April 17, 1962 R. A. RAPUANO 3,030,501

MICROWAVE DUPLEXERS

Filed Jan. 28, 1959 2 Sheets-Sheet 1

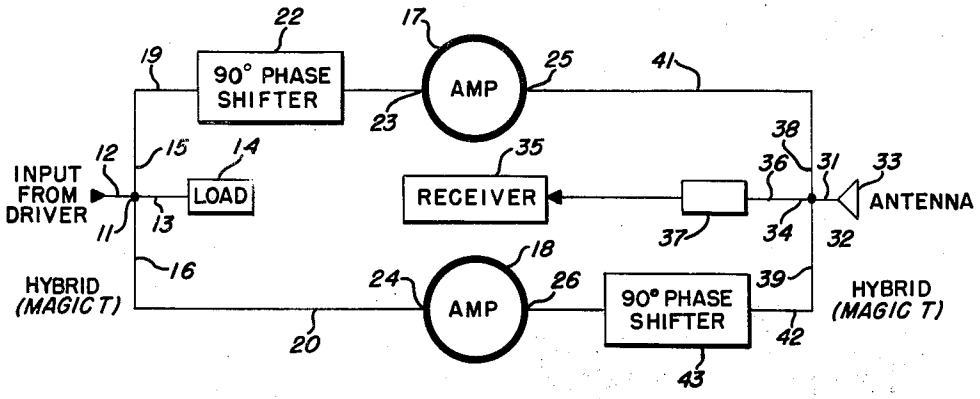

FIG. 1

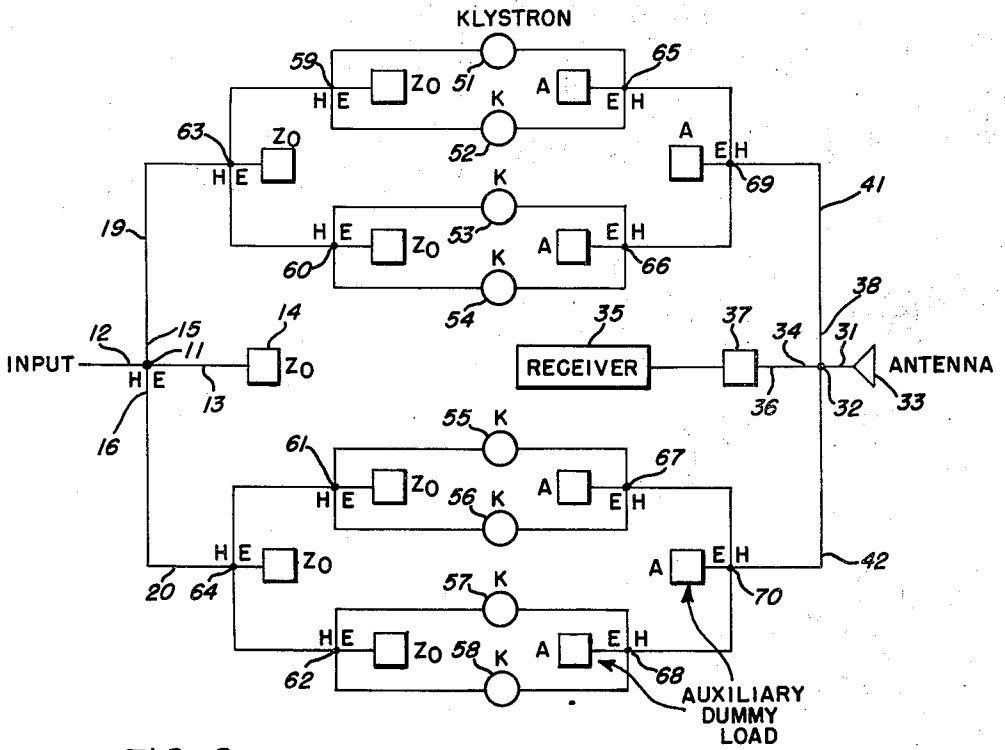

FIG. 2

INVENTOR
ROBERT A. RAPUANO

BY N. Vincent Harris

ATTORNEY

April 17, 1962 R. A. RAPUANO 3,030,501

MICROWAVE DUPLEXERS

Filed Jan. 28, 1959 2 Sheets-Sheet 2

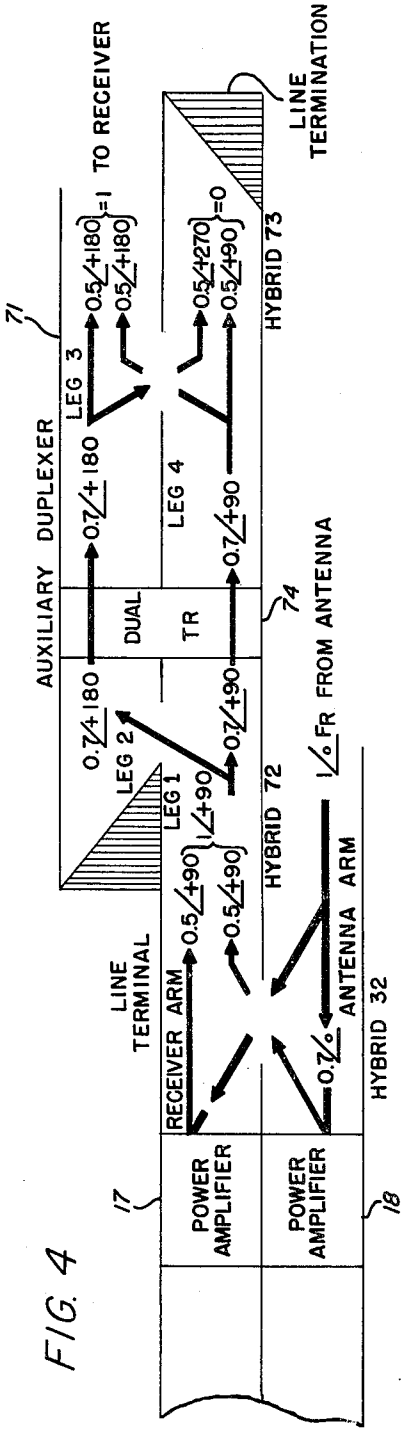

FIG. 4

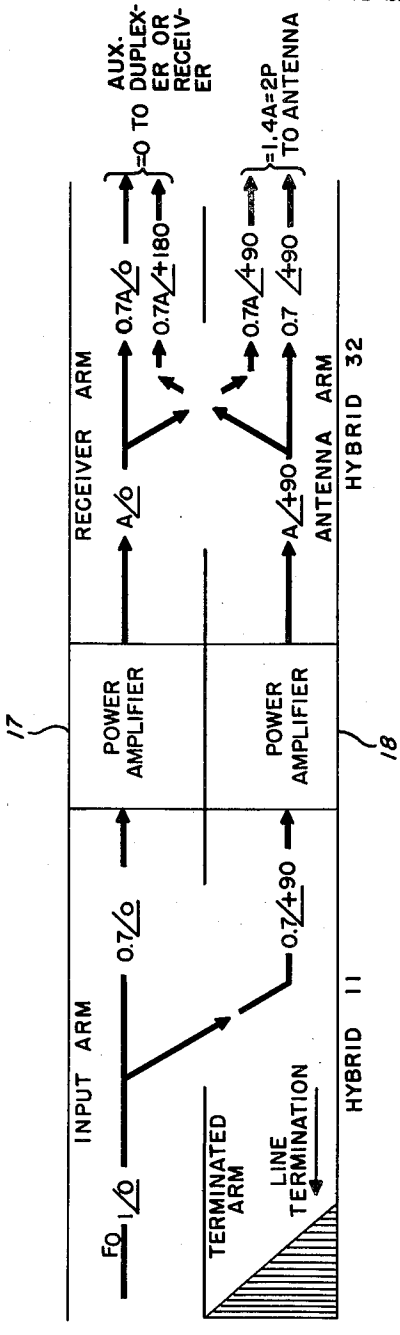

FIG. 3

INVENTOR
ROBERT A. RAPUANO

BY H. Vincent Harsha

ATTORNEY

United States Patent Office 3,030,501 Patented Apr. 17, 1962

3,030,501

MICROWAVE DUPLEXERS

Robert A. Rapuano, Dedham, Mass., assignor to Raytheon Company, a corporation of Delaware

Filed Jan. 28, 1959, Ser. No. 789,642
13 Claims. (Cl. 250—13)

This invention relates to a microwave duplex circuit for transmission and reception of radio signals and more particularly to a circuit for duplexing very high power radars which use non-reciprocal final amplifiers.

Microwave duplexers most commonly used today in radar, radio and the like employ transmit-receive (TR) tubes to perform switching functions and are capable of operating only with relatively high power transmitters. The two most common types of duplexers capable of handling relatively high amounts of power are generally referred to as "branched" and "balanced." Briefly, a conventional branched duplexer is one wherein a main transmission line containing an ATR tube connects the transmitter to the antenna and a branch transmission line containing a TR tube connects the receiver to the main transmission line intermediate the ATR tube and the antenna. The TR tubes in a branched duplexer must be capable of switching the full line current resulting from the transmitter at a point which can equal the sum of the incident and reflected currents at the antenna.

