Feb. 15, 1966 J. MUNUSHIAN ETAL 3,235,820

ELECTRICALLY VARIABLE PHASE SHIFTER

Original Filed Jan. 4, 1960 3 Sheets-Sheet 1

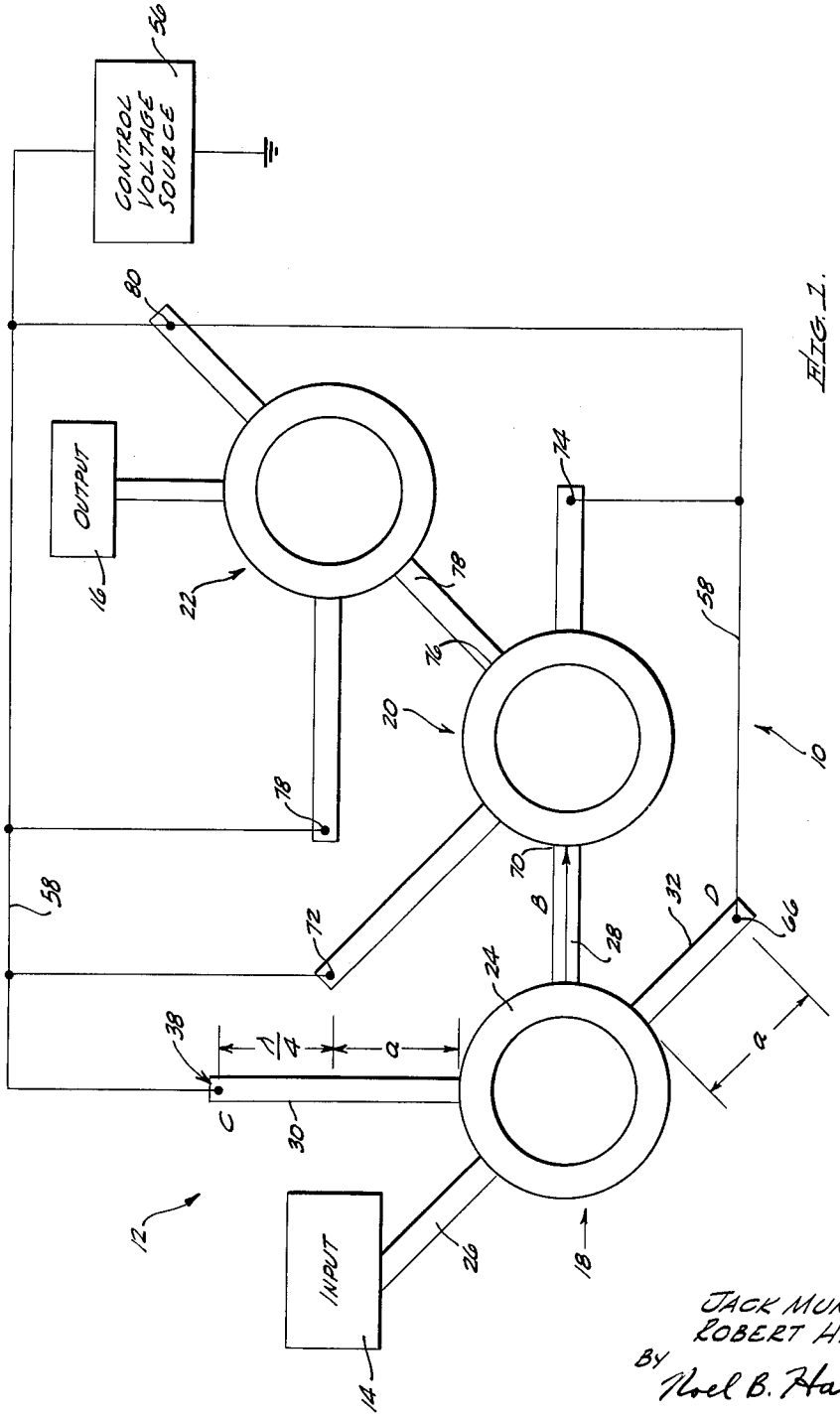



FIG. 1.

INVENTORS.
JACK MUNUSHIAN
ROBERT H. HARDIN,
BY Noel B. Hammond
AGENT

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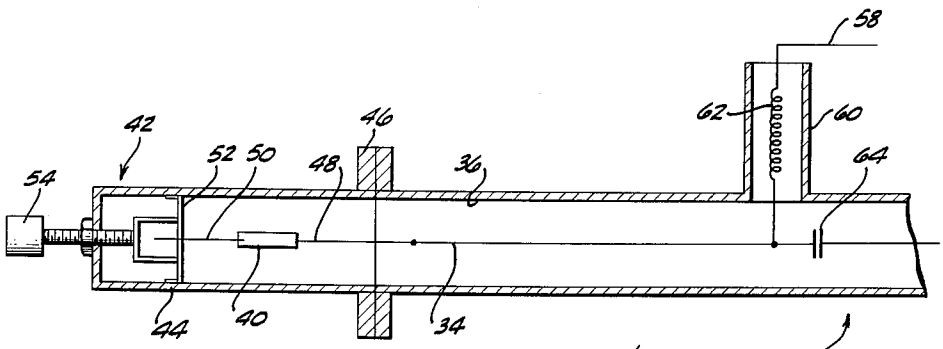



FIG. 2.

