Feb. 27, 1962 R. M. HILL 3,023,380

MICROWAVE SWITCH

Filed Feb. 24, 1960 2 Sheets-Sheet 1

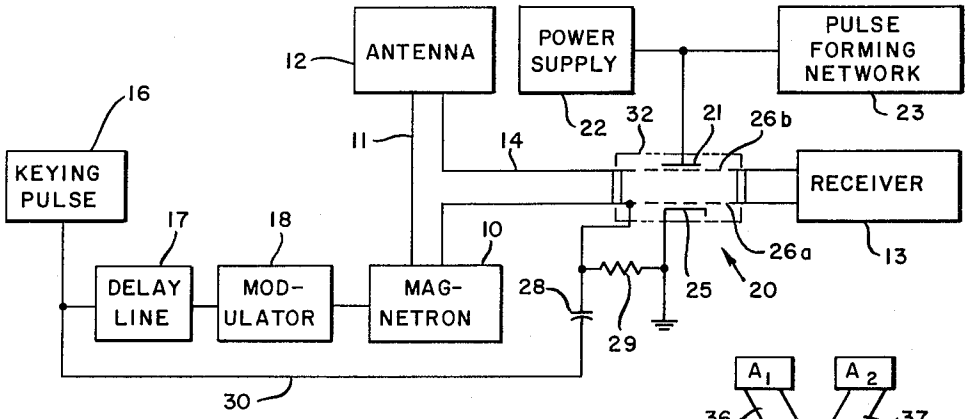


FIG-1

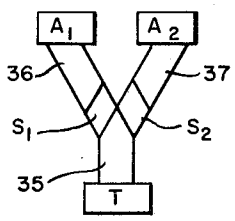


FIG-1A

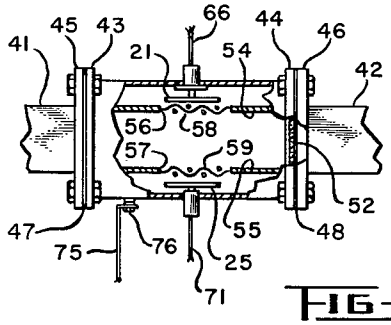


FIG-2

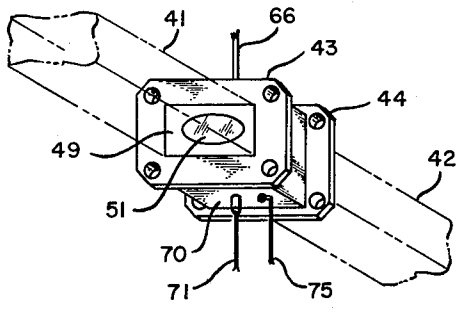


FIG-3

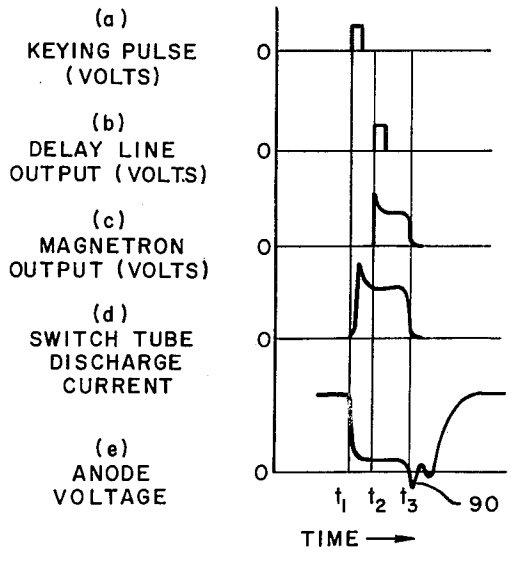


FIG-6

INVENTOR.
ROBERT M. HILL

BY
John F. Lawler
ATTORNEY

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MICROWAVE SWITCH

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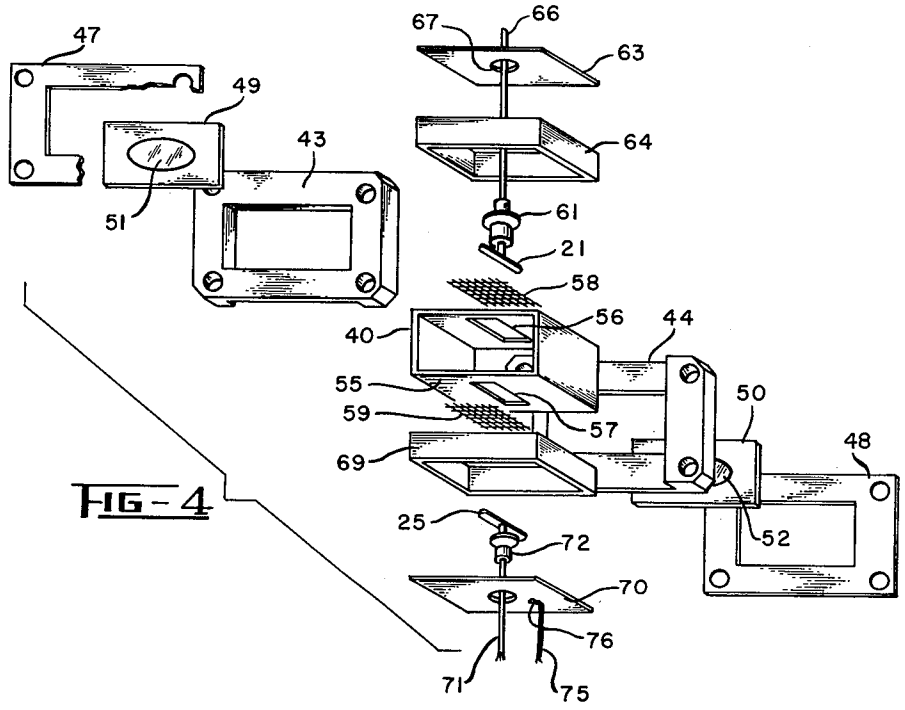


