable amplitude change at the same time. Such an effect is useful, for example, in controlling the pointing angle of the beam of a phase-steerable antenna array. In the past this has been accomplished in one of several different ways by devices known as variable phase-shifters. It is usually possible to classify such devices either as electromechanical or as non-mechanical in nature. The electromechanical types generally have relatively good RF performance but usually respond rather slowly to a control signal.

It is an object of this invention to provide an electromechanical type of variable phase-shifter wherein the required mechanical motions are small, and the masses of the moving parts are also small, thereby permitting relatively rapid response to an electrical control signal.

A further object is to provide a variable phase-shifter responsive to a digital type of electrical control signal.

Another object is to provide a phase-shifter of rugged yet relatively simple construction and which is highly efficient and reliable in operation.

By way of example, one embodiment of this invention provides a length of rectangular waveguide wherein one wall carries a series of inward projections. The opposite wall of the waveguide is a relatively thin sheet of soft iron which is permitted limited transverse deflection. Deflection is produced by magnetic attraction of the iron wall by electromagnets positioned outside the waveguide.

In the drawings:

FIG. 1 is a central longitudinal sectional view of a complete device embodying the present invention.

FIG. 2 is a cross-sectional view of the same device, taken along the line 2—2 of FIG. 1.

FIG. 3 is a graph showing typical attenuation and phase characteristics.

The exemplary device illustrated in the drawings comprises an elongated hollow waveguide formed in part by a channel member (see FIG. 2) having a bottom wall 4 and side walls 2 and 6 and an upper flexible wall formed of longitudinal flexible sections of paramagnetic material 8 and 10. The channel member is provided with end flanges 7 having openings therethrough and by means of which the apparatus may be secured to other circuit components. The upper flexible wall comprising sections 8 and 10 is split longitudinally leaving a central groove 12 so that each section may be readily and easily flexed. Sections 8 and 10 are, respectively, made up of longitudinally spaced portions 8*a*, 8*b* and 8*c*, and 10*a*, 10*b* and 10*c*, the portions 8*b* and 10*b* being, for example, twice as long as 8*a* and 10*a*, and 8*c* and 10*c* being twice as long as 8*b* and 10*b*. The portions 10*a*, 10*b* and 10*c* are not separately shown in the drawings but are identical to and opposite 8*a*, 8*b* and 8*c*, respectively. The flexible upper wall portions are mounted to the upper edges of the side walls 2 and 6 of the channel member by being clamped thereto between those upper edges and clamping elements 18 and 20, respectively. The elements 18 and 20 further constitute pole pieces for electromagnetic coils 14 and 16. The members 18 and 20 are longitudinally spaced in accordance with the spacing of the coils 14 and 16 and are held in clamping relation to the sections 8 and 10 by longitudinally extending bars 17 and screws 19.

The portions 8*a*, 8*b* and 8*c* and 10*a*, 10*b* and 10*c* are divided by transverse slots 44 which are bridged by conductive bridge pieces 46 so that all portions are electrically connected.

A central member 22 is secured in any suitable manner to the bottom wall 4 of the channel and is provided with transverse loading holes 24 from which slots extend to the upper surface of the member 22 to define a series of longitudinally spaced projections. Insulating bumper stops 26 are mounted on the projections of member 22 to insure a predetermined spacing between the ends of these projections and the flexible wall portions 8*a*, 8*b*, etc. when coils 14 and 16 are deenergized.

The core pieces 18 and 20 are provided with lateral ears 21 through which adjustable stops 28 are threaded. The stops 28 may be adjusted to limit upward flexure of the wall portions 8 and 10 when the coils 14 and 16 are energized.

As shown, the coils 14 and 16 and their corresponding pole pieces 18 and 20 are uniformly spaced longitudinally of the device. As shown, the portions 8*a* and 10*a* may be flexed by a single pair of coils, the sections 8*b* and 10*b* are flexed by two pairs, whereas the sections 8*c* and 10*c* are flexed by four pairs of coils. Thus, the magnetic force applied to each portion is proportional to its length. It is contemplated that opposing pairs of coils 14 and 16 will be simultaneously energized, although such manner of operation is not critical nor a limiting feature of the invention.

A waveguide containing a periodic loading ridge of the type which has been described with reference to member 22 exhibits a band-pass characteristic illustrated typically by the solid curves in FIG. 3, wherein:

α=attenuation component of transmission
β=phase component of transmission
f=applied frequency
f_1=lower cut-off frequency
f_2=upper cut-off frequency

It is found that the lower cut-off frequency f_1 may be computed to good approximation by considering the structure to be a standard ridged waveguide, ignoring the effects of the loading holes. The upper cut-off frequency f_2 may be approximated by considering the periodic structure of the ridge as a low-pass filter where the cut-off is computed conventionally from the product LC. Here, L represents the inductance per section and depends upon the diameter of the holes 24, while C represents the capacitance per section and may be computed from the spacing between the ridge and the movable wall together with the area of the ridge surface facing the movable wall between adjacent holes. Longitudinal slot 12 does not appreciably affect the field within the waveguide if the slot is narrow and well centered.