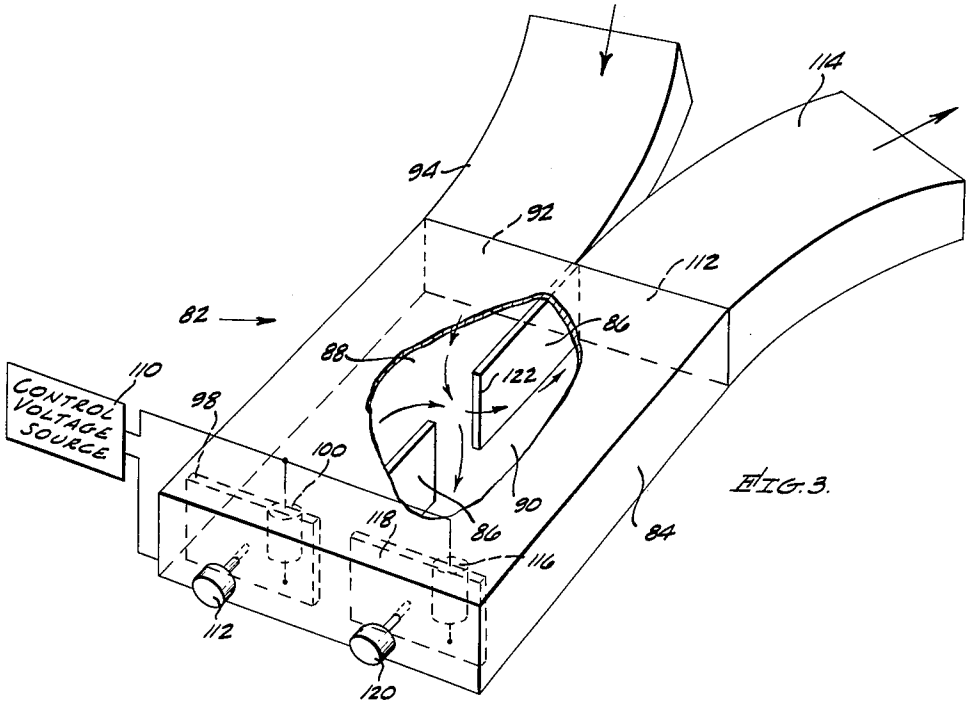



FIG. 3.

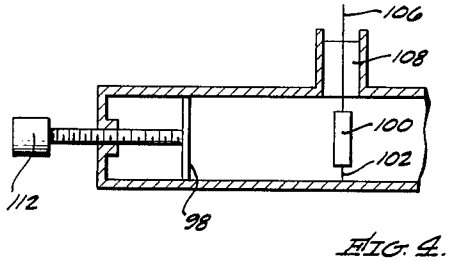



FIG. 4.

INVENTORS.
JACK MUNUSHIAN,
ROBERT H. HARDIN,
BY
Noel B. Hammond
AGENT

Feb. 15, 1966 J. MUNUSHIAN ETAL 3,235,820

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Original Filed Jan. 4, 1960 3 Sheets-Sheet 3