FIG-4

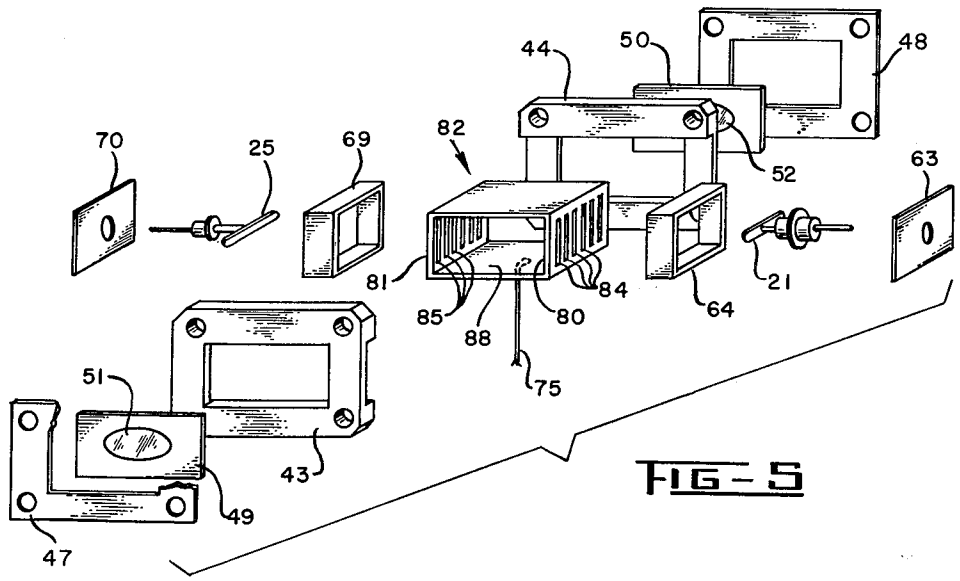


FIG-5

INVENTOR.
ROBERT M. HILL

BY John F Lawler
ATTORNEY

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MICROWAVE SWITCH

Robert Matteson Hill, Palo Alto, Calif., assignor to Sylvania Electric Products Inc., a corporation of Delaware

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10 Claims. (Cl. 333—13)

This invention relates to microwave switching apparatus, and more particularly to a high power microwave gas discharge switch.

