United States Patent [19]

Burns

[11] **3,790,908**

[45] **Feb. 5, 1974**

[54] **HIGH POWER DIODE PHASE SHIFTER**

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[73] Assignee: **Hughes Aircraft Company**, Culver City, Calif.

[22] Filed: **Dec. 29, 1972**

[21] Appl. No.: **319,271**

[52] **U.S. Cl.** ..... **333/31 A**, 333/7 D, 333/84 R, 333/98 S

[51] **Int. Cl.** **H03h 7/18**

[58] **Field of Search** .... 333/31 A, 84 R, 98 S, 98, 7, 333/73 W, 81 A; 307/320; 343/768; 329/161; 332/29 R, 30 R, 16 R, 16 T, 9 R, 9 T, 17

[56] **References Cited**

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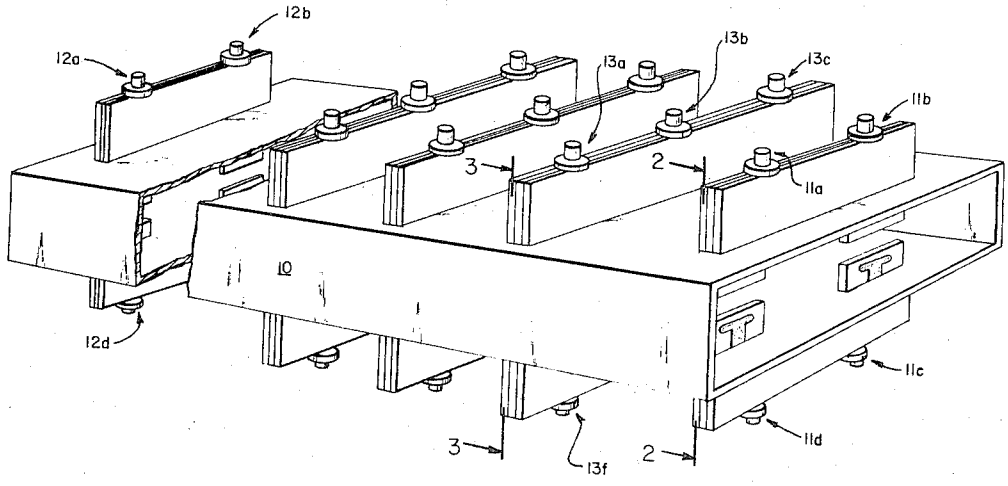
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Primary Examiner—Eli Lieberman
Assistant Examiner—Marvin Nussbaum
Attorney, Agent, or Firm—W. H. MacAllister; Martin E. Gerry

[57] **ABSTRACT**

A voltage-controlled phase shifter of the loaded-line type is disclosed employing arrays of diode switches coupled to probes in quarter wavelength spaced planes of a rectangular waveguide by stripline circuits. The strip-line circuits and probes are adjusted in design and position to give a small value of susceptance per diode in shunt with the waveguide. The total shunt susceptance across the waveguide in the same plane is thus divided between two or more diode switches to achieve a division of the power being propagated in the waveguide.

