Nov. 11, 1969 J. BLASS ET AL 3,478,284

MICROWAVE PHASE SHIFTER INCLUDING ADJUSTABLE TUNED REACTANCE MEANS

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FIG. 1.

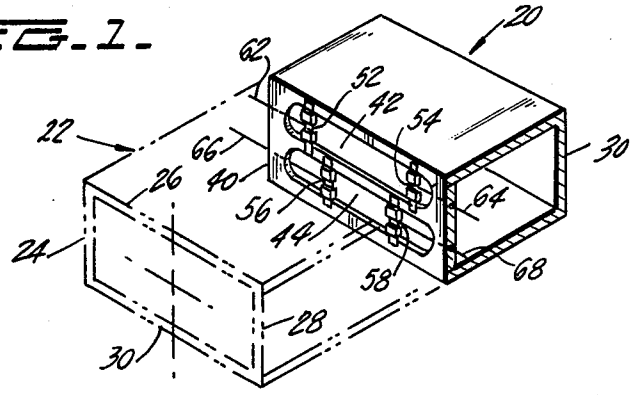


FIG. 2.

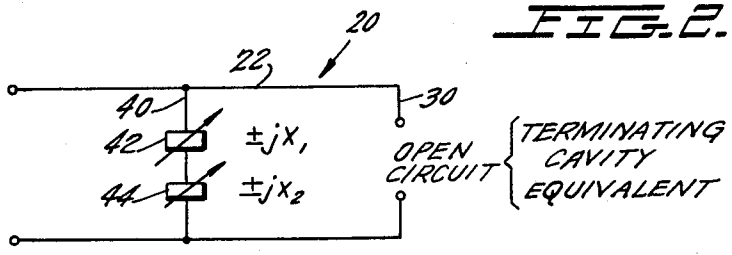
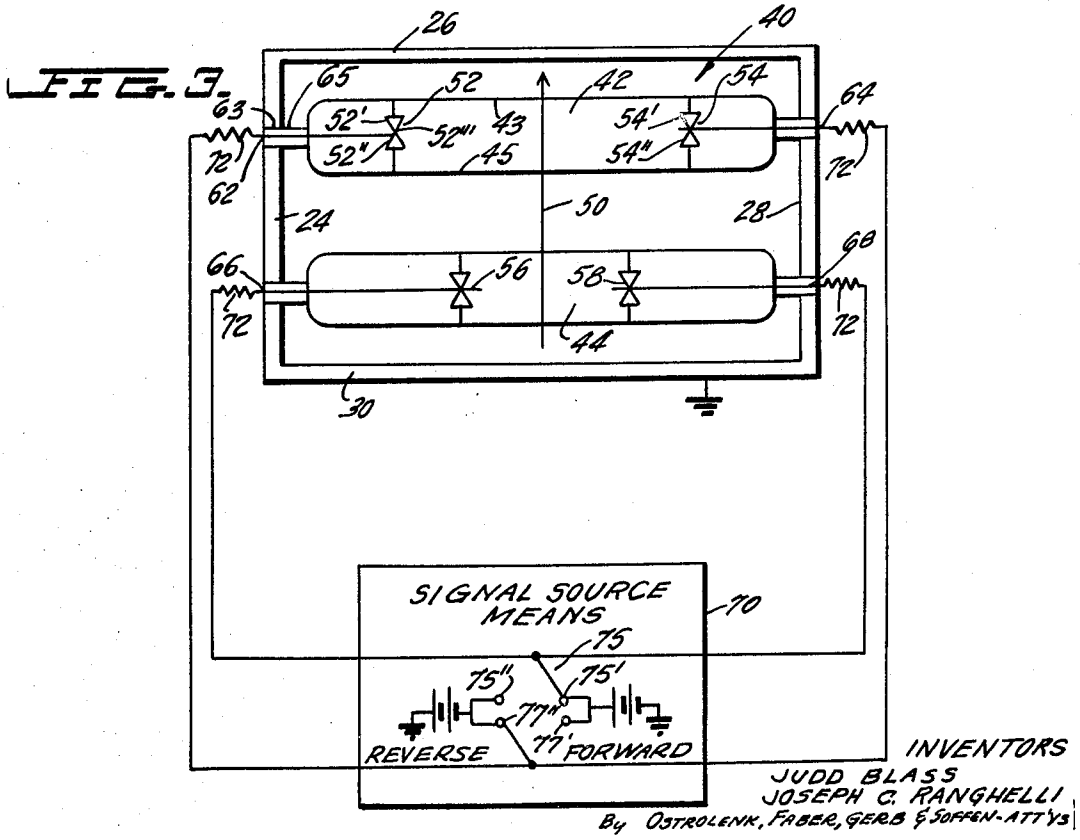


FIG. 3.



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FIG. 2a.

SLOT 42	SLOT 44	SLOT 42 REACTANCE	SLOT 44 REACTANCE	TOTAL INS. REACTANCE	PHASE SHIFT
OPEN	OPEN	$-j1$	$-j1.415$	$-j2.415$	0
SHUT	OPEN	$+j1$	$-j1.415$	$-j.415$	90°
OPEN	SHUT	$-j1$	$+j1.415$	$+j.415$	180°
SHUT	SHUT	$+j1$	$+j1.415$	$+j2.415$	270°

FIG. 4.

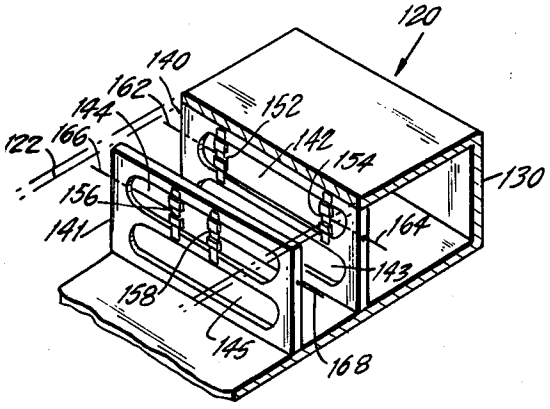


FIG. 5.

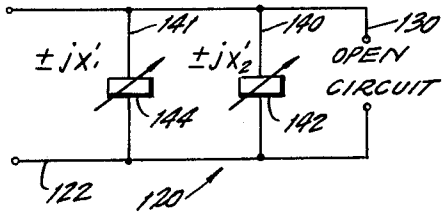
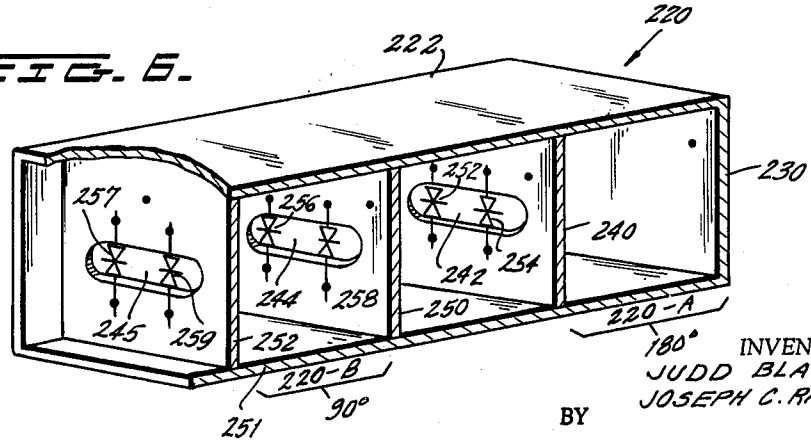


FIG. 6.