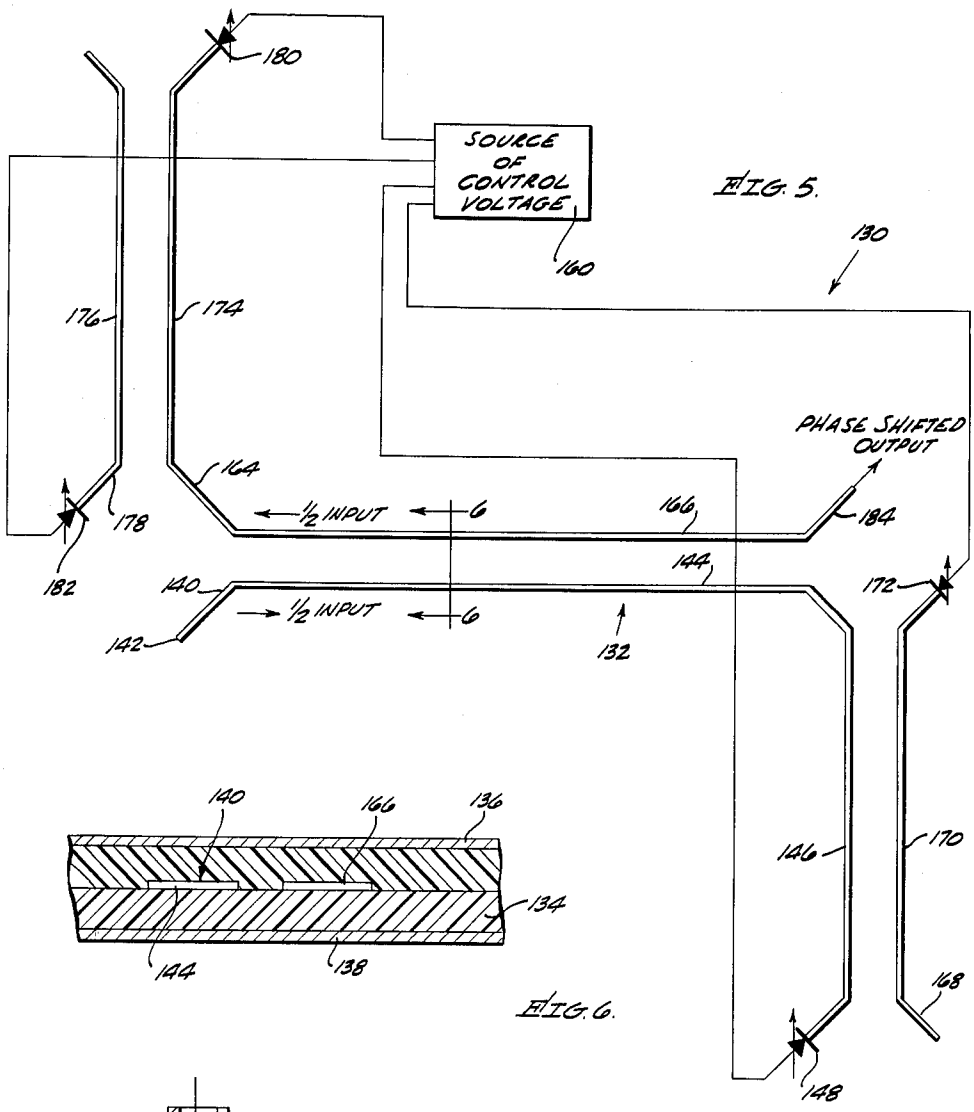



FIG. 5.




FIG. 6.

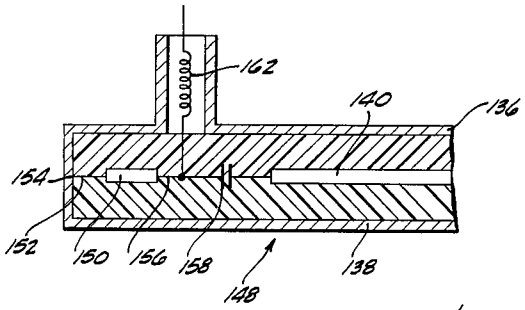



FIG. 7.

INVENTORS.
JACK MUNUSHIAN,
ROBERT H. HARDIN,
BY
Noel B. Hammond
AGENT.

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3,235,820

# ELECTRICALLY VARIABLE PHASE SHIFTER

Jack Munushian, Los Angeles, Calif., and Robert H. Hardin, Littleton, Colo., assignors to Hughes Aircraft Company, Culver City, Calif., a corporation of Delaware

Continuation of application Ser. No. 446, Jan. 4, 1960. This application Aug. 12, 1963, Ser. No. 301,576
4 Claims. (Cl. 333—31)

The present invention relates to phase shifters and, more particularly, to apparatus for shifting the phase of a wave in which the amount of phase shift is controlled electrically.

This is a continuation of a prior copending application Serial No. 446, filed January 4, 1960, now abandoned.

In the past there have been numerous attempts to devise satisfactory means for shifting the phase of electromagnetic energy at ultra high or microwave frequencies. In one form of phase shifter, a section of waveguide is provided with a reflector such as movable wall. Any energy incident upon the wall is reflected back along the waveguide. By mechanically moving this reflector axially along the waveguide, the distance over which the energy travels can be controlled. As a result, this in turn will control the phase of the reflected energy. Unfortunately, such systems are normally bulky and difficult to operate. Moreover, the inertia inherent in such a mechanical device limits the response time. In addition, as the wavelength of the energy decreases it becomes more difficult to obtain the required accuracy from such a phase shifter without employing excessive precision in producing the parts.

In another form of phase shifter, the gyromagnetic resonance characteristics of a ferrite material are employed for shifting the phase. In such devices a ferrite member is disposed in the path of the electromagnetic energy so that the energy will travel therethrough. By creating a steady magnetic field in the ferrite material the resultant gyromagnetic effects will cause the phase of the energy to be changed. Such phase shifters have normally required an excessively long length of transmission line and/or excessively large magnetic fields to provide the required amount of phase shifting. Such a magnetic field requires a considerable amount of power to maintain. Also, as the frequency of the energy increases there are increased losses in the ferrite material.

It is therefore an object of the present invention to provide a phase shifting device which is free of mechanically moving parts and which provides a maximum amount of phase shift while consuming a minimum amount of power.

In accordance with this and other objects of the invention, electrically variable capacitance elements are employed to reflect incident energy with a phase angle that is a function of the capacitance thereof. The electrically variable capacitance elements are incorporated in a network of intercoupled wave transmission elements which is arranged and adapted to provide solely reflected energy at an output terminal. In exemplary embodiments, the electrically controllable capacitance elements are reverse-biased semiconductor devices or the like, and the network of intercoupled wave transmission elements is a ring hybrid bridge circuit, a waveguide short-slot hybrid coupler, a plurality of strip transmission lines intercoupled by suitable juxtaposition of the conductive strips, or the like.

The following specification and the accompanying drawings describe and illustrate exemplary embodiments of the present invention. Consideration of the specification and the drawings will provide an understanding of the



invention, including the novel features and objects thereof. Like reference characters denote like parts throughout the figures of the drawings.