11 Claims, 7 Drawing Figures



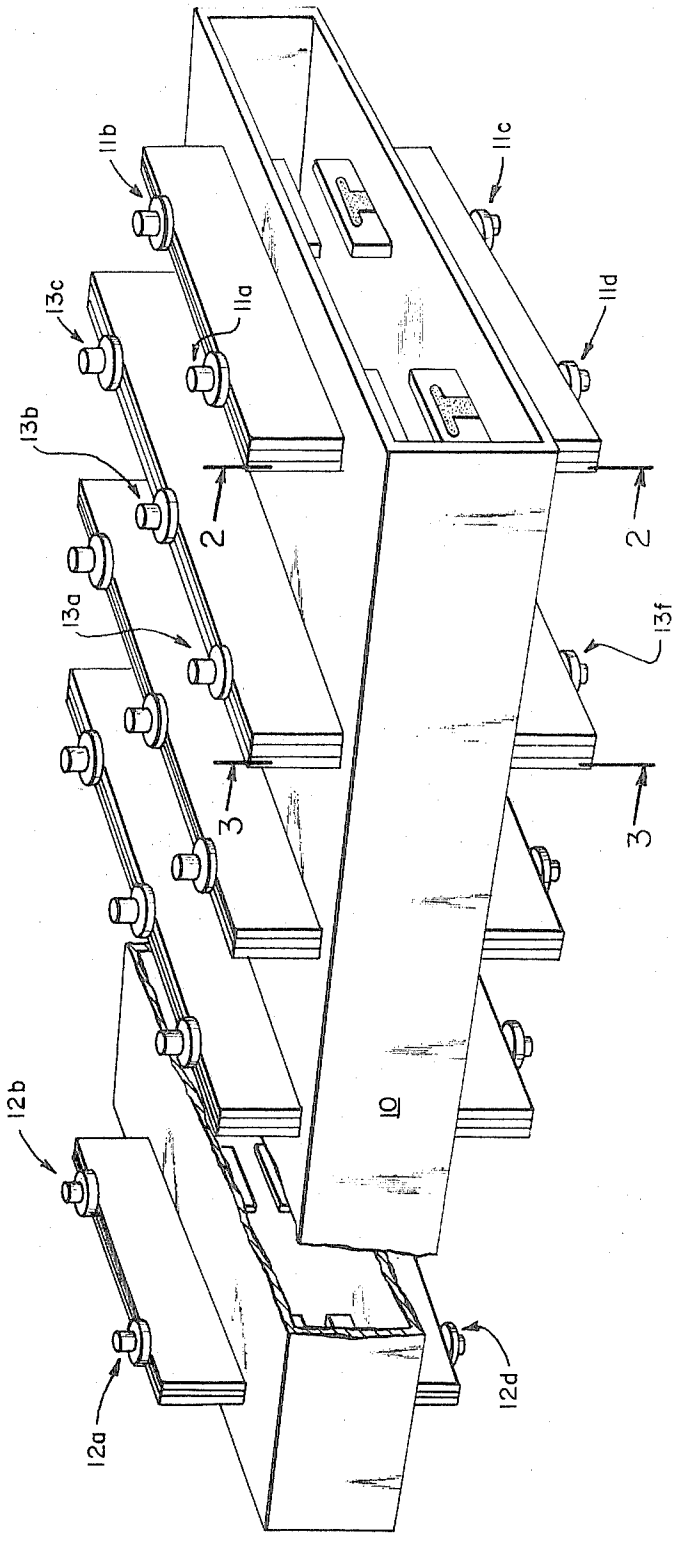


Fig. 1.