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MICROWAVE PHASE SHIFTER INCLUDING ADJUSTABLE TUNED REACTANCE MEANS

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FIG. 7

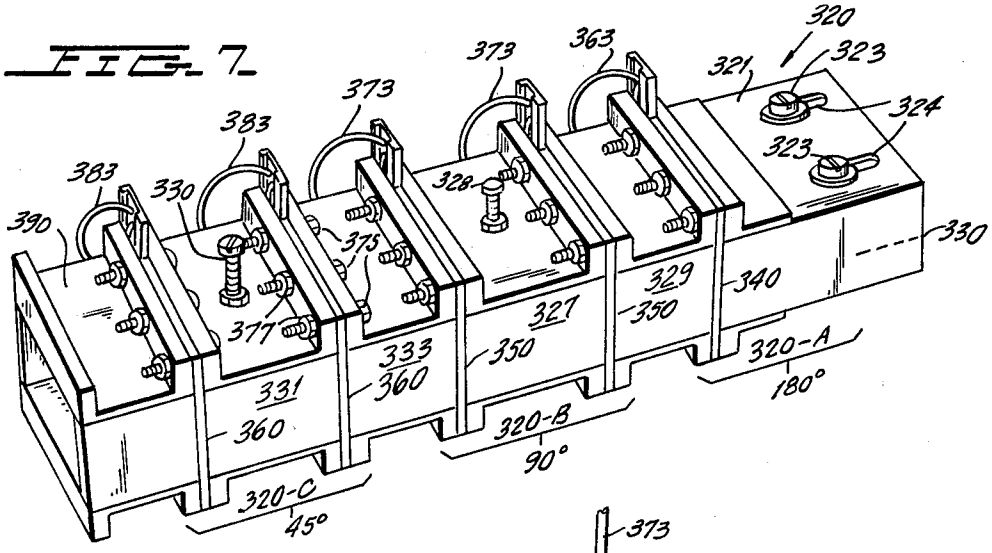


FIG. 9

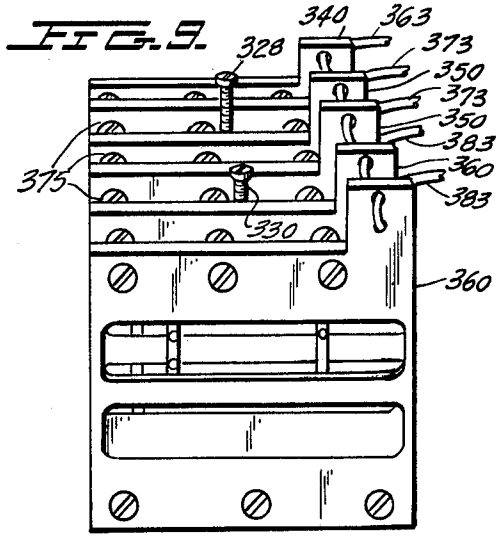


FIG. 11

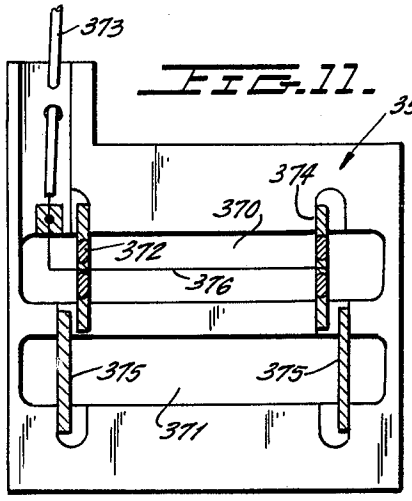


FIG. 10

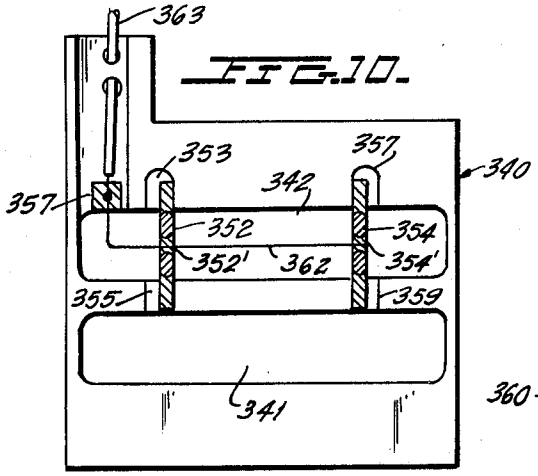
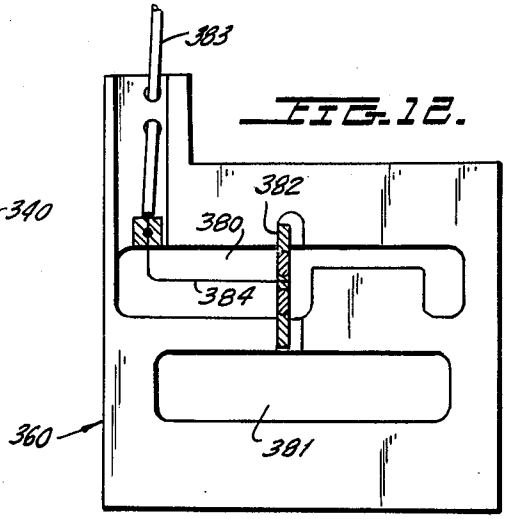


FIG. 12

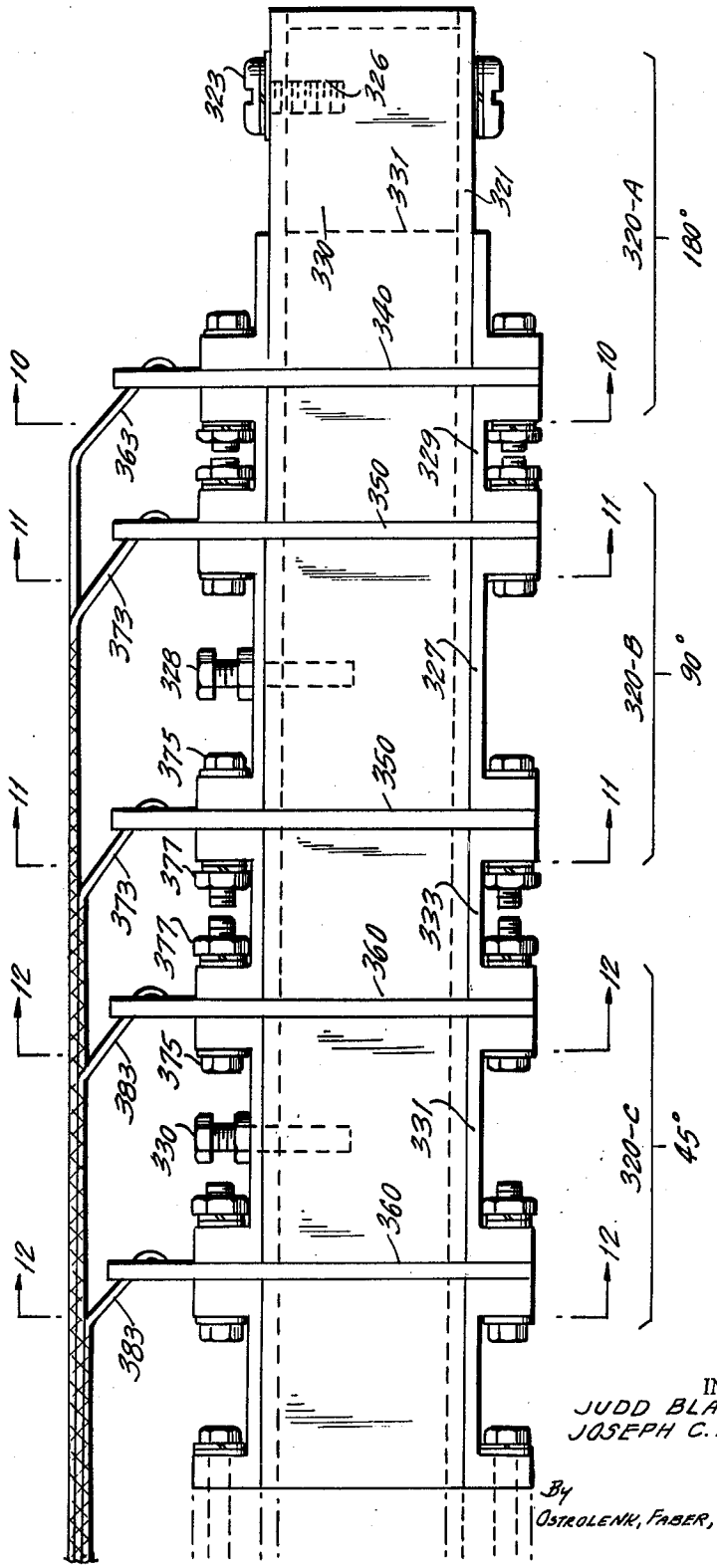


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MICROWAVE PHASE SHIFTER INCLUDING ADJUSTABLE TUNED REACTANCE MEANS

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FIG. 8.



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FIG. 13.