FIG. 1 is a diagrammatic view of one embodiment of the present invention;

FIG. 2 is a cross-sectional view of a portion of the embodiment of FIG. 1;

FIG. 3 is a perspective view of another embodiment of the present invention;

FIG. 4 is a cross-sectional view of a portion of the embodiment in FIG. 3;

FIG. 5 is a plan view of a network of conductive strips for a phase shifter employing strip transmission line;

FIG. 6 is a cross-sectional view taken substantially along the lines of **6—6** in FIG. 5; and

FIG. 7 is a cross-sectional view of the terminal end of the network of FIG. 5.

Referring now to FIG. 1 of the drawings, the present invention is embodied in a phase shifter **10** adapted to be employed in an ultra high frequency or microwave system for interconnecting an input device **14** and an output device **16** so that electromagnetic energy may be coupled therebetween with a variable phase. The input device **14** may be of any desired variety from which electromagnetic energy of the desired frequency range is available. The output device **16** may be of any variety suitable for utilizing the electromagnetic energy that is supplied thereto.

The present phase shifter **10** includes a plurality of individual units **18**, **20** and **22** that may be used separately or cascaded, as shown, so as to provide the desired range of phase shift. These units **18**, **20**, **22** which are preferably identical to each other may comprise hybrid rings, hybrid junctions, circulators, etc., employing any desired form of waveguiding means. In the present instance the first unit **18** comprises a hybrid ring **24** of coaxial transmission line wherein an outer conductor is disposed concentrically about an inner conductor and is spaced therefrom by a suitable dielectric medium.

The inner and outer conductors of the ring **24** are unbroken and free from any discontinuities so that electromagnetic energy may be propagated therearound in either direction with a minimum amount of loss.

The energy is supplied to the unit **18** by means of a coaxial cable **26** that has one end thereof connected to the input device **14**. The other end of the cable **26** has the inner and outer conductors connected to the inner and outer conductors, respectively, of the ring **24**. The energy is coupled out of the unit **18** by means of a coaxial cable **28** having its inner and outer conductors connected to the inner and outer conductors, respectively, of the ring **24** at a point located approximately one-third of the ring's circumference from the point at which power is supplied to the ring **24**.

The circumference of the ring **24** is preferably equal to approximately one and one-half electrical wavelengths at the frequency of the energy which is applied to the ring **24**. Thus, from the input **26** to the output **28** in a clockwise direction around the ring **24** is one-half wavelength while in the counterclockwise direction the energy travels a full wavelength. Consequently, the portions of energy propagating by these two paths arrive at the output **28** 180 degrees out of phase with each other. Thus there is a complete cancellation of the energy and no energy appears in the output cable **28** as a result of following such a direct route.

In addition to the input **26** and output **28**, a pair of arms **30**, **32** are connected to the ring **24** at predetermined locations. The first arm **30** comprises a section of coaxial cable that has the inner and outer conductors **34**, **36** (see FIG. 2), connected to the inner and outer

conductors, respectively, of the ring **24**. The arm **30** extends outwardly from the ring for a distance equal to one-quarter wavelength plus a distance "*a*." The arm **30** is preferably connected to the ring **24** midway between the input **26** and output **28** so as to be substantially one-quarter of a wavelength from each. The outer end of the arm **30** is terminated by a variable reactance device **38**. In the present instance the variable reactance device is a reversely biased semiconductor diode **40** which has a capacitance that varies as a function of the bias voltage thereacross.

The diode **40**, as may be seen in FIG. 2, is mounted in a holder **42** that includes an outer conductive case **44**. One end of this case **44** includes a flange **46** that is connected to a similar flange on the end of the outer conductor **36** of the arm **30**. The interior of the case **44** registers with the inside of the outer conductor **36** and forms a continuation thereof. The diode **40** is disposed axially in the center of the passage and has the conductive lead **48** on one end connected to the center conductor **34** of the arm **30**. The conductor **50** from the other end of the diode **40** extends through the center of a conductive end wall **52** so as to be connected thereto. The wall **52** is slidable within the case **44** so that it can be moved axially toward and away from the diode **40**. A screw adjustment **54** is provided for controlling the movement and position of the wall **52** relative to the diode **40**.

The center conductor **34** of the coaxial cable is connected to a control voltage source **56** by any suitable means. In the present instance a conductor **58** extends axially through the center of a half wave stub **60** and is connected to the center conductor **34** of the arm. It may be desirable to provide a choke **62** in the conductor **58** and a condenser **64** in the conductor **34** of the arm **30** to prevent loss of RF (radio frequency) energy to the voltage source and the leakage of D.C. (direct current) into the system **12**.

The position of the movable wall **52** is adjusted relative to the diode **40** to tune the total reactance of the diode **40** and the section of coaxial line therebehind to resonate at approximately the center of the frequency range in which it is desired to operate. The capacitance of the diode **40** for this tuning should be the capacitance at which the smallest amount of change in the bias voltage will produce the maximum amount of change of capacitance. It will be seen that when the movable wall **52** is properly adjusted, the diode **40** and wall **52** act as a tuned shorted half-wave stub. Consequently, the angle of the reflection coefficient is substantially 180 degrees at the resonant frequency.