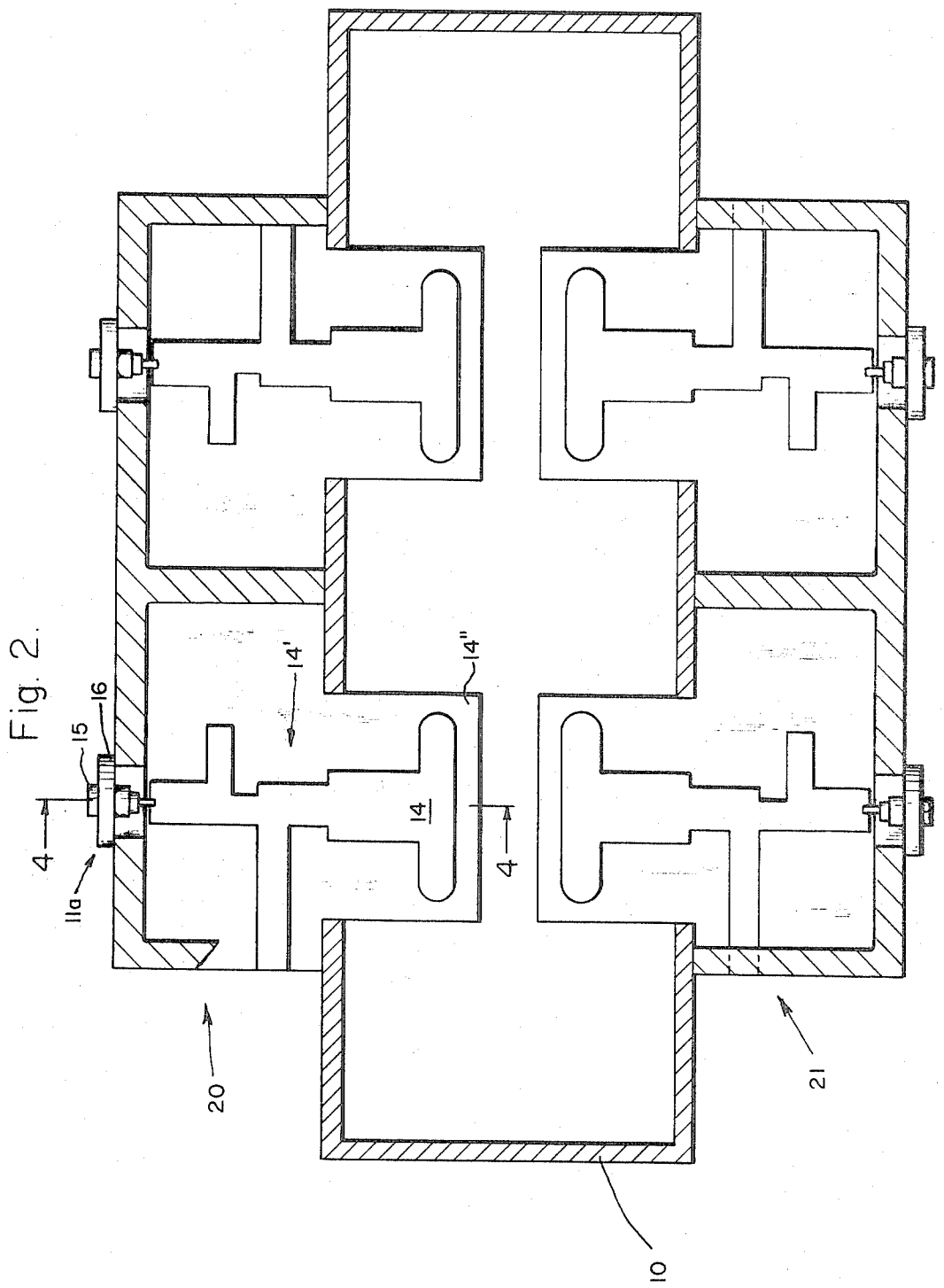


Fig. 2.

Fig. 3.

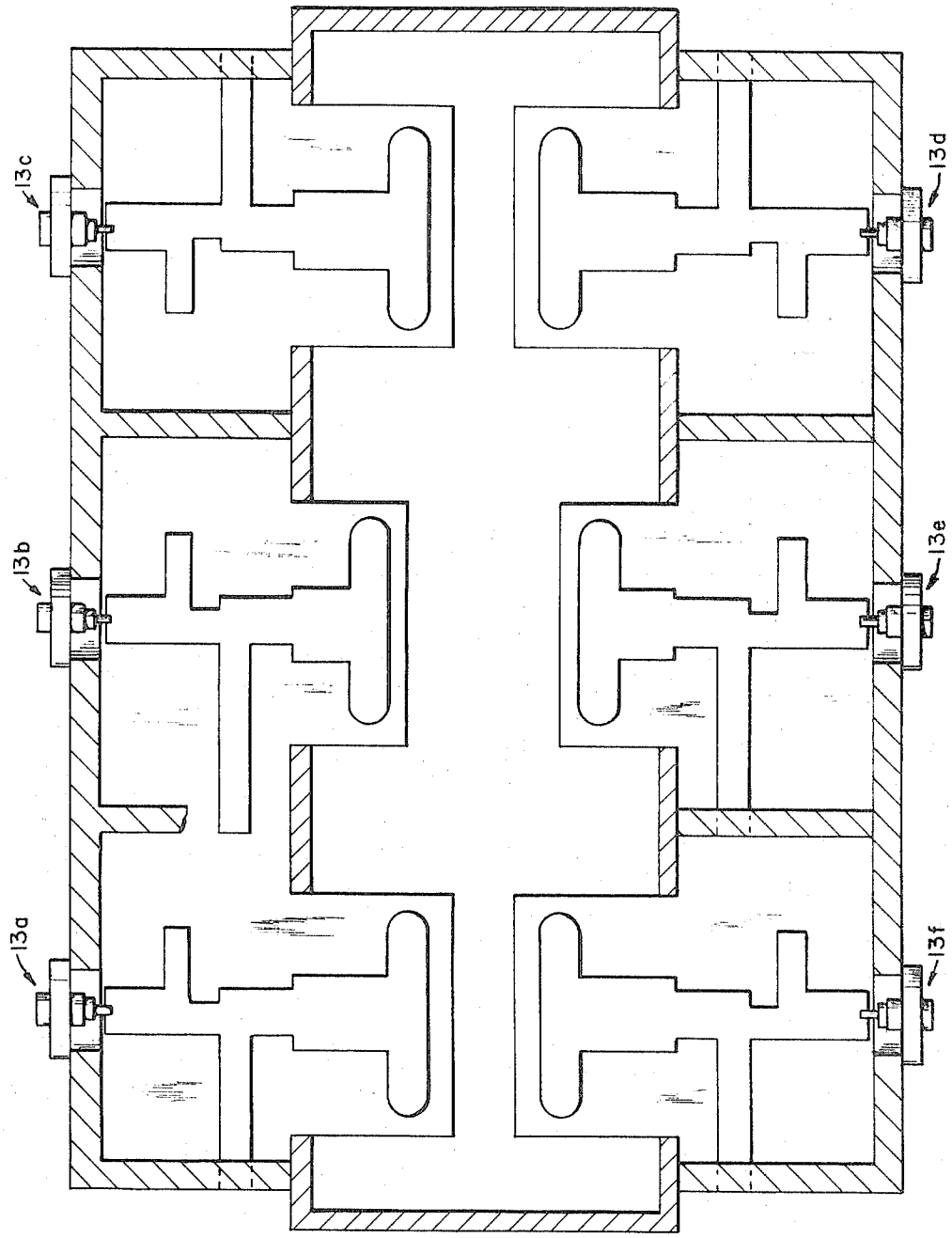


Fig. 4.