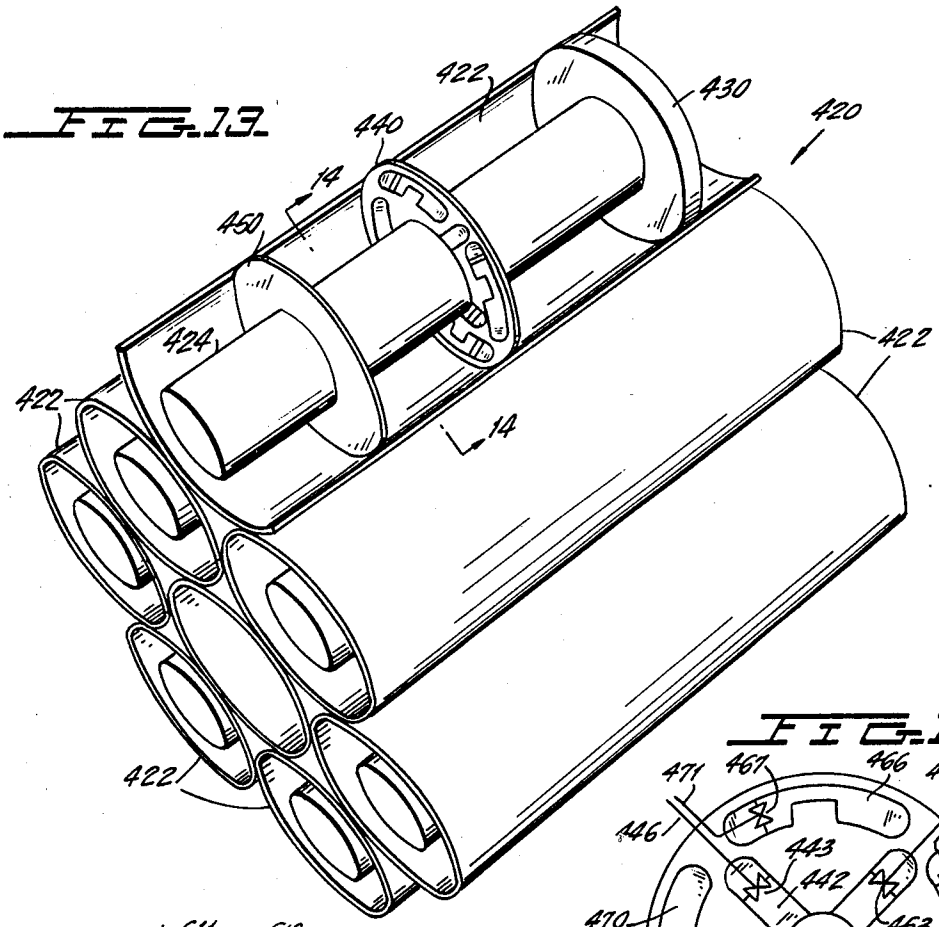
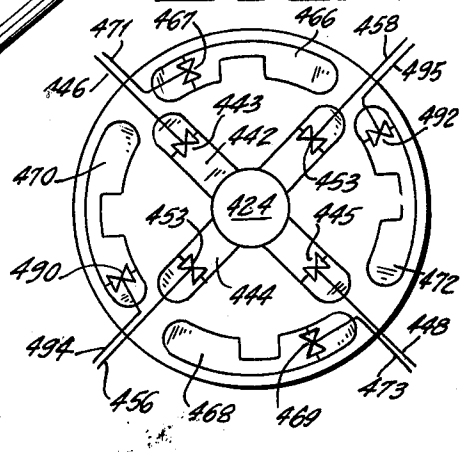


FIG. 14.



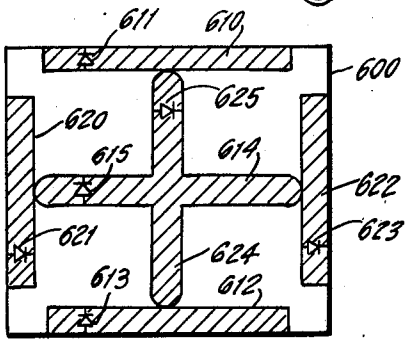


FIG. 16.

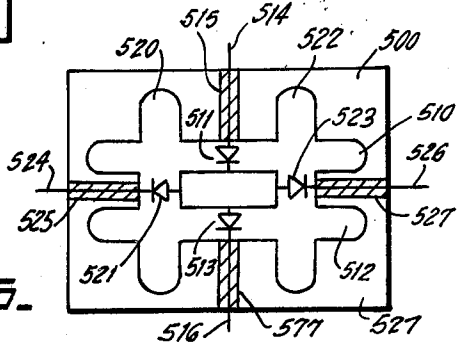


FIG. 15.

United States Patent Office 3,478,284
Patented Nov. 11, 1969

3,478,284

MICROWAVE PHASE SHIFTER INCLUDING ADJUSTABLE TUNED REACTANCE MEANS

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Int. Cl. H01p 1/18
U.S. Cl. 333—98 14 Claims

ABSTRACT OF THE DISCLOSURE

An electrically switchable microwave phase shifter is described which utilizes an adjustable tuned reactance means to adjustably vary the phase condition of the associated microwave signal. This adjustable tuned reactance is provided by a planar iris means (which is shown as one or more individual iris members in the various illustrative embodiment) including slotted openings having an electrically actuable switching means. The switching means is shown as diode elements positioned in the slotted openings, which are changed between their blocking and conducting states to alter the reactance magnitudes offered by the iris means. Linearly polarized and dual polarized embodiments are described.

Our invention relates to microwave phase shifter devices, and more particularly to such phase shifters which will provide a rapid adjustment of the signal phase between predetermined values, with low power loss, and may be designed to handle high average and peak power signals within a compact assembly.

In a variety of microwave systems, the need arises to adjustably vary the phase of the associated microwave signal. As for example, U.S. Patent No. 3,274,601, issued Sept. 20. 1966, in the name of Judd Blass, entitled "Antenna System With Electronic Scanning Means," and assigned to the assignee of the instant invention, shows one such application wherein the phase shifter of the instant invention has demonstrated particularly advantageous operation. The antenna system shown in that patent includes a reflective surface formed of an adjacently arrayed plurality of waveguide signal channels. Each of the waveguide signal channels includes a phase shifter which must rapidly adjust the phase of its associated microwave signal between predetermined values (e.g., in the order of nanoseconds). As shown in that patent, the phase shifter in each of the individual waveguide signal channels includes a plurality of longitudinally spaced diode members which may be individually switched between their blocking and conducting states. As longitudinally successive ones of the diodes are switched to their conducting states, a longitudinally displaced short is presented across the waveguide signal channel, thereby altering the effective physical length of the waveguide, and thereby introducing a predetermined path differential of its associated microwave signal. This path differential provides the adjustment of signal phase. A similar phase shifter utilizing a plurality of longitudinally spaced diode members along one end of a waveguide is also shown in co-pending U.S. patent application Ser. No. 230,358, filed Oct. 15, 1962, in the name of Judd Blass, entitled "Antenna System" now U.S. Patent No. 3,316,553, and also assigned to the assignee of the present inventoin.

A variety of mechanical phase shifters are also known in the art for adjustably varying the phase shift of an associated microwave signal. As an example, adjustable shorting plungers are known whereby an actual physical movement of the shorting plunger within the waveguide is required to vary the physical length of the guide, thereby resulting in a phase shift of its associated microwave signal. However, such devices are rather slow-acting and do not lend themselves to the type of antenna system described in aforementioned U.S. Patent No. 3,274,601.

The phase shifter of our invention is substantially simpler in construction than the previously known devices, and is capable of handling higher average and peak power loads while providing extremely rapid phase shift adjustments with a high degree of accuracy and with a very low power loss. These advantageous results are achieved by the provision of a novel adjustable tuned reactance means, placed within a waveguide.

The adjustable tuned reactance means is provided by one or more planar iris members which are constructed to offer a substantially pure reactance to the propogated microwave signals within the desired frequency band of operation. Typically, the planar iris members include tuned slotted openings having electrical switching means, such as diode means placed across the slotted openings. By switching selected ones of the diode means between their blocking and conducting states, the reactance of the tuned iris is varied between predetermined magnitudes.

In accordance with the various illustrative embodiments of our invention, one planar iris member is positioned a quarter wavelength away from the shorted end of the waveguide. Such a shorted waveguide terminus will effectively by an open circuit at the planar iris, spaced a quarter wavelength therefrom. Hence, the pure reactance of the iris will cause substantially complete microwave power reflection. By selective control of the diode means, so as to vary the specific tuned reactance magnitude provided by the planar iris between predetermined magnitudes, the phase condition of the microwave signal will be varied at the planar iris location. Such phase variation will correspondingly vary the phase condition of the microwave signal along the entire waveguide. That is, by switching the pure reactance value at the planar iris, the phase of the microwave signal will be varied as if the effective electrical length of the waveguide has been changed, e.g., as by movement of the shorting plunger in the prior art mechanical phase shifter, or by activating a longitudinally displaced diode short in the arrangement shown in aforementioned U.S. Patent Nos. 3,274,601 and 3,316,553.