The trend in present day microwave practice is toward higher power requirements in transmission systems and in microwave system components, including switching devices. A principal problem with present high power microwave switches is the limitation on switching times inherent in their construction and mode of operation. Mechanical microwave switches, for example, are characteristically slow, requiring about 0.01 second to open and close. A controllable cyclotron resonance gas discharge switch of the type described in copending application of Robert M. Hill and Sidney J. Tetenbaum, Serial No. 756,752, filed August 25, 1958, is limited by the switching time of the magnetic field to switch action requiring tens of microseconds. The standard resonant type T.-R. tube, described in Electronic and Radio Engineering by F. E. Terman, fourth edition (McGraw-Hill, 1955), page 1026, is triggered by incident microwave power and therefore is not a controllable switch, and further allows a small spike of energy to leak through.

A primary object of this invention is the provision of a high power microwave switch which is capable of firing in less than a microsecond and recovering in less than ten microseconds.

The noise level of a high power microwave switch or T.-R. tube is also a measure of its utility in systems which include ultra-sensitive electronic equipment, such as receivers. A typical example is a radar system. Present practice of applying an igniter voltage, sometimes called "keep alive" voltage, to the radar T.-R. switch in order to shorten the firing time also increases the noise level of the switch and correspondingly decreases the sensitivity of the receiver.

Another object of this invention is the provision of a fast-acting noise-free gas discharge microwave switch.

The present invention utilizes an arc discharge across a microwave transmission line to achieve controlled switching in an elapsed time heretofore unattainable. More particularly, the switching element comprises a section of waveguide in which a pulsed D.-C. arc discharge is generated. During the discharge, an arc plasma of high electron density traverses the section of waveguide and completely blocks the passage of microwave signals. In the absence of a trigger pulse which initiates the discharge, the tube remains unfired in the presence of incident microwave energy and functions as a low loss section of waveguide. The firing of the switch is caused by application of trigger voltage to a control grid which preferably forms part of the wall of the switch waveguide section. In its most fundamental form, the switch fires in the manner of a thyratron tube.

A general object of the invention is to provide an improved microwave switch having the following general characteristics:

(*a*) Switching time of 1 microsecond or less.
(*b*) Recovery time (time from end of the arc to 3 db transmission point) of 3 microseconds or less.
(*c*) Isolation—with arc fired—greater than 50 db.
(*d*) Insertion loss—without arc—less than ½ db.
(*e*) Bandwidth equal to full waveguide bandwidth.

(*f*) High peak power handling ability—40 kw. or more.
(*g*) Low spike leakage—0.1 erg or less.

The manner by which the above objects are achieved will be more fully understood from a reading of the following description of a preferred embodiment of the invention, reference being had to the accompanying drawings in which:

FIGURE 1 is a block diagram of a microwave transmission circuit which includes a microwave switch embodying my invention;

FIGURE 1–A is a block diagram wherein a transmitter selectively feeds plural antennas, selectivity being effected by triggering plural switches;

FIGURE 2 is a side elevation of the gas switch, a portion of the side wall thereof being broken away to show details of construction;

FIGURE 3 is a perspective view of the assembled switch;

FIGURE 4 is an exploded view of the switch;

FIGURE 5 is an exploded view of a modified form of the switch; and

FIGURE 6 is a waveform diagram showing a comparison on a time scale of pulse wave forms at various points of the circuit of FIGURE 1.

A high power microwave switch of the type with which this invention is concerned has several applications. It may be used to change the output of a transmitter sequentially between several antennas. Also it may be used along with a delay line as a crystal protector in a transmit and receive system wherein a signal above a certain threshold is detected and used to fire the switch ahead of the transmitted pulse. Generally, the switch of this invention may be used with advantage in any microwave system for controlling the flow of high-power electromagnetic energy.