Any electromagnetic energy that leaves the ring **24** and enters the arm **30** is propagated radially outward along the arm **30** toward the end thereof. When the energy reaches the diode **40** and the short circuit provided by the wall **52** therebehind, the energy is reflected back along the arm **30** toward the ring **24**. If the diode **40** has a high Q, i.e., the ratio of reactance to resistance is high, substantially complete reflection occurs and there is little or no loss of energy. The angle of the reflection coefficient is a function of the voltage across the diode **40**.

The second arm **32** is very similar to the first arm **30** in that it also comprises a section of coaxial cable that has the inner and outer conductors connected to the inner and outer conductors of the ring **24**. The second arm **32** is connected to the ring **24** at a point substantially diametrically opposite to the input and has a length equal to "*a*," i.e., it is one-quarter wavelength shorter than arm **30**.

The outer end of the arm **32** is terminated by means of a second variable reactance device comprising a diode **66** substantially identical to the variable capacitance diode in the first arm **30**. The diode **66** is mounted in a holder similar to the one illustrated in FIG. 2. The holder includes an adjustable wall and means for supplying a bias voltage to the diode **66**. It may thus be seen that any energy traveling radially outward along the arm **32** is reflected from the diode **66** and wall at the end of the arm **32** and the angle of the reflection coefficient is a function of the capacitance of the diode **66** which in turn is a function of the bias voltage thereacross.

It may thus be seen that the energy applied to the input cable **26** enters the ring **24** where it divides into two portions that propagate around the ring **24** in opposite directions. The portion of energy traveling clockwise arrives at the output **28** with a one-half wavelength delay while the portion traveling counterclockwise arrives at the output **28** with a delay of one full wavelength. Consequently, the energy is one-half wavelength out of phase so as to cancel and prevent this unreflected energy from appearing at the output **28**.

However, the portion of the energy propagating in a clockwise direction from the input **26** arrives at the first arm **30** with only one-quarter wavelength delay. The other portion of energy propagating in a counterclockwise direction is delayed by one and one-quarter wavelengths before arriving at the first arm **30**. Consequently, both portions of the energy are in phase when they arrive at the first arm **30** and enter into the arm **30**. Thus, energy is propagated radially outward toward the end of the arm **30**.

The energy arriving at the second arm **32** is delayed by three-quarters of a wavelength irrespective of which direction it travels around the ring **24**. Consequently, the energy enters the arm **32** and propagates radially outward toward the end where it is reflected back toward the ring **24**.

The energy that is reflected from the two diodes **40**, **66** at the ends of the arms **30**, **32** has a phase angle that may be varied by varying the bias across the diodes **40**, **66**. However, the energy that leaves the arms **30**, **32** has a phase angle that is also determined by the length of the arms **30**, **32**.

As previously stated, the first arm **30** is one-quarter wavelength longer than the second arm **32**. The energy thus experiences an additional delay of one-half wavelength in traversing the arm **30** in both directions. It may thus be seen that the energy that travels from the input **26** to the end of the first arm **30** and is reflected back into the ring **24** is returned to the input **26** with a delay of an integral wavelength (plus or minus the phase shift occurring at the point of reflection) irrespective of whether the energy travels in clockwise or counterclockwise directions. In addition, the energy that travels from the input **26** to the arm **32** so as to enter the second arm **32** and be reflected back to the input **26** is displaced by an odd multiple of half wavelengths (plus or minus the phase shift occurring at the point of reflection). This difference is a result of the one-quarter wavelength difference in the lengths of the arms **30**, **32** and prevents any reflected energy being propagated back into the input **26**, provided the coefficients of reflection are identical.

A similar analysis will show that the energy which is reflected from the diodes **40**, **66** and is returned to the ring **24** will arrive in phase at the output **28** and is propagated through the output **28** if the coefficients of reflection in the arms **30**, **32** are identical. It may thus be seen that all of the energy that enters the ring **24** from the input **26** is reflected from the diodes **40**, **66** and appears in the output **28**. The phase of this energy may then be readily varied by merely varying the bias across the diodes **40**, **66**.

In the event a greater range of phase shifting is required than can be obtained from a single unit, a plurality of substantially identical units may be connected in series or cascaded. In the present instance the input **70** to the second unit **20** is connected to the output **28** of the first unit **18**. This unit **20** includes a pair of variable capacitance diodes **72**, **74**, that are connected to the control voltage source **56**. The output **76** thereof is in turn connected to the input **78** of a succeeding unit **22** that also includes a pair of variable capacitance diodes **78**, **80** and has the output connected to the utilizing device **16**.

Each of these units **18, 20, 22** thus provides a phase shift of the energy therein in response to the bias from the voltage source **56**.

As an alternative, the embodiment of FIGS. 3 and 4 may be employed wherein the phase shifter **82** is particularly adapted for use in a microwave system that utilizes conventional rectangular waveguide. The phase shifter **82** is contained in a hollow coupling unit **84** that defines a large rectangular chamber having one side thereof open. A septum or partition **86** extends longitudinally of the chamber so as to divide it into two separate compartments **88, 90** that are substantially identical to each other.