The basic concept of our invention lends itself to providing a variety of phase adjustments for linearly polarized or orthogonally polarized signals (including circularly polarized signals). As an example, in accordance with one embodiment of our invention, a single planar iris member is provided, having a pair of slotted openings, each of which includes switchable diode means. The tuned reactance magnitude provided by one of the slotted openings is switchable between plus or minus jx_1, corresponding to the blocking and conducting states of its diode means, while the tuned reactance magnitude of the other slotted opening is switching between plus or minus jx_2. These reactance magnitudes are in series such that four different combinations of reactances are obtainable by the single planar iris means, which may be represented by the expressions: $+jx_1+jx_2$ $+jx_1-jx_2$ $-jx_1+jx_2$ $-jx_1-jx_2$. By proper design of the slotted openings and diode placement, these reactances may effectively provide phase shift of 0°, 90°, 180°, and 270° over the desired frequency band of operation (or any other desired phase shifts).

As a modification thereof, instead of providing both of the adjustable slotted openings within a single iris member, a second planar iris member may include one of the diode actuated slotted opening. The tunable reactance provided by the second iris member is selected and located relative ot the first iris member, such that their parallel sum will combinedly provide the desired reactance magnitudes for effectuating the required microwave signal phase shifts. This arrangement is particularly advantageous

where smaller waveguide sizes would make it difficult to include both of the diode actuated slots within a single iris member. The use of a multiplicity of iris members advantageously provides increased bandwidth capabilities and power handling.

In accordance with another embodiment of our invention, which has exhibited particularly favorable bandwidth capabilities, the over-all phase shifter is constructed of a cascaded plurality of differential phase shifters adjacently located along the waveguide, each of which includes the novel tuned reactance means of the instant invention. As an example, one tuned iris phase shift assembly may provide phase shift of either 0° or 180°. An adjacently located and separately switched phase shift assembly may have its tuned iris reactance magnitudes designed so as to effect either a 0° or a 90° phase shift of the same microwave signal. Similarly, a third adjacently located and separately switched phase shift assembly may be provided having tuned iris reactance magnitudes for shifting the microwave signals either 0° or 45°. Hence, by selective actuation of the diode switching means contained in the slotted openings of each of the tunable iris assemblies, a differential phase shift can be provided in 45° increments, between 0° and 315°.

In accordance with other embodiments of our invention, the slotted openings may be constructed to offer a tuned reactance to orthogonally related components of a microwave signal supported within a single guide. Such othorgonally related components may, for example, be propagated within a square guide or circular guide.

As an extremely advantageous aspect of our invention, the electrical input signals which provide the switching of the diode means between their blocking and conducting states offer negligible interference with the microwave signal propagation. More specifically, the diode means is positioned in the slotted opening such that the connecting wire for presenting the switching signal thereto is disposed within the waveguide in a direction generally perpendicular to the E vector orientation of the propagated microwave signal. This orientation of the connecting wire is preferably obtained by arranging the switchable diode means in pairs of elements, the anode treminals of which are connected to opposed, spaced walls of the planar iris slotted openings, and the cathode terminals of which are connected to a common junction, physically located intermediate the opposed walls of the slotted opening. The iris, and hence the diode anode terminals, is connected to ground potential. The connecting wire from the common junction passes through the waveguide wall to a switching signal source means, external to the waveguide. This signal source means typically provides either a reverse voltage of sufficient magnitude to bring the diode pair into a blocking condition, or a forward current of sufficient magnitude to bring the diode pair into an appreciable conducting condition.

It is therefore seen that an essential concept of our invention resides in the provision of a tuned reactance means within a waveguide, and includes means for switching the reactance magnitude thereof between predetermined values to effectively vary the phase of the microwave signal within the waveguide.

It is therefore seen that a primary object of our invention is to provide an improved microwave phase shifter.

A further object of our invention is to provide a microwave phase shifter wherein stationarily located tuned reactance means are electrically switched to vary their reactance magnitude and effectively vary the phase of the associated microwave signals.

Another object of our invention is to provide a means of adjustably varying the phase shift of a microwave signal by switching the magnitudes of a tuned reactance between predetermined values.

An additional object of our invention is to provide such a microwave phase shifter in which the adjustable reactance is provided by tuned planar iris means, including slotted openings containing diode elements which are switched between their blocking and conducting states to effect the desired variation of reactance magnitude.

Still a further object of our invention is to provide such a phase shifter wherein the switching signal inputs to the diode members are presented by connecting wires disposed in the waveguide to have a negligible interference to the microwave signal propagation.

Still another object of our invention is to provide a phase shifter for microwave signals, which includes a plurality of cascaded differential phase shifters, including separately tuned iris assemblies which are individually controllable to provide a stepped function of signal phase shift.

Still an additional object of our invention is to provide such an improved phase shifting device which may be designed to operate in conjunction with linearly or dual polarized wave signals.

Yet a further object of our invention is to provide an improved microwave phase shifter which is rapid-acting, exhibits low power loss, and is capable of handling high power signals within a compact assembly.

These, as well as other objects of our invention, will become readily apparent upon a detailed analysis of the following description and drawings in which:

FIGURE 1 shows, in simplified form, one embodiment of our invention, operable in conjunction with linearly polarized waves, which includes a pair of series associated tuned reactances within a single iris member.

FIGURE 2 schematically shows the operation of the phase shifter shown in FIGURE 1.

FIGURE 2*a* summarizes in table form the various series reactance magnitudes and accompanying microwave signal phase shifts obtainable with the phase shifter of FIGURES 1 and 2.

FIGURE 3 schematically shows the manner in which the switching signals may be presented to the diode means within the tuned iris, in a preferable manner which minimizes interference with the propagated electromagnetic wave signal.

FIGURE 4 is another embodiment of our invention, partially cut away, wherein the tuned reactances are provided by a pair of parallel associated individual panar iris members.

FIGURE 5 schematically shows the operation of the phase shifter shown in FIGURE 4.

FIGURE 6 shows still another form of the phase shifter of the type shown in FIGURE 4, but wherein cascaded sections of separately tuned iris assemblies are provided.

FIGURE 7 is a perspective view of a phase shifter constructed in accordance with the theoretical concepts of our invention, and including a plurality of cascaded separately tuned sections.

FIGURE 8 is a longitudinal view of the microwave phase shifter shown in FIGURE 7.

FIGURE 9 is a perspective view of the phase shifter of FIGURES 7 and 8, looking along the line **12—12** of FIGURE 7.

FIGURE 10 is a cross-sectional view along the line **10—10** of FIGURE 8 showing the dimensional configuration of one of the cascaded tuned iris assemblies.

FIGURE 11 is a cross-sectional view looking along either of the lines **11—11** of FIGURE 8, showing the dimensional configuration of another of the cascaded tuned iris assemblies; and

FIGURE 12 is a cross-sectional view along either of the lines **12—12** of FIGURE 8, showing the dimensional configuration of still another one of the cascaded tuned iris assemblies.

FIGURE 13 is a perspective view of still another form of a shifter, constructed in accordance with the theoretical concepts of our invention, adaptable for a circularly polarized signal.

FIGURE 14 is a cross-sectional view along the line **14—14** of FIGURE 13, showing the construction of the tuned iris means utilized therein.

FIGURE 15 shows another arrangement for a tuned iris assembly in accordance with our invention, designed for dual polarized signals within a square waveguide.

FIGURE 16 shows still another form of a tuned iris assembly in accordance with our invention, for dual polarized orthogonally related signals within a square waveguide.

Referring initially to FIG. 1, the phase shifter **20** constructed in accordance with our invention, includes a waveguide **22**, having internal walls **24**, **26**, **28** and **30** defining a generally rectangular internal volume, which is adapted to efficiently support microwave signals within a desired frequency band of operation. More specifically, as is known in the art, microwave energy is propagated in association with an electromagnetic field, and its propagation within a waveguide must satisfy certain mathematical conditions imposed by Maxwell's equations. The satisfaction of these requirements result in particular geometrical configurations of varying electric and magnetic field, capable of existing in a particular waveguide, each such configuration being known as a mode. Each mode can propagate through a waveguide only if its frequency is higher than a particular cut-off value. This value will depend upon the geometric configuration of the electromagnetic field and the waveguide dimensions. The mode having the lowest cut-off frequency for a particular waveguide is nomenclated the TE_{10} mode. The rectangular cross-section of waveguide **22** typically has a 2:1 ratio between its long walls **30**, **26** and short walls **24**, **28**, this ratio being termed the aspect ratio. In such a waveguide, the cut-off wave length of the dominant TE_{10} mode will be equal to twice the long dimension. This dominant TE_{10} mode has its E field vector orientated parallel to walls **24**, **28** and the orthogonally related H field parallel to walls **30**, **26**.