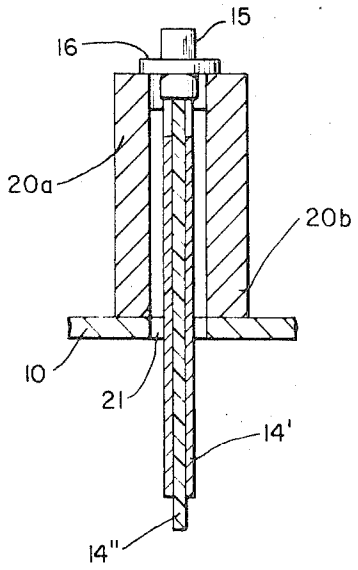


Fig. 6.

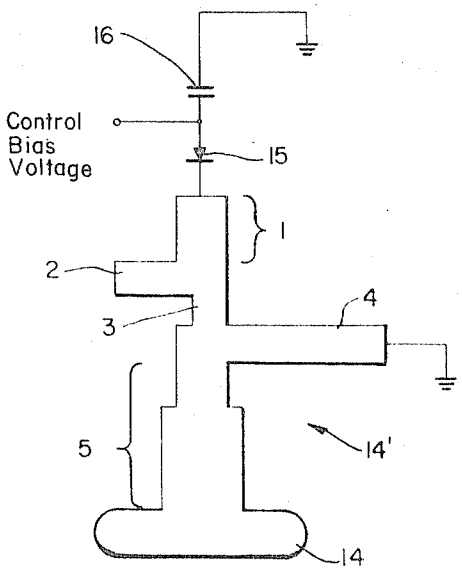


Fig. 5.

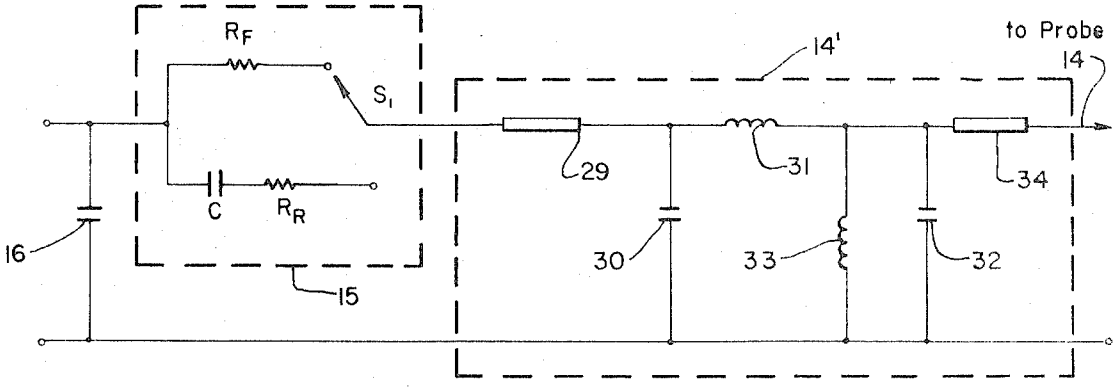
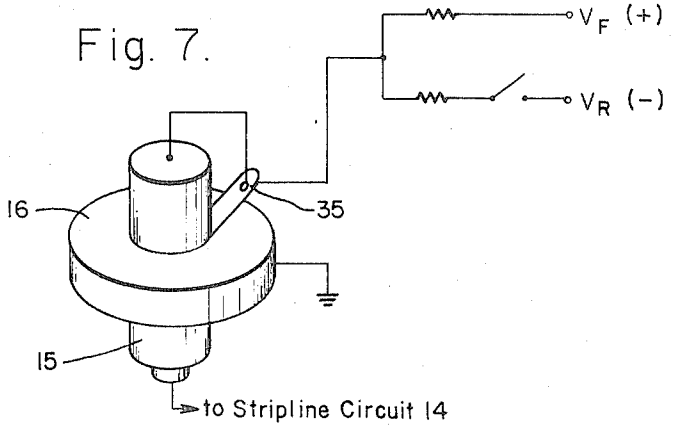


Fig. 7.