The outer end of the first compartment **88** is open to form an input **92** interconnected with a first section of waveguide **94** for receiving electromagnetic energy therefrom. The interior cross section of this chamber **88** is preferably substantially identical with the interior cross section of the waveguide **94**. Thus, the energy flows from the waveguide **94** into the compartment **88** with no mismatching and/or development of standing waves.

The inner end of the compartment **88** is terminated by a variable reactance semiconductor device or diode **100** and a conductive wall **98** that is disposed therebehind. The conductive lead **102** from one side of the diode **100** is connected to the coupling unit **84**. The lead **106** from the other side of the diode **100** extends through a dielectric block **108** disposed in a wall of the coupling unit **84** so as to be electrically insulated therefrom. This lead **106** is connected to a suitable control voltage source **110** so that a reverse bias may be applied to the diode **100** and thereby control the capacitance thereof.

The wall **98** disposed behind the diode **100** preferably has a rectangular shape that fits the interior of the compartment **88** and forms a sliding fit therein. The wall **98** is secured to the end of a screw **112** that extends from the end of the coupling unit **84** so that the wall **98** may be moved axially of the compartment **88** toward and away from the diode **100**. This permits the impedance terminating the compartment **88** to be tuned to resonate at the frequency employed. This impedance is preferably so tuned when the diode **100** is biased to a condition which provides the maximum variation of capacitance with a minimum change in bias. Thus, if the diode **100** and the wall **98** therebehind have a high Q, substantially complete reflection occurs and there is little or no loss of energy. Moreover, the angle of the reflection coefficient is a function of the terminating capacitance which in turn is a function of the bias voltage across the diode **100**.

The second compartment **90** is substantially identical to the first compartment **88**. The outer end thereof is also open to form an output **112** that is interconnected with a second or output section of rectangular waveguide **114**. The compartment **90** and waveguide **114** are preferably of the same size and shape so that the energy may flow from the compartment **90** into the waveguide section **114** with little or no mismatch whereby no standing waves or reflections occur.

The inner end of the compartment **90** includes a diode **116** that is mounted transversely of the narrow dimension of the compartment **90** substantially identical to the first diode **100**. This diode **116** is disposed in a position corresponding to that of the first diode **100** and it is also connected to the control source **110**. Thus, the capacitance of the diode **116** may be varied simultaneously and identically with that of the first diode **100**. In addition, a movable wall **118** is mounted on a screw adjustment **120** so that the termination of the second chamber **90** may be tuned similar to the first chamber **88**.

The partition **86** which separates the two compartments **88, 90** includes an aperture **122** that forms a short-slot hybrid or Riblet coupler which interconnects the two compartments **88, 90** with each other. The aperture **122** couples the energy from one compartment **88** into the other compartment **90**. The energy which is thus coupled experiences a 90 degree shift in phase.

In operation, the energy propagated through the first section of waveguide **94** enters the input opening **92** and travels into the first chamber **88**. When this energy arrives at the aperture **122**, it divides into two substantially equal portions. One portion is coupled through the aperture into the second chamber **90**. This energy is shifted **90** degrees in phase and is propagated through the second chamber **90** toward the end thereof. The other portion continues on to the end of the first chamber **88**. When this energy arrives at the end of the chamber **88** it is reflected from the diode **100** and the wall **98** therebehind. The phase of the reflected energy is determined by the impedance of the termination. This, of course, is determined in part by the capacitance of the diode **100** which in turn is fixed by the bias voltage applied thereto by the voltage source **110**.

The reflected energy is propagated back through the chamber **88** toward the input **92**. When this energy arrives at the aperture **122** at least a portion thereof is coupled through the aperture **122** into the second chamber **90** with a 90 degree phase shift.

As previously stated, the portion of the energy that travels from the input **92** directly through the aperture **122** is shifted 90 degrees and is propagated toward the terminal end of the chamber **90**. This energy is then reflected from the termination past the aperture **122**. A portion thereof is coupled into the first chamber **88** with a phase shift of 90 degrees. Thus, if the angles of the coefficients of reflection from the terminal ends of the two compartments **88, 90** are equal, the energy coupled back through the aperture **122** is 180 degrees out of phase with the energy remaining in the first chamber **88**. As a result, there is a cancellation of these two portions of energy and no energy is reflected back into the first section of waveguide **94**.

The energy that is reflected from the termination of the first chamber **88** and coupled through the aperture **122** is in phase with the energy that is reflected from the termination of the second chamber **90**. Thus, all of the energy in the second chamber **90** is in phase and is propagated into the second section of waveguide **114**.

It will thus be seen that all of the energy in the first section of waveguide **94** which is propagated through the input **92** into the phase shifter **82** is reflected from one or the other of the terminations at the inner ends of the chambers **88, 90** and is then discharged through the output and into the second section of waveguide **114**. Since this energy has been reflected from one or the other of the terminations it has a phase angle that is determined by the impedance of the terminations. Thus, since the capacitances of the diodes **100, 116** are controlled by the voltage thereacross, the phase angle of the energy may be readily varied by regulating the output of the control voltage source **110**.