Now, if opposed movable wall sections 8, 10 are deflected outwardly as a result of energizing coils 14, 16, the cut-off frequencies both increase to new values designated f_1' and f_2'. Further, it is found experimentally that, by suitably proportioning the various dimensions of the waveguide and the periodic loading ridge, the two frequency increments may be made the same: that is; $f_1'-f_1=f_2'-f_2$. Thus, the phase-curve in the pass-band simply moves parallel to itself as indicated by the dotted curve of B in FIG. 3. This is a desirable condition in that it yields a sizeable region within the pass-band wherein the phase-shift introduced by the wall deflection does not change appreciably with the operating frequency.

The phase-shift produced by the device is essentially

the sum of the phase-shifts of the individual sections of the movable wall. In general it is desired that the total control range correspond to 360 electrical degrees of phase-shift. Referring to FIG. 1, in order to provide a digital type of control, the magnet coils are operated in unison in groups containing different numbers of coils according to the various binary digits. Thus, leads **30**, **32** control the largest group containing, in this case, 4 pairs of coils **14** and **16**, for flexing wall sections **8***c* and **10***c*. This group is capable of introducing 180 degrees of phase-shift, or just half the total range required of the device. Leads **34**, **36** control the next group containing 2 pairs of coils, for sections **8***b* and **10***b*. This group introduces 90 degrees of phase-shift, and is shown in the energized position as signified schematically by the battery **38**. Leads **40**, **42** control the smallest group containing one pair of coils, for sections **8***a* and **10***a*, capable of introducing 45 degrees phase-shift. Digital control of the total phase-shift throughout the desired 360-degree range is exercised in 45-degree steps according to the following table wherein the symbol 0 represents an unenergized coil group while the symbol 1 represents an energized coil group:

	Degrees
000	0
001	45
010	90
011	135
100	180
101	225
110	270
111	315

In order to facilitate the deflection of that section of movable wall **8**, **10** under a particular coil-group without affecting the sections under the adjacent coil-group, transverse slots **44** are provided between wall sections **8***a* and **8***b*, **10***a* and **10***b*, etc. However, such transverse slots do couple to the field within the waveguide. It is therefore necessary to bridge the transverse slots with flexible shorting-straps **46** wihch are spot-welded or otherwise conductively joined to the adjacent movable wall sections.

It should be understood that, for the sake of clarity, certain dimensions have been exaggerated in FIG. 1 and FIG. 2. This applies to the thickness of the movable wall sections and to the amount of their deflection. If a movable wall section is assumed to deflect as a cantilever of length approximately one inch, and if the wall thickness is about .007 inch and the required deflection .020 inch, it will be found that the metal is not overly stressed and the response to a control signal will take place in a time of the order of one millisecond. This is much faster than other electro-mechanical types of phase-shifters presently existing.

If the deflection is limited to a smaller value, the response time decreases. A further advantage of smaller

deflection is that the impedance variation and resultant mismatch are less. Of course the phase-shift produced is also less, but this fact may be compensated for to any arbitrary extent desired simply by increasing the total number of sections in the device without affecting the response time or impedance variation.

While a single specific embodiment of the invention has been shown and described herein, it is to be understood that the same is merely illustrative and that the invention may embody other forms falling within the scope of the appended claims.

I claim:

1. A microwave phase-shifter comprising: means defining an elongated waveguide having three rigid and fixed conductive side walls and a flexible conductive fourth wall; the rigid wall opposite said fourth wall having a longitudinal series of inwardly directed spaced conductivity projections thereon conductively connected to said rigid wall; said fourth wall comprising separate sections of ferromagnetic material mounted for flexure toward and from said projections; and separate selectively operable magnetic means adjacent said fourth wall sections, respectively, for selectively flexing said wall sections whereby to incrementally and digitally vary the distance between said flexible wall sections and said projections to thereby vary the capacitance of said waveguide.

2. A device as defined in claim 1 wherein said fourth wall sections are of unequal lengths and are aligned and spaced longitudinally of said waveguide.

3. A device as defined in claim 2 including flexible conducting straps joining adjacent edge portions of adjacent sections.

4. A device as defined in claim 2 wherein each succeding fourth wall section is twice as long as the next preceding one whereby successive flexure thereof effects multiple digital changes in the capacitance of said waveguide.

5. A device as defined in claim 1 wherein each of said fourth wall sections is split longitudinally substantially along its center line; said magnetic means comprising simultaneously actuable magnetic devices adjacent each half of each of said sections.

6. A device as defined in claim 1 including insulated stop means on said inwardly directed projections, engageable with said fourth wall sections for limiting inward flexure thereof; and adjustable stop means adjacent the outer faces of said fourth wall sections for regulating and limiting outward flexure of said sections.

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