HIGH POWER DIODE PHASE SHIFTER

BACKGROUND OF THE INVENTION

This invention relates to a voltage-controlled transmission phase shifter, and more particularly to a high power phase shifter in a rectangular waveguide.

Many radar systems require electronically variable phase shifters, such as in phased array antennas for beam steering at high speed. Ferrite devices, or traveling-wave tubes, are not suitable because of their excessive weight, size or power requirements. Diode switches are much more suitable from the point of view of size and weight, and when reverse biased, require very little control power because of the high impedance of the diodes. Only power to forward bias the diodes is required.

The use of diode switches in phase shifters has developed along three distinct types. One type, referred to as a switched line phase shifter, consists of two pair of diode switches, each pair functioning as a single-pole, double-throw switch electronically controlled to selectively switch the microwave transmission through a delay line. Another type, referred to as a transmission-reflection phase shifter, consists of a circulator with a diode controllable reflective phase termination. A variant of this, called a hybrid-coupled phase shifter, employs a hybrid coupler having an input and an output port cross coupled by a third port terminated by a diode switch. A fourth port is similarly terminated by a diode switch to maintain a match at the couplers input and output ports and to make bilateral performance possible.

These two types of phase shifters, the switched line type and the transmission-reflection type, are not suitable for many high power applications, because of their limited power capacity. The third type, the transmission type commonly referred to as a loaded line phase shifter, is more suitable.

In a loaded-line phase shifter, diode switches provide variable susceptance to perturb the phase of the transmitted wave. Line sections one quarter wavelength long between switched diodes make reflections practically mutually cancel over the frequency band range. These diode switches provide a maximum phase shift commensurate with their peak power capacity, as shown in Table 9 of chapter 12, RADAR HANDBOOK (McGraw-Hill, 1970) by Louis Stark, R. W. Burns (the present inventor) and W. P. Clark. Assuming a maximum phase shift of 5° per line section, and a required capability for shifting up to 180°, the transmission waveguide must be 9 wavelengths long to accommodate the 36 line sections required. The result is an inefficient phase shifter due to its long length and therefore high loss.

At low power, it is practical to mount the diodes directly in the waveguide. At high power, the usual practice is to insert a probe or stub in the waveguide. The diode is then connected in a series or shunt circuit which permits selectively switching a capacitance load onto the probe. In either case, the diodes are closely coupled to the power of the waveguide. This limits the maximum phase shift that can be achieved per section between spaced diode switches to that of the peak power capacity of the diodes. For some applications, particularly high power phase shift applications, it would be desirable to decrease the stress across the diodes without decreasing the phase shift per section, or, stated differently, having determined the phase shift desired between diode switching stations, to provide some way of achieving the necessary susceptance per station without overstressing the diodes.

OBJECTS AND SUMMARY OF THE INVENTION

An object of this invention is to provide a shorter transmission waveguide phase shifter than has heretofore been possible for a given degree of phase shift.

Another object is to allow use of inexpensive, low-voltage diodes in a high power transmission waveguide phase shifter.

Another object is to provide an arrangement of diode switches in a transmission waveguide phase shifter to effectively divide the high power in a section of the phase shifter so that each diode is subjected to only a small portion of the total input power.

Still another object is to provide a transmission waveguide phase shifter with light electrical loading for a wide frequency bandwidth in the transmission through the phase shifter.

Yet another object is to provide an improved and inexpensive mounting for diodes in a transmission waveguide phase shifter.

These and other objects are achieved in a rectangular wave guide by arranging switching diodes in arrays of 2N diodes, where N is a whole integer, such as two or three, successive arrays being spaced a quarter wavelength apart to form phase-shift sections of a transmission phase shifter. The integer N need not be the same for each array, and is preferably selected for arrays at the ends of the phase shifter to be less than inbetween to provide lighter loading at the ends of the phase shifter. Each diode is mounted outside of the waveguide and connected in series between a probe in the waveguide and a control voltage terminal outside of the waveguide by a stripline circuit. A capacitor is connected between the terminal and the waveguide. The stripline circuit is adjusted in geometry to provide a shorted shunt stub next to the probe, an open-circuit shunt stub next to the diode and a narrow section connecting the shunt stubs to provide series inductance, all for the purpose of providing a small value of susceptance in shunt with the waveguide which can be changed by a small amount when the diode is reverse biased. The stripline circuit thus effectively decouples the diodes from the high power in the waveguide while providing the appropriate shunt susceptance. The total shunt susceptance across the waveguide in one plane is split between 2N diode switching circuits in that plane, and the total susceptance change of the diodes in that plane, achieved by switching the diodes from forward bias to reverse bias by conventional means, yields a phase shift $\Delta\phi$. In that manner greater phase shift per section can be achieved without overstressing the diodes, which implies that a shorter phase shifter (less sections) is required for a desired total phase shift of, for example, 90° or 180°. The probes for the switching circuits of one plane are symmetrically spaced to pick up an equal amount of power for the particular propagation mode.