A conventional balanced duplexer utilizes two four-terminal hybrid junctions having a TR tube disposed in each of two lines connecting two conjugate or colinear arms of the hybrid junctions. A transmission line connects a particular one of the remaining arms of one of the hybrid junctions to the transmitter and the other arm is connected to the antenna. The arms of the other hybrid junction are connected in the proper relation respectively to the receiver and a non-reflective and dissipative load. One of the principal advantages of a balanced duplexer over a branched duplexer is the fact that the TR tubes in a balanced duplexer switch currents of about one and a half times the amount of current they switch in a branched duplexer. The TR tubes used must have excellent isolation between input and output, so that high line current in the input will not result in damage to the receiver. Use of a balanced duplexer reduces this isolation requirement somewhat because of cancellation, but at the price of higher current in each TR tube.

Obviously, one of the important limiting factors in the amount of power a duplexer can handle is the TR tube. Another important limiting factor is that the design of present-day duplexers is based on the assumption that the power to be transmitted will be developed from a single source and coupled to the duplexer by a single transmission line and that TR tubes will perform the switching action. This type of design places serious limitations on the power generating means and on the maximum amount of power that can be generated, irrespective of the problem of switching the power once it has been produced.

The present invention contemplates a new and novel approach to high power duplexing wherein the switching function is performed by the transmitter output stage and TR tubes or other low power switching devices are used only to protect the receiver. This may be achieved if the output stage of the transmitter is comprised of microwave space charge amplifiers or klystrons, the output impedances of which are substantially equal one with another.

The present invention provides a balanced type duplexer having klystron or space charge final amplifiers disposed between the balanced or conjugate arms of

two four-terminal hybrid junctions. The input signal to the klystrons are connected to the symmetrical arms of a directional coupler or hybrid. The outputs of the klystrons, which must be substantially the same, are connected to the symmetrical arms of a similar coupler. One of the remaining arms of the last-mentioned coupler is connected to an antenna and the remaining arm is connected to a load or receiver through a suitable switch. The principle of operation of the present invention is based on the premise that the output of a klystron or equivalent space charge amplifier may be considered nonreciprocal and that if the number of amplifiers used equals 2^n, where n equals 1, 2, 3, etc., transmitted power may be greatly increased over that heretofore possible, it only being necessary to protect the receiver with a TR tube or switch capable of handling only a small fraction of the line current. For ideal conditions of operation, the amplifiers should have the following properties:

(1) Phase shifts equal, or capable of being made equal

(2) Amplitude of output equal

(3) Equal amplitude and phase reflection coefficients of the output (equal output impedances).

It is, therefore, an object of the present invention to provide a novel wave propagation device capable of handling high power.

Another object of the present invention is to provide a novel duplexer or power combining device by means of which the outputs of a plurality of microwave amplifiers may be combined in a common load without interaction between the amplifiers.

Another object of the present invention is to provide a novel duplexer for high power radars wherein the switching function is performed by the output stage of the transmitter.

A still further object of the present invention is to provide a novel duplexer for radars which allows the transmission of power greatly in excess of that heretofore considered feasible and which allows the use of means to protect the receiver that is capable of handling only a small fraction of the line current.

A still further object of the present invention is to provide a balanced duplexer for very high power radars which utilizes space charge amplifiers such as triodes and klystrons having nonreciprocal and nonlinear characteristics to accomplish duplexing with switching means of comparatively low power handling ability.

These and other objects and features of the invention, together with their incident advantages, will be more readily understood and appreciated from the following detailed description of some exemplifications thereof selected for purposes of illustration and shown in the accompanying drawings in which:

FIG. 1 is a schematic diagram of the circuit of the invention utilizing magic T's and two amplifiers;

FIG. 2 is a schematic diagram of the circuit of the invention utilizing eight amplifiers;

FIG. 3 is a diagrammatic representation of the electrical-vector relationships during transmission for short-slot hybrids; and

FIG. 4 is a diagrammatic representation of the electrical-vector relationships during reception for short-slot hybrids.

Referring now to FIG. 1 which illustrates a pair of space charge amplifiers and associated circuitry incorporating the present invention, a driver (not shown) is connected to a hybrid four-terminal junction **11**. To facilitate understanding and illustration of the invention, it is assumed that the separate hybrid junctions are of the magic T type and that the amplifiers are klystrons although it is to be understood that the invention is not so limited. The H plane arm **12** of hybrid **11** is adapted to

receive an input signal from a suitable low power source or driver and the E plane or conjugate arm **13** is connected to a dissipative load **14**. The other two conjugate or coplanar arms **15** and **16** are connected to a pair of separate amplifiers **17** and **18** such as klystrons or triodes having the properties noted hereinbefore. These connections are made through two conductors **19** and **20**, which are, for example, similar hollow, rectangular microwave guides. A 90° phase shifter **22** is disposed between arm **15** and amplifier **17**. The 90° phase shifter **22** may be a conventional and reciprocal phase shifter or, alternately, it may be comprised of a quarter wavelength of waveguide such that conductor **19** is longer than conductor **20** by an odd integral multiple of one quarter wavelength, or

$$\frac{(2N+1)\lambda g}{4}$$

in which N is any integer including 0 and λg is the wavelength in the rectangular waveguide.