The waveguide **20** is terminated by a short circuit shown as **30**. In accordance with our invention, a pure reactance provided by planar iris member **40** is stationarily located within the waveguide **22** a quarter wavelength away (at the mean operating frequency) from shorted termination **30**. Planar iris member **40** includes first and second slotted openings **42**, **44**, respectively. Positioned within slotted opening **42** is a switchable diode means comprising pairs **52**, **54** of individual diode elements. Positioned within slotted openings **44** is a similar diode means comprising pairs **56**, **58** of individual diode elements.

The diode means within each of the slotted openings **42**, **44** preferably includes two such diode pair assemblies to provide increased power capabilities, and an improved arrangement for presenting the externally originated switching signals thereto via connecting wires **62**, **64**, **66**, **68**, as will henceforth be discussed in conjunction with FIG. 3. While this diode arrangement has been found to provide particularly advantageous overall operating results, it should be understood that the basic concept of our invention is inclusive of other electrical switching means, such as a single pair of diodes within each of the slotted openings, or only a single diode element.

The slotted openings are of a dimensional configuration, and the diodes properly placed therein with respect to the propagated signal energy, such that iris means **40** will present a substantially pure reactance at its waveguide location, having a matched impedance with respect to the waveguide impedance. As is known in the microwave art, the shorted terminus **30**, separated a quarter wavelength away from the pure reactance provided by iris means **40**, will electrically function as an open circuit at the location of planar iris **40**. A waveguide so terminated by the pure reactance of iris member **40** causes substantially complete power reflection. However, the phase of the reflected microwave signal will depend on the magnitude of this reactance. Therefore, by proper choice of the reactance provided by planar iris member **40**, the phase condition of the associated microwave signal can be controlled.

According to our invention, the tuned reactance provided by iris member **40** is given a multiplicity of magnitudes by the electrical switching of the diode means located within slotted openings **42**, **44**. That is, as diode means **52**, **54** are switched between their blocking and conducting states, the tunable reactance provided by slotted opening **42** will be switched between values which may be mathematically represented as $+jx_1$ and $-jx_1$, respectively. Similarly, the switching of diode means **56**, **58** between their blocking and conducting states switches the tuned reactance provided by slotted opening **44** between values which may be mathematically represented as $+jx_2$ and $-jx_2$, respectively. The reactance magnitudes provided by the individual slots **42**, **44** are in series as schematically shown in FIG. 2.

The diode means in slotted openings **42**, **44** may be individually switched between their blocking and conducting states. Thus, four conditions of reactance provided by the tunable reactance means **40** are possible, with these four conditions being summarized in the table of FIG. 2*a*. By proper selection of the slotted opening configuration and diode locations, the reactance magnitudes may be designed to provide stepped reactance magnitudes corresponding to microwave signal phase shifts of 0°, 90°, 180° and 270°. Slot **42** provides a reactance of either $+j1$ and slot **44** a reactance of $+j1.415$. It should naturally be understood that these values are given for illustrative purposes, with other reactance magnitudes and accompanying phase shifts being obtainable by proper design of the slotted openings and diode placement.

Reference is now made to FIG. 3 which shows a preferable arrangement for presenting the switching signals to the diode means located within the tunable iris slotted openings. The microwave energy propagating within waveguide **20** will be in the dominant TE_{10} mode, with the E field vector being parallel to the short dimension of the waveguide as shown by the arrow **50**. In order to minimize the interference of the electrical switching signals to the diode means with such microwave signal propagation, the switching signals should be connected to the diode means **52–58** by connecting wires disposed in a direction generally perpendicular to arrow **50**. We adavntageously achieve this by having each of the diode means include a pair of diodes, such as **52'–52''** of diode means **52**. The utilization of such a pair of diodes also advantageously serves to increase the peak tower handling capabilities of the phase shifter. Preferably another pair of diodes such as **54'**, **54''** is located within the slotted opening **42** to also increase the average power handling capabilities of the phase shifter.

The iris member **40** is connected to electrical ground, such that the opposed walls **43**, **45** of slotted opening **42** will also be at ground potential. The anode terminals of the individual diode elements **52'**, **52''** are electrically connected to the opposed walls **43**, **45**. Hence, the diode anode terminals will be at ground potential. The cathode terminals of the diode pair are connected to a common junction, designated as **52'''**. This common junction is located intermediate the opposed walls **43**, **45** of the slotted opening **42**. The switching signals to the diode pairs are presented by connecting wires shown as **62**, **64**, **66**, **68**, which pass through the walls to the waveguide and iris planar member. As for example, connecting wire **62** to diode pair **52** passes through aligned apertures **63**, **65** in waveguide wall **24**, and planar member **40**, respectively. The switching signal connecting wire includes an internal portion which is connected to common junction **52'''**. It is to be noted that the internal portion of connecting wire **62** (as well as the internal portion of the connecting wires **64**, **66**, **68** leading to the other diode pairs) is disposed generally perpendicular to the direction of the E vector orientation **50** to minimize interference with the electromagnetic field.

The switching signal connecting wires are connected to a signal source means, generally shown as **70**. Signal source means includes appropriate switching circuitry for rapidly presenting either a reverse voltage signal of sufficient magnitude to individually switch the diode pairs to their blocking condition, or a forward current of sufficient magnitude to individually switch the diodes to their appreciable blocking state. This switching is functionally shown by **75**, **77**. However, it should be understood that in the actual operational system, the switching will typically be rapidly effected by means of computer controlled circuitry. As schematically represented in FIG. 3, the forward bias is presented to the switch **75**, contact **75'**, such that the diode means **56**, **58** of slotted opening **44** are in their conducting state. A reverse voltage is shown presented to the terminal **77''** of switch **77**, such that the diode means **52**, **54** of slotted opening **42** are in their blocking state. Thus, slotted opening **42** will be shut, and slotted opening **44** will be opened, corresponding to the condition tabulated in FIG. 2*a* for providing a 90° phase shift. In a typical phase shifter constructed in accordance with our invention, the individual diode elements may typically be commercially available high voltage switching diodes. These diodes may be rapidly switched (in the order of nano seconds) between blocking and conducting by a reverse bias of 400 volts, or a forward bias of 100 milliamperes, respectively.

FIGURE 4 shows a modified form of phase shifter **120** in accordance with our invention. The significant difference between phase shifter **120** and the previously discussed phase shifter **20** is that the two switchable diode actuated slotted openings are now located in two separate planar iris members **140** and **141**. The use of two separate planar iris members serves to increase the band width and power handling abilities. This arrangement is particularly advantageous in smaller waveguides, e.g. X band.

Planar iris member **140** is spaced a quarter wavelength away from the shorted terminus **130** of waveguide **122**. Planar iris **140** includes a slotted opening **142**, having two sets of switchable diode pairs **152**, **154**. Diode pairs **152**, **154** are switched between their blocking and conducting states, preferably in the manner shown in conjunction with FIG. 3, by signal inputs provided by connecting wires **162**, **164**. Planar iris member **140** is also shown including another slotted opening **143**, which does not have switchable diode means. The reactances provided by tuned reactance member **140** when diode means **152**, **154** is switched between its blocking and conducting states, represented by plus and minus jx'_2 in electrical schematic FIG. 5, may typically be 0 or infinity. Such a reactance will add in parallel with the reactance provided by tuned reactance member **141**, and is properly spaced from iris **141** will provide a reactance of plus or minus $j1$ at the latter location.

Iris **141** includes a slotted opening **144**, having diode pairs **156**, **158**, respectively. Diode pairs **156**, **158** are switched between their blocking and conducting states by signal inputs provided by the connecting wires **166**, **168**. The reactance provided by the slotted opening **144** in conjunction with slotted opening **145** will be such as to provide a pure reactance of plus or minus $j1.415$ at its waveguide location. Thus, the individual switching of the diode means provided in slotted openings **142** and **144** will permit the parallel sum of the reactances to assume the values shown in Table 2*a* and will thereby provide phase shifts of 0°, 90°, 180° or 270°. It should naturally be understood that the slot configurations, diode locations and reactance magnitudes above discussed are given as an illustrative example, and the theoretical concepts of our phase shifter permit the embodiment of FIG. 4 to yield various other adjustable phase conditions.

FIG. 6 schematically shows the physical relationship of another form of phase shifter in accordance with our invention, which includes a cascaded assembly of individual phase sections. Each of the phase sections include switchable tuned reactance means constructed to provide a differential phase shift. As for example, one such phase section may provide a differential phase shift of the microwave signal between 0 or 180°, while the adjacent phase section will provide a differential phase shitf of either 0 or 90°. Thus, the cumulative phase shift provided by the two cascaded sections will permit phase shifts of 0°, 90°, 180° or 270°. As a further modification of this concept, as will be subsequently discussed in conjunction with FIGS. 7–12, an additional phase section may be provided to provide a phase shift of either 0 or 45°. Hence, phase shifts between 0 and 315°, in 45° increments can be achieved.