A typical though not limiting example of the use of the switch is as a crystal protector in a radar system shown in block form in FIGURE 1. The system comprises a microwave transmitter **10** joined by waveguide **11** to antenna **12**, the latter communicating with a receiver **13** through waveguide **14** and a portion of interconnecting guide **11**. Transmitter **10** generates a relatively high energy pulse in response to a keying pulse from a suitable source **16** connected to the transmitter through a delay line **17** and modulator **18**. The switch **20** of my invention is placed in the line **14** ahead of receiver **13**. When the switch is unfired, it is "closed" (i.e., microwave energy can pass through) and the receiver is connected to line **11**; when it is fired, the switch is "open" (i.e., the flow of microwave energy is blocked) and the receiver is disconnected from the circuit.

Switch **20** is an assembly comprising an anode **21** connected to a power supply **22** and to a pulse forming network **23**, a grounded cathode **25**, and grid elements **26***a* and **26***b* connected through condenser **28** across resistor **29** and by line **30** to the source **16** of keying pulses. Grid elements **26***a* and **26***b* preferably form part of the waveguide section **14** as will appear more fully below. Anode **21**, cathode **25** and grid elements **26***a* and **26***b* are enclosed in an envelope **32**, indicated by the broken line rectangle, and the envelope is filled with a low pressure ionizable gas, such as neon or hydrogen, which supports the arc discharge.

In operation, a potential is applied to the anode **21** by power supply **22** through network **23**, and grids **26***a* and **26***b* are biased below cut-off and no current flows in the tube. The pulse forming network **23** permits the use of a low current power supply and also provides a means of cutting off the discharge in the tube. With no current flowing, line **14** to the receiver is open and signals received by the antenna pass through the switch to the receiver. The switch is fired ("opened") in advance of the

transmitter power pulse by a keying pulse from source 16 which acts through delay line 17 and modulator 18 to trigger the transmitter but which acts directly on the switch tube. The trigger raises the switch tube bias above cut-off and in a few tenths of a microsecond the current between plate and cathode builds up to the full rated emission of the cathode. This heavy flow of current instantaneously ionizes the gas so that the heavy electron and ion density of the discharge plasma prevents any flow of microwave energy through the switch. The transmitter pulse which follows is thus blocked at the switch and passes entirely to the antenna. As soon as the high energy pulse is transmitted, switch 20 closes (returns to the unfired state) as a result of sudden reduction of anode voltage below ionization potential of the gas. This is accomplished by the pulse forming network 23. This network provides a current pulse of time duration substantially equal to the width of the transmitter pulse. The trailing edge of the latter pulse substantially coincides with the trailing edge of the anode current pulse. The pulse forming network is designed to produce a voltage "overshoot" at the end of the pulse, as explained more fully below, so that the switch is returned to its "closed" or unfired state instantaneously.

In another application, gas switch 20 may be used to control the connection of a high power microwave transmitter to two or more antennas. The switch may be connected directly in series between transmitter and antenna because the gas does not break down in the presence of the high power energy and because the switch has a low insertion loss (less than 1 db) as well as broadband characteristics. This application of the switch is illustrated in FIGURE 1–A wherein the transmitter T is connected by waveguides 35, 36 and 37 to antennas A_1 and A_2. Switches are located at the intersection of branches 36 and 37 with the trunk 35 and are designated as S_1 and S_2. The switches are fired selectively by application of triggering pulses so that the transmitter is connected to antenna A_2 when S_1 is fired and S_2 is unfired, and, when S_2 is fired and S_1 is unfired, the connection is made to antenna A_1. Similarly, a single antenna may be connected to several transmitters, or several transmitters may be connected to several antennas through appropriate waveguide circuitry and switching combinations.