As a further alternative, the embodiment of FIGS. 5, 6 and 7 may be employed. This phase shifter **130** is particularly adapted for use in a microwave system utilizing so-called strip transmission line wherein electromagnetic energy is guided from one location to another by means of conductive strips that are disposed between a pair of conductive plates and separated therefrom by a dielectric material.

This phase shifter **130** includes a network **132** of center conductors that are mounted on a dielectric material **134** and are arranged between a pair of uniformly spaced conductive plates **136, 138**.

The network **132** includes a first conductive strip **140** which has one end thereof arranged to form an input **142** adapted to be connected to a source of electromagnetic energy. In addition, the conductor **140** also includes a substantially straight first coupling section **144** and a substantially straight second coupling section **146**. The other end of the conductor **144** includes a termination **148** that causes microwave energy to be reflected therefrom.

The termination **148** includes a variable reactance de-

vice such as a variable capacitance diode **150** similar to those in the foregoing embodiments. The conductive lead **152** from one end of the diode is electrically connected to an end wall **154** formed by the outer conductors **136, 138.** The conductive lead **156** from the other end of the diode **150** is coupled to the end of the center conductor **140** by a condenser **158** so as to prevent the loss of D.C. into the rest of the system. The lead **156** is also connected to a variable voltage source **160** by a choke **162** which prevents the loss of RF energy from the microwave system. It may thus be seen that energy arriving at the end of the center conductor **140** is reflected from the diode **150** and the angle of the coefficient of reflection is a function of the capacitance of the diode **150.**

A second conductor **164** is provided which includes a straight portion **166** that is juxtaposed to the coupling section **144** of the first conductor **140.** These two sections **144, 166** are sufficiently close to each other to cause approximately one-half of the energy traveling from the input **142** toward the termination **148** of the conductor **140** to be coupled into the second conductor **164.** The half of the energy remaining in the first conductor **140** continues along the conductor **140** toward the second coupling section **146.**

A third conductor **168** is provided which includes a coupling section **170** that is closely spaced to the second coupling section **146.** These two sections **146** and **170** are juxtaposed so that approximately half of the energy remaining in the first conductor **140** is coupled into the third conductor **168** and the rest remains in the first conductor **140.** One end of the third conductor **168** is terminated in a variable capacitance diode **172.** The diode **172** is similar to the diode **150** and is connected to the voltage source **160** in the same manner. The other end of the conductor **168** is terminated with a short circuit.

The second conductor **164** includes a second substantially straight coupling section **174** which is juxtaposed to a coupling section **176** in a fourth conductor **178** so that substantially one-half of the energy in the second conductor **164** is coupled into the fourth conductor **178.** The end of the second conductor **164** is terminated in a variable capacitance diode **180.** This diode **180** is mounted similar to diode **150** and is biased by the source **160** to control the capacitance thereof.

The fourth conductor **178** is substantially identical to the third conductor **168** in that one end thereof is terminated by a variable capacitance diode **182** and the other end is terminated with a short circuit.

In operation, microwave energy is supplied to the input **142** of the first conductor **140** so that it is propagated therealong. As this energy is propagated across the first coupling portion **144,** approximately one-half of the energy is coupled into the second conductor **166** while the remaining one-half of the energy continues to follow the first conductor **144.** When this energy arrives at the second coupling section **146,** half of the remaining energy, i.e., one-quarter of the input energy, is coupled into the third conductor **168** and a corresponding portion continues on to the termination of the first conductor **140** where it is reflected from the diode **150.**

The energy in the third conductor **168** is reflected from the diode **172** at the end thereof and is coupled back into the first conductor **140.** The lengths of the conductors **140, 168** and couplers are such that the energy reflected from the diodes **150, 172** cancels except the energy which is being propagated back along the first conductor **140.**

The energy in the second conductor **166** is divided at the coupling sections **174, 176** so that the energy is reflected from the diodes **180, 182** and is propagated back along the second conductor **164.** The lengths of the conductors **140, 166, 168, 178** are such that the various portions of the energy reflected from the diodes **150, 172, 180, 182** are all in phase at the output **184** and, accordingly, may be coupled from the output to a utilizing device. The energy that would otherwise be coupled from the second conductor **164** back to the first conductor **140** would be out of phase with the energy remaining in the first conductor and would cause cancellation of the energy. Thus, none of the reflected energy appears at the input **142.**

It may be seen that all of the energy that arrives at the output **184** has been reflected from one or the other of the four diodes **150, 172, 180, 182.** Thus, the phase of the energy at the output **184** is a function of the angles of the coefficients of reflection from the various diodes. This in turn is a function of the capacitances of the diodes. Thus the control voltage source is effective to bias the diodes so as to provide the desired capacitances and therefore the desired phase shift. It should be noted that since the energy is reflected equally from four separate diodes, the amount of power that may be phase shifted is four times the amount of power that an individual diode can safely handle.

Thus, there has been described several embodiments of an electrically variable phase shifter which is free of mechanically moving parts and which provides a maximum amount of phase shift while consuming a minimum amount of power by utilizing electrically variable capacitance elements incorporated in a network of intercoupled wave transmission elements. In this manner applied input energy is reflected from the capacitance elements with a phase angle that is a function of the capacitance thereof and appears at the output terminal.