The cascaded arrangement of differential phase shift sections permits greater power handling capabilities and increased band width with rapid switching of the phase shifter being achieved in a particularly advantageous fashion; as for example, the phase shifter shown in FIG. 6 requires a two-bit input, while the phase shifter which will be subsequently discussed in conjunction with FIGS. 7–12 requires a three-bit input. These inputs may be generated by a digital source.

As shown in FIG. 6, the phase shifter **220** includes a 180° differential phase shift section **220**–A, which comprises planar iris member **240**, adjacent the waveguide shorted terminus **230**; and a 90° differential phase shift section **220**–B comprising planar iris members **250**, **252**.

Planar iris **240** includes diode pairs **252**, **254**, located within slotted opening **242**. The slotted opening **242** is of a configuration which in conjuuction with the diode placements **252**, **254** will provide either a 0° or 180° phase shift as the diode means **252**, **254** are switched between their blocking and conducting states.

The 90° phase shift section **220**–B which physically precedes the 180° phase shift section **220**–A within waveguide **222** is a transmission type phase shifter. That is, the incoming wave signals will pass through the 90° differential phase shift section, be reflected by the 180° phase shift section, and then pass a second time through the 90° phase shift section. Thus, the microwave signal is phase shifted twice by the phase section provided by reactance members **250**, **252**. Therefore, the one way differential phase shift of this phase section must be 45°. Since this phase section is a transmission device, it must also be designed to present a match to the waveguide (i.e., VSWR=1.00). The phase section **220**–B designed to achieve the required action is a filler composed of two diode tuned iris members **250**, **252** separated by a particular length **251** of waveguide. Iris member **250** includes a slotted opening **244** having a spaced pair of diode assemblies **256**, **258**. Similarly, iris member **252** includes a slotted opening having a spaced pair of diode assemblies **257**, **259**. When the bias signal to the diode means **256**, **257**, **258** and **259** is such that the diodes are in their blocking condition, the irises will be an open circuit across the line. This will be equivalent to a matched length of waveguide. When the diode means are forward biased to their appreciable conducting state, both irises **250**, **252** will present a specific value of tuned reactance which when separated by the proper length **251** of waveguide will become a matched filter at the center frequency of the desired operating band. Thus, by proper selection of the tuned reactances provided by iris means **250**, **252**, a phase shift between the biased states is achieved while maintaining a matched transmission line.

FIGS. 7–12 illustrate a cascaded phase shifter constructed in accordance with the theoretical concepts of our invention, and which has demonstrated successful operation at C band. Phase shifter **320** includes a longitudinally adjustable short **330** at one end thereof. The positioning of the short surface **331** along waveguide section **321** is obtained by screw means **323**, the forward ends of which en-

gage the shorting elements at aperture **326**, and which are longitudinally positioned in elongated openings **324**. The 180° differential phase section **320**–A includes the short **330** in conjunction with iris member **340**, the latter being shown in greater detail in FIG. 10. Longitudinally adjacent the 180° differential phase shift section **320**–A is a 90° differential phase shift section **320**–B of a transmission type, which includes a pair of similar iris members **350** (as shown in FIG. 11), separated by waveguide section **327**. The 90° differential phase shift section is separated from planar iris member **340** by a waveguide section **329**. Adjacent section **320**–B is a 45° transmission type differential phase section **320**–C, including tuned reactance means **360**, spaced by waveguide section **331**. The 45° phase shift section is spaced from the 90° differential phase shift section by waveguide section **333**. Tuning screws **328**, **330** are shown located within waveguide sections **327**, **331** to permit an adjustment for variation of diode parameters, and waveguide constructional manufacturing tolerances. The individual waveguide sections **321**, **329**, **327**, **331**, **333** are connected, in the conventional manner, by machine screws generally shown as **375**, which are tightened by bolts **377** which also serve to maintain the respective planar iris means between the indicated waveguide sections.

Each of the planar iris members have slotted openings of a particular configuration which, in conjunction with the iris separation and diode placement, provide the required reactance magnitudes to achieve the designated differential phase shifts.

More specifically, iris member **340** which operates in conjunction with the shorted terminus surface **331** to provide the 180° phase shift includes a pair of slotted openings **341**, **342**, respectively. Slotted opening **342** includes two pairs of diode assemblies designated as **352** and **354**, respectively. The diode assemblies **352** and **354** are welded to the transversely extending locating openings **353**, **355**, **357**, **359**, respectively. Each of these diode assemblies include a pair of diodes, the anodes of which are electrically connected to the planar iris member at their weld connection, and the cathodes of which are connected to common junctions **352'**, **354'**. The cathode junction points are electrically connected to switching input wire **362**. It is to be noted that wire **362** extends across the slotted opening in a generally horizontal direction and thereby presents minimum interference with the propagated microwave signal, as discussed above, in conjunction with FIG. 3. Switching input connecting wire **362** is preferably connected through an RF trap, which includes capacitor **357**, before emerging from the waveguide at **363**.

Iris member **350** of the transmission type 90° differential phase shift section includes slotted openings **370**, **371**, respectively. Slotted opening **370** includes diode assemblies **372**, **374**, each of which are welded to the iris member. Each of the diode assemblies includes a pair of individual diode elements, the anodes and cathodes of which are electrically connected in the manner schematically shown in FIG. 3. Slotted opening **371** is shown including shorting strips **375**, in order to provide the desired reactance magnitude. The switchable input to the diode assemblies **372**, **374** is provided via externally extending wire **373** to the internally located connecting portion **376**.

Iris member **360** of the cascaded 45° differential phase shift section include slotted openings **380**, **381**. Slotted opening **380** includes a single diode pair **382**, the switching input thereto being presented via connecting wire **383** to the internally located connecting portion **384**.

The diode assemblies, shorting strips and capacitors are preferably located in cavities, within the iris members, which serve the two-fold purpose of positioning their components and presenting a flat surface to the waveguide sections. The iris members and the waveguide sections are preferably silver-plated to improve their soldering and welding characteristics, to improve microwave performance and to prevent galvanic corrosion between the phase shifter **320**, typically constructed of brass, and the associated radiating elements (not shown) connected thereto, via waveguide section **390**, which may be typically constructed of aluminum.

The above-described embodiment of FIGS. 7–12 has been designed to operate at C band, having a frequency band of operation between 5450 and 5850 kmc. This phase shifter can handle 25 watts average power and 5 kilowatts peak power. Typical units tested have demonstrated maximum insertion loss of less than 1.5 db over the band width and an average loss of less than 1.3 db, with such insertion loss including the sum of diode loss, waveguide loss, scatter loss and phase error loss.

Reference is now made tod FIGS. 13 and 14 to show a phase shifter **420**, in accordance with our invention, designed for dual polarized microwave signals propagated within a circular waveguide **422**. An arrayed plurality of such waveguides **422** are shown in FIG. 13, forming a dual polarized antenna surface to provide an array antenna of the general type shown in aforementioned U.S. Patent No. 3,274,601. An antenna system constructed with such dual polarized phase shift elements can be interchangeable circular or linear on transmit, and circular linear or dual linear polarized on receive. Such a dual polarized system preferably presents the possibility of operating a radar system simultaneously in a searchlight mode for one polarization and another mode e.g., track while scan, in the other polarization. Such a dual polarized beam can also find application in monopulse systems.

The phase shifter **420** is shown loaded with a dielectric rod **424** to decrease the cut-off frequency compatible to the rest of the antenna system. Tuned iris member **440** includes slotted openings having switchable diode means for effecting a change in its reactance magnitude. Member **450** at the other side of iris **440** is provided to improve the impedance match from the phase shifter to free space.

Considering the orientation of the slotted openings provided in iris member **440** it must be recognized that the E vectors of the dual polarized signal can have any orientation. The tunable iris **440** which is utilized must be operable with any E vector orientation. That is, the reactance provided by the iris must be independent of E vector orientation. Thus, each of the single slots of the linear phase shifter must now be replaced by two slotted openings to operate upon arbitrary orthogonal components of the E field vector. One such slot means operating on orthogonal components is provided by the slotted openings **442**, **444**. Another such set of orthogonally related slotted openings is provided by **466**, **468** and **470**, **472**. The inclusion of both such slotted opening arrangements within the single iris member **440** is analogous to two independently adjustable slotted openings operable upon each of the arbitrary orthogonal components.