Referring now to FIGURES 2, 3 and 4, a preferred embodiment of this invention is shown as a section 40 of rectangular waveguide having the same cross-sectional dimensions as the associated waveguides 41 and 42. Section 40 is connected by flanges 43 and 44 to corresponding flanges 45 and 46 of waveguides 41 and 42. Thin Teflon washers 47 and 48 at these joints provide direct current isolation of section 40 from associated waveguides without impairing substantially the flow of microwave energy. The opposite ends of section 40 are closed and sealed by end walls 49 and 50 which have centrally disposed microwave permeable windows 51 and 52, respectively. Broad walls 54 and 55 of the section are formed with central longitudinal aligned openings 56 and 57, respectively, through which the arc discharge passes when the switch is fired. Screens 58 and 59 of conducting material cover these openings and make section 40 electrically continuous to microwave energy.

Anode 21 extends the length of opening 56 and is supported adjacent to screen 58 by means of an insulator 61 which is secured to and sealed in the top wall 63 of a spacer 64. Anode lead 66 extends through opening 67 in top wall 63 for connection to the outside circuitry. Spacer 64, including its end wall 63, comprises a hermetically sealed enclosure and support for the anode and so is suitably sealed to the section 40 for this purpose. Cathode 25 extends the length of opening 57 and is similarly supported and sealed adjacent to screen 59 by spacer 69 with its end wall 70. Cathode lead 71 supports the cathode in proper position by means of insulator 72. The space within the switch assembly is filled with a suitable ionizable gas, such as neon or hydrogen, at a relatively low pressure, in the order of 100 microns of mercury.

The input lead 75 of the trigger pulse is connected to terminal 76 on end wall 70 so the entire section 40 including screens 58 and 59 is pulsed. The rest of the waveguide circuitry is suitably insulated from this pulse as by the Teflon washers 47 and 48 at the junction flanges, or by means of choke joints. Alternatively, grids 56 and 59 may be directly connected to the trigger pulse source and insulated from the body of the section.

The medium which physically blocks the flow of microwave energy through the switch when it is fired is the gas discharge plasma, that is, the portion of the discharge comprising substantially equal numbers of positive ions and electrons. The dielectric constant of an ionized plasma is a function of both frequency of propagated electromagnetic energy and the electron density. When the electron density exceeds a critical frequency-dependent value, the dielectric constant becomes imaginary and propagation is no longer possible. When this happens, the electromagnetic wave is reflected from the surface of the plasma and switching action is made possible. The rapidity with which switching takes place, that is, the time between initiation of the trigger and attainment of a 60 db or more level of attenuation, has been improved by utilizing a thyratron type of action to create this plasma. Because of the high currents supported by the arc discharge—in the order of tens of amperes per square centimeter—high ion concentrations, in excess of 10^{13} electrons per cubic centimeter, are produced which are capable of fully reflecting microwave signals up to 30 kilomegacycles. Build-up of electron density, and thus the plasma, to its equilibrium value is exceedingly rapid, being accomplished in the order of ten to a hundred milli-microseconds. This time of ionization of the gas is a function of the pressure of the gas and the applied grid and anode voltages; the ionization time decreasing with increasing grid and anode voltages and with increasing gas pressure.

After the discharge has been initiated by the signal applied to grids 58 and 59, control of the discharge is lost until potential on the anode is reduced below that required to support discharge in the gas. The rapidity with which the switch returns to its pre-discharge state, i.e., its recovery time, is also a measure of the switch action time. Recovery time is defined as the time from the moment of beginning of decay of the arc (electron density decay) to the time when attenuation of a signal through the switch tube is no more than 3 db above the attenuation in the absence of discharge. In order to minimize recovery time, the potential on the anode not only is reduced below that required to support discharge, but also is caused to reverse polarity for a short period of time, that is, the anode voltage is driven negative momentarily. This voltage reversal contributes significantly to shortening the recovery time by sweeping out electrons and restoring the gas to its original unfired state. Further improvement in recovery time is afforded by optimizing the geometry of the tube. By utilizing these techniques, recovery times in the order of ½ to 1 microsecond have been achieved.