The novel features that are considered characteristic of this invention are set forth with particularity in the appended claims. The invention will best be understood from the following description when read in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view of an exemplary transmission phase shifter constructed in accordance with the present invention.

FIG. 2 is a sectional view taken on a line 2—2 of FIG. 1.

FIG. 3 is a sectional view taken on a line 3—3 in FIG. 1.

FIG. 4 is a sectional view taken on a line 4—4 in FIG. 2.

FIG. 5 is an equivalent circuit for the diode and stripline circuit arrangements shown in FIGS. 2 and 3.

FIG. 6 is a schematic diagram of the diode switching circuit of FIG. 5.

FIG. 7 is a perspective view of a toroidal capacitor and diode assembly for each of the diodes of the arrays shown in FIG. 1.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to FIG. 1, a section of rectangular waveguide is provided with a plurality of diode switching circuits arrayed in separate planes in groups of four and six. The first plane includes four switching circuits 11*a* through 11*d* shown in a sectional view in FIG. 2. The last plane also includes four switching circuits 12*a* through 12*d*. The intervening planes each include six diode switching circuits, such as circuits 13*a* through 13*f* for the second plane shown in a sectional view in FIG. 3. These arrays are spaced a quarter wavelength apart to provide a bandpass filter for use as a transmission phase shifter, i.e., to provide a low mismatch over a wide bandwidth. Only four diode switching circuits are arrayed in the end planes, while six diode switching circuits are arrayed in the other planes, for the purpose of providing lighter loading at the ends of the filter.

Each of the diode switching circuits is coupled to the waveguide 10 by a probe, such as a probe 14 for the circuit 11*a*, and each diode is mounted on a toroidal capacitor, which in turn is mounted on a stripline circuit board, such as a diode 15 mounted on a capacitor 16 for the circuit 11*a*, as shown in FIGS. 2, 4 and 7. Stripline conductor patterns 14' etched on both sides of circuit boards 14'' of dielectric material, such as teflon impregnated glass fiber cloth, connect the several diodes in an array to respective probes, such as a stripline conductor pattern 14' for the probe 14. The patterns are the same for all switching circuits of the first and last arrays, and differ only as shown in FIG. 3 for the intervening arrays. Accordingly, a description of one stripline pattern will suffice for all circuits, however, before proceeding to that, the general description of the phase shifter construction will be completed. Suffice it to say for the present that the stripline pattern is selected to give a small value of susceptance in shunt with the waveguide. When the bias on a diode is reversed by conventional means (not shown in FIG. 1), the susceptance across the waveguide in the plane of the diode is changed by a small value. A normalized susceptance change of 0.2 for one diode switching circuit yields a phase shift of typically 5°. The total shunt susceptance across the waveguide in a given plane is made up of the susceptances of the individual stripline circuits. Therefore, the total phase shift provided by a change of susceptance in a given plane is four or six times that of one diode, depending upon how many diode switching circuits are in the plane.

The stripline circuits effectively decouple the diodes from the high power in the waveguide while providing the appropriate susceptance across the waveguide. The power capability of the phase shifter is therefore high since the RF voltage across the diode is inversely proportional to the susceptance contributed by the diode, i.e., each diode is lightly stressed.

Referring to FIG. 2, a housing 20 mounted on the waveguide 10 holds the stripline circuit board for one half of the waveguide such that the upper probes are positioned symmetrically off center for coupling of energy propagated in the waveguide mode TE_{10}. A housing 21 is mounted on the other side of the waveguide. Each housing may be in two parts with the stripline circuit board sandwiched between the parts, such as parts 20*a* and 20*b* for the housing 20 as shown in FIG. 4. Slots in the waveguide permit the probes to protrude into the waveguide without shorting out the stripline circuit. Slot 21 for probe 14 shown in FIG. 4 illustrates this. The arrangement for the planes having six diode switching circuits is essentially the same, but with the probe distribution as shown for switching circuits 13*a* through 13*f* in FIG. 3 for maximum coupling of energy in the waveguide.