Slotted opening **442** includes switchable diode pairs **443**, **445**, respectively, having switching signal input connectors **446**, **448**, respectively. Slotted opening **444** includes a similar set of diode pairs **453**, **455**, connected to the external signal source by connector means **456**, **458**, respectively. The associated set of slotted openings **466**, **468** include diode pairs **467**, **469**, respectively, which are connected to the external switching source by connecting wires **471**, **473**, respectively. Orthogonally related slotted openings **470**, **472** include diode means **490**, **492** which are connected to the external source by connecting means **494**, **495**. It is to be noted that the connecting means pass through their respective slotted opening in a direction perpendicular to the associated E field orientation so as to minimize the interference with the microwave signal propagation. The diode means of the slotted openings may be individually switched so as to independently control the phase of the orthogonally related signal components.

FIGURE 15 shows a switchable tuned reactance means which may be utilized in conjunction with dual polarized signals (of the TE_{10} and TE_{01} modes) supported within

a square waveguide. Slotted openings **510, 512** provide a switchable tuned reactance to one of the modes (TE_{10}) and orthogonally orientated slotted openings **520, 552** provide a switchable tuned reactance to the orthogonally related mode (e.g., TE_{01}). Slotted openings **510, 512** include switchable diode elements **511, 513**, respectively. Orthogonally related slotted openings **520, 522** include switchable diode elements **521, 523**, respectively. The switching signal inputs to diodes **511, 513** are provided by connecting wires **514, 516** which pass through apertures **515, 517**, respectively, within the iris member. Similarly the connecting wire inputs **524, 526** to diode elements **521, 523** pass through apertures **525, 527** of the iris member. By individually switching the respective diodes between their blocking and conducting states, the tuned reactance, provided by iris member **500**, to the orthogonally related components may be individually varied so as to individually control the phase of each of said orthogonal components.

Reference is made to FIG. 16 which shows another form of iris means **600** which may be used for phase shifting orthogonally related components supported within a square waveguide. One of the orthogonally related components is switched between predetermined phase conditions by a pair of slotted openings represented as **610, 612** and **614**, respectively. The orthogonally related component of microwave energy is similarly controlled by switching the reactance provided by slotted openings **620, 622** and **624**. Associated slotted openings **610, 612** include switchable diode means schematically shown as **611, 613**, respectively. Although these diode means are shown as single diodes, this is essentially for purposes of simplicity with such single diodes being replaced by one or more diode pairs as discussed above in conjunction with FIG. 3. The other slotted opening **614** for adjusting the phase of this orthogonal component includes diode means **615**. Orthogonally orientated slotted openings **620, 622** include diode means **621, 623**, respectively. The other slotted openings **624** for effectively controlling the phase of this orthogonally related microwave signal includes diode means **625**. The signals to the diodes permit individual switching of the slotted openings associated with each of the orthogonally related components of microwave energy.

It is therefore seen that our invention provides a microwave phase shifter which is operable in conjunction with linear or dual polarized microwave signals, for adjustably varying the phase of the microwave signals between predetermined phase conditions. Such phase adjustment is preferably obtained in an extremely rapid manner, with a low power loss and a broad frequency band of operation. Although the foregoing description includes preferred embodiments of our invention, it should be recognized that many variations and modifications will now become obvious to those skilled in the art, and we therefore prefer to be limited not by the specific disclosure herein but only by the appended claims.

The embodiments of the invention in which an exclusive privilege or property is claimed are defined as follows:

1. A phase shifter of the signal reflected variety for adjustably varying the phase of microwave signals within a desired frequency band of operation, comprising:

a waveguide having enclosed walls defining a longitudinally extending internal volume having a cross-sectional area adapted to efficiently support microwave signals within the desired frequency band;

at least a first planar iris stationarily located at a predetermined first waveguide position within said waveguide, and extending across said internal volume in a plane transverse to the longitudinal waveguide direction;

said planar iris including tuned reactance means for presenting a substantially pure reactance at said first waveguide position;

means for causing substantially complete reflection of the microwave signals at said first waveguide position;

switch means operatively associated with said tuned reactance means for switching the reactance thereof between predetermined values, including at least a first and second reactance magnitude;

said first reactance magnitude of a predetermined value to effect, at said first waveguide position, a first phase condition of microwave signals within the desired frequency band;

said second reactance magnitude of a predetermined value to effect, at said first waveguide position, a second phase condition of microwave signals within the desired frequency band;

whereby said switching means switches the tuned reactance magnitude of said first planar iris to adjustably vary the microwave signal phase at said first reflected waveguide position, and throughout said waveguide between predetermied first and second phase conditions; with

(a) said tunable reactance means including at least a first slotted opening;

(b) said slotted opening of an appreciable extent in a first direction, and of a substantially lesser extent in a second direction perpendicular to said first direction;

(c) said second direction corresponding to the E vector orientation of the microwave signal;

(d) said switching means including diode means in said slotted opening and switching signal input means;

(e) said switching signal input means circuit connecting said diode means to a switching signal source means external of said internal volume for switching said diode means between blocking and conducting states;

(f) said diode means operatively related to said tuned reactance means for switching said tuned reactance means between said first and second reactance magnitudes, corresponding to said blocking and conducting states, respectively;

(g) said switching signal input means including a connecting wire having an internal portion extending into an intermediate region of said slotted opening between said diode means and the waveguide wall, and an external portion passing through an opening in said wall, external of said internal volume;

(h) said connecting wire internal portion disposed along said first direction, perpendicular to the E vector orientation of the microwave signal, whereby the electrical signal input to said switch means offers negligible interference to the microwave signal propagation.

2. A phase shifter in accordance with claim **1**:

(a) said diode means including at least one pair of first and second diode elements, each including anode and cathode terminals;

(b) said diode pair positioned along said slotted opening and extending in said second direction between spaced first and second walls of said slotted opening;

(c) the anode terminal of said first diode element circuit connected to said first wall and the anode terminal of said second diode element circuit connected to said second wall, said first and second walls being at a common electrical potential;

(d) the cathode terminals of said first and second diode elements circuit connected to a common junction, said switching signal connecting wire circuit connected to said common junction.

3. A phase shifter in accordance with claim **1**:

(a) said diode means including at least a first and second pair of individual diodes:

(b) each of said pairs including first and second diode elements having anode and cathode terminals;

(c) said diode pairs spaced in said first direction along said slot, and extending in said second direction be-

tween spaced first and second portions of said slotted opening;

(d) the anode terminals of said first diode elements circuit connected to said first wall and the anode terminals of said second diode elements circuit connected to said second wall, said first and second walls being at a common electrical potential;

(e) the cathode terminals of said first diode pair connected to a first common junction, and the cathode terminals of said second diode pair connected to a second common junction, the internal portion of said switching signal connecting wire extending between said common junctions, along said first direction.

4. A phase shifter of the signal reflective variety for adjustably varying the phase of mcirowave signals within a desired frequency band of operation, comprising:

a waveguide having enclosed walls defining a longitudinally extending internal volume having a cross-sectional area adapted to efficiently support microwave signals within the desired frequency band;

planar iris means stationarily located within said waveguide, and extending across said internal volume in a plane transverse to the longitudinal waveguide direction;

said planar iris means including tuned reactance means for presenting a substantially pure reactance;

means for causing substantially complete reflection of the microwave signals at an intermediate first waveguide location of said planar iris means;

switching means operatively associated with said tuned reactance means for switching the reactance thereof between a predetermined plurality of reactance magnitudes;

each of said reactance magnitudes of a predetermined value to effect, at the first waveguide location of its associated planar iris, a selectable phase condition of the microwave signals within the desired frequency band;

said tunable iris means including at least a first and second slotted opening;

said switching means including diode means in each of said first and second slotted openings, nad switching signal input means;

said switching signal input means circuit connecting said diode means to a switching signal source means external of said internal volume for switching said diode means between blocking and conducting states;

said diode means operatively related to said tuned reactance means for switching said tuned reactance means between predetermined ones of its reactance magnitudes, corresponding to said blocking and conducting states respectively;

said first slotted opening characterized as providing an iris reactance of jx_1, corresponding to its diode means being in the conducting state, and $-jx_1$ corresponding to its diode means being in the blocking state;

said second slotted opening characterized as providing an iris reactance of jx_2 corresponding to its diode means being in the conducting state, and $-jx_2$ corresponding to its diode means being in the blocking state;

said switching signal input means including separate inputs to the diode means of said first and second slotted openings, such that the reactances provided by said first and second slotted openings may be individually switched between reactance magnitudes represented as:

$$+jx_1+jx_2$$
$$+jx_1-jx_2$$
$$-jx_1+jx_2$$
$$-jx_1-jx_2$$

with

(a) each of said slotted openings of an appreciable extent in a first direction, and of a substantially lesser extent in a second direction perpendicular to said first direction;

(b) said second direction corresponding to the E vector orientation of the microwave signal;

(c) said switching signal input means including a connecting wire having an internal portion extending into an intermediate region of said slotted opening between said diode means and the waveguide wall, and an external portion passing through an opening in said wall, external of said internal volume;

(d) said connecting wire internal portion disposed along said first direction, perpendicular to the E vector orientation of the microwave signal, whereby the electrical signal input to said switch means offers negligible interference to the microwave signal propagation.