An important feature of my switch tube is that it has essentially waveguide bandwidth in the unfired state. This is due in part to the insensitivity of the low pressure gas to frequency changes and to the switch configuration which provides an unobstructed, essentially continuous, microwave transmission line, the only practical limitation in this regard being in the waveguide windows at opposite ends of the tube. The fine wire screening or gauze strips 58 and 59 which cover the openings in the waveguide eliminate adverse effects of electrical discontinuity in the waveguide walls and yet provide for the flow of electrons across the transmission path. Anode 21, cathode 25, and grids 58 and 59 of the tube

are out of the path of propagated energy thereby contributing to relatively low insertion loss (when the tube is unfired) which may be in the order of 0.1 db or less throughout the band.

A further feature of my invention, especially when a switch tube embodying it is used in conjunction with a sensitive receiver is the absence of noise in the tube. Electrons emitted by the cathode are prevented from entering the path of the microwave energy propagated in the switch when the latter is unfired because of the bias applied to the grid element of the tube. The advantage of low noise level is gained, however, without loss of time in firing the switch.

The switch tube shown in FIGURE 4 and having the following dimensions and characteristics has been built and successfully operated:

Size:	
X-band waveguide—	
Overall length	5/8 inch.
Height	2 inches.
Approximate weight	¼ lb.
Anode voltage	500 volts.
Keying (trigger) pulse:	
Amplitude	60 volts.
Duration	0.5 to 1.0 μsec.
Gas:	
Type	Neon.
Pressure	200 μ.
Power switched at 1 μsec. pulse length	Low level to >50 kw. peak.
Isolation	65 db.
Spike leakage isolation	65 db.
Arc loss	½ db.
Insertion loss	Approx. ½ db.
Recovery time	~3 μsec.
Switch firing time	½ μsec.
VSWR	1.25.
Bandwidth	Full waveguide bandwidth.

A modified form of the invention is shown in FIGURE 5 wherein the discharge occurs across the long dimension of the waveguide as distinguished from the discharge across the short dimension as shown in FIGURES 2–4. Since the switch tube of FIGURE 5 is essentially identical to that previously described, like parts are indicated by like reference characters on the drawings. As shown in FIGURE 5, anode **21** and cathode **25** are supported adjacent to the exterior of the narrow walls **80** and **81**, respectively, of waveguide section **82**. Walls **80** and **81** are formed with a series of openings **84** and **85** to provide for passage of electrons across the tube. Spacers **64** and **69**, together with their respective end walls **63** and **70**, support the anode and cathode in position and seal these parts within the tube. End mounting flanges **43** and **44**, together with end walls **49** and **50** and windows **51** and **52**, respectively, complete the assembly. The input lead **75** for the trigger signal connects directly to the bottom wall **88** of section **82**. The switch operates in the same manner as described above, the only difference being that the discharge occurs across the long dimension of the waveguide rather than its short dimension.

FIGURE 6 shows a series of pulse waveforms on a time scale for illustrating the operation of the switch tube in a microwave transmisison system of FIGURE 1. Keying pulse in FIGURE 6*a* begins at time t_1 and is delayed until time t_2 (FIGURE 6*b*) as it passes through delay line **17** to the modulator **18**. The latter drives the transmitter whose output (FIGURE 6*c*) is generated after a delay time (t_2-t_1) from initiation of the trigger pulse. The trigger pulse is applied directly to the grids **26***a* and **26***b* of switch tube **20** and discharge across the transmission path occurs instantaneously as indicated by the sharp rise in discharge current in FIGURE 6*d*. During the period from t_2 to t_3 discharge in tube **20** continues, blocking transmission of the high power pulse to the receiver. The relatively high voltage on the anode (FIGURE 6*f*) drops suddenly to a low value when discharge occurs. The duration of the magnetron output pulse (t_3-t_2) is known and the pulse forming network **23** connected to anode **21** is so designed as to cut off the anode voltage sharply at the end of the transmitter pulse and stop the current discharge. In other words, pulse forming network **23** is designed to cut off discharge in the switch tube after passage of a time interval equal to or slightly greater than the duration of the transmitter pulse. In addition to reducing anode voltage at time t_3, this network also serves to drive the anode voltage negative as indicated at **90** in FIGURE 6*f* prior to increasing it before that voltage rises to its initial positive pre-firing value. As a result of this reversal of anode voltage, electron decay (deionization) in the tube is hastened and the recovery time of the switch is reduced considerably. The application of a negative voltage to the anode of the tube simultaneously with cutting off of the discharge has a significant effect on sweeping out the remaining electrons and ions rapidly and in restoring the switch to its "closed" state for transmission of electromagnetic energy.