An equivalent circuit for a typical diode and stripline circuit, such as the diode 15 and stripline circuit 14' (FIG. 2), is shown in FIG. 5. A simplified equivalent circuit of the diode 15 is shown to demonstrate its cooperation with the stripline circuit 14', the latter consisting of a coupling stripline 29, a shunt capacitor 30, a series inductor 31, a shunt capacitor 32 in parallel with an inductor 33, and a coupling stripline 34. Referring to the equivalent circuit of the diode 15, a switch S_1 represents the action of the diode under forward and reverse bias conditions. When forward biased, it places a resistance, R_F, in series with the stripline circuit 14' as shown, and when reverse biased, it places a capacitive reactance, C, and resistance, R_R, in series with the stripline circuit.

FIG. 6 is a schematic diagram of the diode switching circuit comprised of the stripline circuit 14', the diode 15 and the capacitor 16. The coupling stripline 29 in the equivalent circuit shown in FIG. 5 is provided by section 1 of the stripline conductor pattern shown in FIG. 6. Similarly, the shunt capacitance 30 in the equivalent circuit of FIG. 5 is provided by section 2 of the stripline conductor pattern shown in FIG. 6. The end of section 2 is provided as a stub open circuit. The series inductance 31 is provided by a narrow section 3 of the conductive pattern, and the capacitance 32 in parallel with the inductance 33 is provided by a section 4 of the conductive pattern. The end of that section 4 is connected to circuit ground through the housing, as shown in FIGS. 2 and 3, to provide a shorted shunt stub. The coupling stripline 34 in the equivalent circuit shown in FIG. 5 is provided by section 5 of the stripline conductor pattern connected to the probe 14 as shown in FIG. 7. The inside terminal of the toroidal capacitor 16 is connected through a tab 35 to the anode of the diode 15 as shown in FIG. 7. The other terminal of the capacitor is connected to circuit ground (waveguide) through its metal container. The cathode of the diode 15 is connected to the coupling section 1 of the stripline pattern 14' as schematically illustrated in FIG. 6.

From FIGS. 6 and 7, it is evident that reverse biasing the diode 15 will yield a susceptance change, and that at all times the stripline circuit pattern 14' effectively decouples the diode from the probe 14, i.e., from the high power of the waveguide, while providing the appropriate shunt susceptance. The result is high power capability for the phase shifter since the RF voltage across the diode is inversely proportional to the susceptance contributed by the diode. Individual diodes are limited by thier breakdown voltage, hence power capacity would be limited but for the present invention which decouples the diodes, and distributes the susceptance necessary for the phase shift desired among a plurality of diodes, such as four or six diodes in one plane, thus placing only a light stress on each diode. Consequently, the power capacity of the phase shifter is increased, and the length of the phase shifter for a given phase shift, such as 90° or 180°, is shortened.

As noted hereinbefore, switched loading susceptances spaced a quarter-wavelength along a transmission line are commonly used for electronic beam steering of phased array antennas by switching discrete sections according to the magnitude of the steering angle desired. Accordingly, the present invention may be used by cascading a plurality of separately controlled sections, each constructed as shown and described. However, beam steering is usually accomplished by phase shifting at the antenna elements where power is so low relative to the power at the transmitter that diodes with suitable power capacity are available at relatively low cost. In that event, there would be need to use a plurality of diodes at each plane to divide the susceptance, i.e., to effectively share the power. A more practical application of the present invention would be in an arrangement of microwave circuits and voltage controlled phase shifters at the output of a transmitter to switch power from one antenna to another by a combination of splitting and combining energy. For example, to provide 360° coverage with four fixed phased array antennas, it is necessary to selectively switch power from one antenna to another at high speed. By first splitting the power into four high power channels, controlling the phase of each channel separately through phase shifters, and then combining the four channels appropriately, it is possible to always have the propagated wave cancel at three of four output channels. The channel at which the propagated wave does not cancel will at all times depend only upon the phase shift through the phase shifters. Since high power is being processed, it would be of great advantage to construct the phase shifters in accordance with the present invention. Still other applications for the invention will occur to those skilled in the art.

Although a particular embodiment of the invention has been described and illustrated herein, it is recognized that modifications and equivalents may readily occur to those skilled in the art. Consequently, it is intended that the claims be interpreted to cover such modifications and equivalents.

What is claimed is:

1. A voltage-controlled phase shifter comprising
a rectangular waveguide,
arrays of probes in said waveguide disposed in planes spaced a quarter wavelength apart,
a plurality of diodes outside of said waveguide, one for each probe,
a plurality of stripline circuits, one for each probe, coupling each of said probes to a different one of said diodes, each stripline circuit being adjusted in geometry to provide a small value of susceptance in shunt with said waveguide,
a plurality of capacitors, a different one connected in parallel with a separate diode and stripline circuit connected in series,
and means for selectively forward and reverse biasing each of said diodes.