5. A phase shifter as set forth in claim 4:

(a) said diode means including at least one pair of first and second diode elements in said slotted openings;

(b) each of said diode elements including anode and cathode terminals;

(c) each of said diode pairs positioned along its respective slotted opening and extending in said second direction between spaced first and second walls of said slotted opening;

(d) the anode terminal of said first diode element circuit connected to said first wall and the anode terminal of said second diode element circuit connected to said second wall, said first and second walls being at a common electrical potential;

(e) the cathode terminals of said first and second diode elements circuit connected to a common junction, said connecting wire internal portion connected to said common junction.

6. A phase shifter of the signal reflective variety for adjustably varying the phase of microwave signals within a desired frequency band of operation, comprising:

a waveguide having enclosed walls defining a longitudinally extending internal volume having a cross-sectional area adapted to efficiently support microwave signals within the desired frequency band;

planar iris means stationarily located within said waveguide, and extending across said internal volume in a plane transverse to the longitudinal waveguide direction;

said planar iris means including tuned reactance means for presenting a substantially pure reactance;

means for causing substantially complete reflection of the microwave signals at an intermediate first waveguide location of said planar iris means;

switching means operatively associated with said tuned reactance means for switching the reactance thereof between a predetermined plurality of reactance magnitudes;

each of said reactance magnitudes of a predetermined value to effect, at the first waveguide location of its associated planar iris, a selectable phase condition of the microwave signals within the desired frequency band;

said tunable iris means including at least a first and second slotted opening;

said switching means including diode means in each of said first and second slotted openings, and switching signal input means;

said switching signal input means circuit connecting sadi diode means to a switching signal source means external of said internal volume for switching said diode means between blocking and conducting states;

said diode means operatively related to said tuned reactance means for switching said tuned reactance means between predetermined ones of its reactance magnitudes, corresponding to said blocking and conducting states respectively;

said first slotted opening characterized as providing an iris reaction of jx_1, corresponding to its diode means

being in the conducting state, and $-jx_1$ corresponding to its diode means being in the blocking state;

said second slotted opening characterized as providing an iris reactance of jx_2 corresponding to its diode means being in the conducting state, and $-jx_2$ corresponding to its diode means being in the blocking state;

said switching signal input means including separate inputs to the diode means of said first and second slotted openings, such that the reactances provided by said first and second slotted openings may be individually switched between reactance magnitudes represented as:

$$+jx_1+jx_2$$
$$+jx_1-jx_2$$
$$-jx_1+jx_2$$
$$-jx_1-jx_2$$

with

(a) said first slotted opening located within a first iris member at said first waveguide position, and said second slotted opening located within a second iris member at a second waveguide position;

(b) said second waveguide position having a predetermined longitudinal spacing from said first waveguide position.

7. A phase shifter as set forth in claim **6**:

(a) said waveguide having first and second ends;

(b) shorting means located at said first end;

(c) said first waveguide position spaced a quarter wavelength away from said shorting means, with said shorted first end acting as an open circuit at said first waveguide position.

8. (a) A phase shifter of the signal reflective variety for adjustably varying the phase of microwave signals within a desired frequency band of operation, comprising:

(b) a waveguide having enclosed walls defining a longitudinally extending internal volume having a cross-sectional area adapted to efficiently support microwave signals within the desired frequency band;

(c) said phase shifter including a plurality of phase sections, each including a separate tuned iris assembly;

(d) said tuned iris assemblies adjacently located along the longitudinal direction of said waveguide in electromagnetic cascaded relationship;

(e) said tuned iris assemblies each including planar iris means stationarily located within said waveguide, and extending across said internal volume in a plane transverse to the longitudinal waveguide direction;

(f) said planar iris means including tuned reactance means for presenting a substantially pure reactance;

(g) means for causing substantially complete reflection of the microwave signals at the pure reactance tuned reactance means of one of said assemblies;

(h) switching means operatively associated with said tuned reactance means for switching the reactance thereof between a predetermined plurality of reactance magnitudes;

(i) each of said reactance magnitudes of a predetermined value to effect, at the location of its associated planar iris, a selectable phase condition of the microwave signals within the desired frequency band;

(j) each of said tuned iris assemblies including slotted openings;

(k) said switching means including diode means in said slotted openings and switching signal input means;

(l) said switching signal input means circuit connecting said diode means to a switching signal source means external of said internal volume for switching said diode means between blocking and conducting states;

(m) said diode means operatively related to said tuned reactance means for switching said tuned reactance means between said predetermined reactance magnitudes, corresponding to said blocking and conducting states, respectively;

(n) the reactances associated with each of said phase sections characterized as switching between different effective phase variations of the microwave signal;

(o) said switching signal input means including separate inputs to each of said diode means, such that said diode means may be individually switched, to individually adjust the phase shift associated with each of said phase sections.

9. A phase shifter as set forth in claim **8**:

(a) said waveguide having first and second ends;

(b) shorting means located at said first end;

(c) a first of said phase sections including a first planar iris located at a first waveguide position;

(d) said first waveguide position spaced a quarter wavelength away from said shorting means, with said shorted first end acting as an open circuit at said first waveguide position.

10. A phase shifter as set forth in claim **9**; further including:

(a) a second phase section including second and third planar irises at second and third waveguide positions respectively.

11. A phase shifter as set forth in claim **10**; further including,

(a) a third phase section including fourth and fifth planar irises at fourth and fifth waveguide positions respectively.

12. A phase shifter as set forth in claim **11**:

(a) each of said planar irises including diode means having at least one pair of first and second diode elements, each including anode and cathode terminals;

(b) each of said slotted openings of an appreciable extent in a first direction, and of a substantially lesser extent in a second direction perpendicular to said first direction;

(c) said second direction corresponding to the E vector orientation of the microwave signal;

(d) said diode means including at least one pair of first and second diode elements in each of said slots, each of said diode elements including anode and cathode terminals;

(e) said diode pair positioned along said slotted opening and extending in said second direction between spaced first and second walls of said slotted opening;

(f) the anode terminals of said first diode elements circuit connected to said first wall and the anode terminals of said second diode elements circuit connected to said second wall, said first and second walls being at a common electrical potential;

(g) said switching signal input means including a connecting wire having an internal portion extending between said diode means and the waveguide wall, and an external portion passing through an opening in said wall, external of said internal volume;

(h) the cathode terminals of said first and second diode elements circuit connected to a common junction, said switching signal connecting wire circuit connected to said common junction;

(i) said connecting wire internal portion disposed along said first direcion, perpendicular to the E vector orientation of the microwave signal, whereby the electrical signal input to said switch means offers negligible interference to the microwave signal propagation.

13. (a) A phase shifter for adjustably varying the phase of microwave signals within a desired frequency band of operation, comprising:

(b) a waveguide having enclosed walls defining a longitudinally extending internal volume having a cross-sectional area adapted to efficiently support microwave signals within the desired frequency band;

(c) at least a first planar iris stationarily located at a predetermined first waveguide position within said waveguide, and extending across said internal volume in a plane transverse to the longitudinal waveguide direction;

(d) said planar iris including tuned reactance means for presenting a substantially pure reactance at said first waveguide position;

(e) switching means operatively associated with said tuned reactance means for switching the reactance thereof between predetermined values, including at least a first and second reactance magnitude;

(f) said first reactance magnitude of a predetermined value to effect, at said first waveguide position, a first phase condition of microwave signals within the desired frequency band;

(g) said second reactance magnitude of a predetermined value to effect, at said first waveguide position, a second phase condition of microwave signals within the desired frequency band;

(h) whereby said switching means switches the tuned reactance magnitude of said first planar iris to adjustably vary the microwave signal phase between predetermined phase conditions;

(i) said internal waveguide cross-sectional area adapted to simultaneously support first and second orthogonally related microwave signals;

(j) said tuned reactance means including first and second adjustable reactance means for independently and respectively controlling the phase condition of said first and second microwave signals;

(k) said switching means including separate control means for said first and second adjustable reactance means.

14. A phase shifter as set forth in claim **13**:

(a) each of said adjustable reactance means including at least a first slotted opening;

(b) said switching means including diode means in said slotted opening and switching signal input means;

(c) said diode means mounted to said planar iris;

(d) said switching signal input means circuit connecting said diode means to a switching signal source means external of said internal volume for switching said diode means between blocking and conducting states;

(e) said diode means switching the reactance values of its respective slotted openings between said predetermined first and second magnitudes for each of said microwave signals, corresponding to said blocking and conducting states, respectively.

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