Changes, modifications and improvements to the above described embodiments of my invention may be made by those skilled in the art without departing from the precepts of the invention. The appended claims define the features of novelty of the invention.

I claim:

1. A microwave switch comprising a section of rectangular waveguide having two pairs of opposed parallel walls and adapted to propagate electromagnetic waves, one pair of said walls having transversely aligned openings therein, a hot cathode element disposed externally of and adjacent to the opening in one of the walls, an anode element disposed externally of and adjacent to the opening in the other of the walls, means for hermetically sealing said anode and cathode elements to said section, end walls sealed to opposite ends of said waveguide section and enclosing a volume of ionizable gas, each of said end walls having a microwave permeable window, a source of positive voltage connected to said anode, means for applying a negative biasing potential to said section whereby electrons from said cathode are prevented from passing through the adjacent opening into the section, means for applying a relatively positive trigger pulse to said section causing an arc discharge between said anode and cathode elements and instantaneously creating an ionized plasma across the waveguide section which blocks transmission of electromagnetic waves through the section, and means for reducing anode voltage below ionization potential of the gas for restoring the switch to its pre-fired state.

2. A microwave switch comprising a section of rectangular waveguide having two pairs of opposed parallel walls and adapted to propagate electromagnetic waves, one pair of said walls having transversely aligned openings therein, a metallic grid across each of said openings, a hot cathode element disposed externally of one of the walls adjacent the grid thereon, an anode element supported externally of the other of said walls adjacent to its grid, means for enclosing and sealing said anode and cathode elements respectively to said section, microwave permeable end walls extending across and sealed to opposite ends of said section and defining with said section a volume filled with an ionizable gas, a source of positive voltage connected to said anode, means for applying a negative biasing potential to one of said grids whereby electrons from said cathode are prevented from entering into said section, means for applying a relatively positive trigger voltage to said one of said grids whereby an arc discharge occurs between said anode and cathode ele-

ments and instantaneously creates an ionized plasma across the waveguide section which blocks transmission of electromagnetic waves through the section, and means for reducing anode voltage below ionization potential of the gas for restoring the switch to its pre-fired state.

3. The switch according to claim 2 in which said last-named means comprises circuit means for driving said anode voltage momentarily negative before restoring it to the original value.

4. A microwave switch comprising a section of rectangular waveguide having two pairs of opposed parallel walls, one pair of said walls having transversely aligned openings therein, a source of electrons disposed externally of the opening in one of the walls and arranged to continuously direct electrons toward said opening, an anode element disposed externally of and adjacent to the opening in the other of said walls, longitudinally spaced microwave permeable walls sealed to said section on opposite sides of said openings and enclosing within said section a volume of ionizable gas, a source of positive potential connected to said anode, a source of negative bias potential connected to said section whereby electrons from said electron source are prevented from entering the section, and means for applying a trigger pulse to said section causing electrons to flow to the anode and instantaneously creating an ionized plasma in the section thereby blocking transmission of electromagnetic waves therethrough, and means for decreasing the anode potential below the ionization potential of said gas to return the switch to its pre-fired state.