2. A voltage-controlled phase shifter as defined in claim 1 wherein each of said stripline circuits includes a shorted shunt stub next to a probe, an open-circuit shunt stub next to a diode, and a narrow section connecting said shunt stubs to provide series inductance.

3. In a rectangular waveguide for a particular propagation mode, a voltage-controlled phase shifter comprising a plurality of diode switching circuits disposed in arrays along said waveguide a quarter wavelength apart to form phase-shift sections of a transmission phase shifter, each array comprising
a plurality of circuit means coupling said probes to guide,
a plurality of probes disposed in a plane normal to the walls of said waveguide, one probe for each diode, each of said probes being positioned inside said waveguide in said plane for picking up electromagnetic energy, and
a plurality of circuit means coupling said probes to said diodes, a separate circuit means for each diode providing a small value of susceptance in shunt with said waveguide which can be changed by a small amount when the coupled diode is switched from a forward biased to a reverse biased condition,
each of said circuit means includes a capacitor and means for selectively providing forward and reverse bias potential for said diodes, a stripline circuit coupling a probe to a diode, said stripline circuit being adjusted in geometry to provide a shorted shunt stub next to said probe, the end of said shorted shunt stub being connected to said waveguide, an open-circuit shunt stub next to said diode, a section connecting said shunt stubs, said section being sufficiently narrow to provide series inductance between said shunt stubs, a section connecting said shorted shunt stub outside of said waveguide to said probe, and a section connecting said open-circuited shunt stub to said diode, said diode being connected in series between said stripline circuit and said means for selectively providing forward and reverse biasing potential, and means for connecting said capacitor between said waveguide and said diode at a terminal to which said biasing potential means is connected.

4. The combination of claim 3, wherein 2N diode switching circuits are included in each array, N is a whole integer separately selected for each array, and N probes are inserted into said waveguide through slots on each of two opposite sides, each of N probes on one side being disposed to pick up an equal amount of power for said particular waveguide propagation mode as each of N probes on the other side of said waveguide.

5. The combination of claim 4 wherein N is selected for each array to be equal except for end arrays, and

N is selected for each end array to be less than for intermediate arrays for the purpose of providing lighter loading at the ends of said phase shifter.

6. A voltage-controlled phase shifter comprising

a rectangular waveguide for a particular propagation mode,

a plurality of switching diodes grouped in successive arrays spaced a quarter wavelength apart to form phase shift sections between diode arrays, said diodes being mounted outside of said waveguide,

a plurality of probes, one for each diode, each probe being inserted into said waveguide through a slot and all probes associated with diodes of one array being disposed in a single plane normal to the walls of said waveguide axis,

a control voltage terminal outside of said waveguide for receiving selectively forward and reverse bias voltage for each diode,

a separate stripline circuit for connecting each diode in series between said terminal and an associated one of said probes, said stripline circuit including a shorted shunt stub next to said associated one of said probes, an open-circuit shunt stub, and a narrow section connecting said shunt stubs to provide an inductance therebetween, and further including coupling sections at each end of said narrow section for connecting said stripline circuit in series between a diode and an associated one of said probes, and

a separate capacitor connected between said terminal and said waveguide.

7. A voltage-controlled phase shifter as defined in claim **6** wherein each array includes 2N diodes, and N is a whole integer.

8. A voltage-controlled phase shifter as defined in claim **7** wherein N is selected to be the same for every array of switching diodes, except the first and last of said successive arrays, and one less for said first and last arrays.

9. A voltage-controlled phase shifter as defined in claim **8** in which probes in each plane are disposed to pick up an equal amount of power for said particular propagation mode.

10. A voltage-controlled phase shifter as defined in claim **9** wherein each stripline circuit is mounted on said waveguide by a housing comprised of two parallel walls of conductive material forming stripline ground planes, and where said shorted shunt stub is connected at its end to said housing.

11. A voltage-controlled phase shifter as defined in claim **10** wherein each capacitor is mounted on the end of a stripline housing and is connected between a diode and said stripline housing.

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UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 3,790,908

DATED : February 5, 1974

INVENTOR(S) : Richard W. Burns

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 6, Lines 23 and 24, Claim 3:
Claim 4 (amended)
Delete "circuit means coupling said probes to guide" and insert --diodes mounted outside of said wave guide--.

Signed and Sealed this

Twenty-first Day of September 1976

[SEAL]

Attest:

RUTH C. MASON
Attesting Officer

C. MARSHALL DANN
Commissioner of Patents and Trademarks