Although several embodiments of the invention have been shown and described, other variations may be made and it is intended that the foregoing disclosure is to be considered only as illustrative of the principles of the invention and not construed in a limiting sense.

What is claimed is:

**1.** An electrically variable phase shifter comprising:

(a) a hybrid bridge circuit having an input terminal, an output terminal, and a pair of wave transmission arms;

(b) a source of input wave energy coupled to said input terminal to provide points of maximum and minimum input energy in said hybrid bridge circuit, said wave transmission arms being at different points of maximum input energy, said output terminal being at a point of minimum input energy;

(c) electrically controllable capacitive reactance means terminating ends of said wave transmission arms for providing reflected energy in said hybrid bridge circuit, the phase of said reflected energy with respect to said input energy being a function of the reactance of said electrically controllable capacitive reactance means;

(d) means disposed in one of said wave transmission arms to provide an additional 90° phase delay to energy propagated in either direction therein with respect to the other of said wave transmission arms to provide a point of minimum reflected energy at said input terminal and a point of maximum reflected energy at said output terminal;

(e) and electrical control means coupled to said electrically variable capacitive reactance means for controlling the phase of said reflected energy.

**2.** An electrically variable phase shifter comprising:

(a) a ring hybrid bridge circuit including a ring portion and an input member, an output member, and a pair of phase control members connected to said ring portion;

(b) said phase control members being connected to said ring portion at separate points where energy applied at said input member and traveling in opposite directions around said ring portion arrives in phase;

(c) electrically variable capacitive reactance means for reflecting incident energy disposed at the ends of said phase control members remote from said ring portion;

(d) one of said phase control members being ¼ wavelength longer than the other of said phase control members to provide cancellation of reflected energy at said input member;

(e) said output member being connected to said ring portion at a point where energy applied at said input member cancels and where energy reflected from said phase control members is in phase for coupling solely reflected energy out of said ring portion;

(f) and electrical control means coupled to said electrically variable capacitive reactance means for equally varying the reactance thereof to cause equal variation of the coefficient of reflection of said phase control members.

3. An electrically variable phase shifter comprising:

(a) a ring hybrid bridge circuit including a ring portion and an input member, an output member, and first and second phase control members connected to said ring portion;

(b) said ring portion being an odd number of half wavelengths in circumference;

(c) said output member being connected to said ring portion at a point where energy from said input member traveling in opposite directions around said ring portion arrives out of phase and cancels;

(d) said phase control members being connected to said ring portion at separate points where energy from said input member traveling in opposite directions around said ring portion arrives in phase;

(e) electrically variable capacitive reactance means terminating the ends of said phase control members remote from said ring portion for causing reflection of energy entering said phase control members, said variable capacitive reactance means providing equal reactances to cause equal coefficients of reflection in said phase control members;

(f) said second phase control member being ¼ wavelength longer than said first phase control member for causing energy reflected into said ring portion by said second phase control member to be out of phase at said input member and in phase at said output member with respect to energy reflected by said first phase control member, whereby reflected energy enters said output member;

(g) and electrical control means coupled to said electrically variable capacitive reactance means for equally varying the reactance thereof to cause equal variation of the coefficient of reflection of said phase control members, whereby the phase of the energy in said output member is varied with respect to the phase of the energy in said input member.



4. An electrically variable phase shifter comprising:

(a) a ring hybrid bridge circuit formed of coaxial transmission line having a center conductor and an outer conductor, said ring hybrid bridge circuit including a ring portion and an input line, an output line, and first and second phase control lines connected to said ring portion;

(b) said ring portion being 1½ wavelengths in circumference;

(c) said output line being connected to said ring portion a distance of ½ wavelength around said ring portion from the connection of said input line to said ring portion;

(d) said first phase control line being connected to said ring portion a distance of ¾ wavelength around said ring portion from the connection of said input line to said ring portion;

(e) said second phase control line being connected to said ring portion at a point ¼ wavelength distant from the connections of said input and output lines;

(f) said second phase control line being ¼ wavelength longer than said first phase control line;

(g) mechanically movable short circuit means terminating the ends of said phase control lines remote from said ring portion;

(h) electrically variable capacitive reactance means disposed at the ends of said phase control lines remote from said ring portion and connected in series between the center conductor and said mechanically movable short circuit means;

(i) and electrical control means coupled to said electrically variable capacitive reactance means for controlling the reactance thereof.

**References Cited by the Examiner**

UNITED STATES PATENTS

| | | | |
|---|---|---|---|
| 2,834,876 | 5/1958 | Pritchard | 333—31 |
| 2,854,645 | 9/1958 | Arditi | 333—97 |
| 2,874,276 | 2/1959 | Dukes | 333—84 |
| 2,905,902 | 9/1959 | Strandberg | 333—31 |
| 2,908,813 | 10/1959 | Morrison | 333—31 |
| 2,914,671 | 11/1959 | De Lange | 333—11 |
| 2,962,716 | 11/1960 | Englemann | 343—720 |
| 3,051,844 | 8/1962 | Beam et al. | 307—88.5 |

OTHER REFERENCES

Uhlir: Proc. IRE, vol. 46, pages 1099–1115, June 1958.

HERMAN KARL SAALBACH, *Primary Examiner.*