5. In combination with a microwave transmission line, a gas discharge switch consisting of a section of rectangular waveguide having broad and narrow walls and connected to adjacent parts of the line, means providing for direct current insulation of said section from the line, said narrow walls having transversely aligned openings therein, a cathode element disposed externally of and adjacent to the opening in one of said narrow walls, an anode element supported externally of and adjacent to the opening in the other narrow wall, means sealing said anode and cathode elements to said section, longitudinally spaced microwave permeable walls sealed across the interior of said section on opposite sides of said openings and defining with the intermediate portions of the section walls an enclosure containing an ionizable gas, means for applying a potential difference between said anode and cathode elements, means for applying a negative bias potential to said waveguide section whereby to prevent electrons from entering said waveguide section, means for suddenly decreasing the bias potential to cause current to flow between said anode and cathode elements thereby creating an ionized plasma which blocks transmission of electromagnetic waves through the section, and means to reduce said potential difference to a value less than ionization potential of said gas.

6. A controllable switch for controlling the flow of electromagnetic waves through a hollow transmission line having a pair of opposed walls, comprising an anode adjacent to one of said walls external of the transmission path, a cathode opposite said anode and adjacent to the other of said walls external of the transmission path, grid means between said cathode and anode and external of the transmission path, means for confining an ionizable gas in the transmission path between said anode and said cathode, means for applying a positive voltage to said anode, means for biasing said grid sufficiently negative to prevent flow of electrons from the cathode into said transmission path, and means for selectively momentarily pulsing said grid in a positive direction to permit flow of electrons across said path to the anode whereby to produce an ionized plasma in the transmission path for blocking the flow of electromagnetic waves therethrough, and means for reducing the voltage on said anode below ionization potential whereby to restore the switch to its pre-fired state.

7. A controllable microwave switch having an open state and a closed state for controlling the flow of microwave energy along a transmission path, comprising an electron source disposed externally of said path and arranged to direct electrons transversely thereof, a positively charged electrode aligned with and on the opposite side of said path from said source, a control grid between said source and said path and aligned with said electrode, a volume of ionizable gas disposed directly in said transmission path between said source and said electrode and through which said microwave energy propagates when the switch is in the open state, means for biasing said grid to prevent flow of electrons from said source into said transmission path, means for selectively changing the grid bias to permit electron flow into said path whereby instantaneously to create an ionized plasma for blocking the flow of microwave energy and changing the switch to its closed state, and means to restore the gas to the de-ionized state.

8. A controllable switch for controlling the flow of electromagnetic waves along a path defined by a hollow transmission line, comprising an anode disposed adjacent to and external of the transmission path, a cathode transversely aligned with the anode and disposed external of and on the opposite side of the transmission path from said anode, grid means external of said path and arranged to control the flow of electrons between the cathode and anode, means for confining an ionizable gas in the transmission path between said anode and said cathode, a positive voltage source connected to said anode, means for biasing said grid sufficiently negative to prevent flow of electrons from the cathode into said transmission path, and control circuit for selectively momentarily pulsing said grid in a positive direction to cause flow of electrons across said path to the anode whereby to produce an ionized plasma in the transmission path for blocking the flow of electromagnetic waves therethrough, and means for reducing the voltage on said anode below ionization potential whereby to restore the switch to its pre-fired state.

9. The switch according to claim 8 in which said transmission line has electrically conducting electron-pervious walls adjacent to said anode and cathode.

10. In combination, a controllable microwave switch and a waveguide adapted to propagate microwave energy, a portion of said waveguide having opposed conducting walls with a plurality of relatively small openings therein, an external electron source adjacent to openings in one of said walls, a positively charged external electrode adjacent to the openings in the opposite wall, means for confining a volume of ionizable gas within said waveguide between said electron source and said electrode, means for biasing said portion of the waveguide to prevent flow of electrons from said source into the waveguide, circuit means connected to said portion of the waveguide for selectively changing the grid bias thereof to permit electrons to flow into the waveguide and the gas therein whereby instantaneously to create an ionized plasma for blocking the flow of microwave energy through the waveguide, means to provide direct current isolation of said portion of the waveguide from the remaining waveguide parts, and means to restore the gas to the de-ionized state.

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