The klystrons **17—18** may, for example, form the output stage of a radar transmitter and have respectively input electrodes **23—24** for receiving the signal from the driver and output electrodes **25—26** from which their output signal is taken. As pointed out hereinbefore, for optimum operation, the amplifiers must have substantially equal phase shifts or be capable of having their phase shifts made equal; the amplitudes of their output signals must be substantially equal; and the output impedances of the amplifiers must be substantially equal. The H plane arm **31** of a second hybrid junction **32** is connected to an antenna **33** and the E plane or conjugate arm **34** is connected to a load or receiver **35** through conductor **36** and a suitable switch or protective device **37** described more completely hereinafter. The colinear or other conjugate arms **38** and **39** are connected respectively to the output electrodes **25—26** of the amplifiers **17** and **18** through two conductors **41** and **42**. A phase shifting device **43**, identical to phase shifting device **22**, is disposed between the output electrode **26** of amplifier **18** and arm **39** of the second hybrid junction **32**. The discussion with regard to the phase shifting device **22** applies equally to phase shifting device **43**.

In operation, the signal from a driver is split and coupled to the coplanar or conjugate arms **15** and **16** of the hybrid junction **11** and to the input electrodes **23** and **24** of the amplifiers **17** and **18** with a 90° phase difference. The output of amplifier **17** at its output electrode **25** is coupled to the coplanar arm **38** of the second hybrid junction **32** and the output of amplifier **18** at its output electrode **26** is coupled to the coplanar arm **39** with a 90° phase shift whereby the signals at the second hybrid junction **32** are in phase and therefore coupled to the H plane arm **31**. The output signals from the amplifiers **17** and **18** at the second hybrid junction **32** will be in phase, provided the phase shift in each amplifier or klystron **17—18** is the same. Energy received from free space by the antenna **33** is split equally and coupled to the output electrodes **25** and **26** of each amplifier, reflected therefrom without relative phase change and arrives back at the second hybrid junction **32** 180° out of phase one with the other due to the action of the phase shifter **43**. Both signals are then combined and coupled to the E plane arm **34** and the receiver **35**. Antenna reflection as well as transmitter unbalance, also coupled to the E plane arm **34** during transmission, is controlled by a suitable switching device or TR tube **37** more thoroughly described hereinafter.

Phase shift through amplifiers such as, for example, klystrons is determined by tube geometry, anode voltage, and resonator tuning. It is to be noted that differential phase shifts between a pair of amplifiers as shown in FIG. 1 will cause power to feed into the E plane arm **34** and, hence, to the receiver **35**. Differential phase shifts arising from variations in tube geometry may be equalized by placing small trimmers or the like in the input lines **19—20** to the amplifiers and phase differential variations caused by anode voltage fluctuations may be cancelled by the simple expedient of using a common anode supply for the amplifiers. As pointed out hereinbefore, the phase shift through each of the amplifiers must be substantially the same. The tuning of microwave amplifiers having resonant circuits is very important since mistuning of their resonant circuits can introduce serious differential phase shifts. For example, a mistuning of approximately ten percent of bandwidth results in a 10° phase shift. Further, not only is the power coupled to the receiver during transmission a function of differential phase shifts, but it is also a function of antenna and output transmission line mismatch. If the amplitude and phase of these mismatches are constant, the tuneup procedure for the amplifiers or impedance matching means such as an auxiliary duplexer described hereinafter may be utilized to cancel undesirable coupling of power resulting from mismatch. Where, however, a rotatable antenna is utilized there will normally be some variation of mismatch which will cause a variable residue that cannot be cancelled. For the worst possible case, then, the maximum power P_u coupled to the receiver from antenna line mismatch is then

$$P_u=|T_a|^2|T_k|^2P_t$$

where T_a is the reflection coefficient of the antenna line, T_k is the reflection coefficient of the amplifier tanks and P_t is the transmitted power. Assuming a normal antenna line VSWR mismatch of 1.5 or less, $|T_a|^2=0.04$. The value of T_k can be either measured or estimated. Values obtained from known efficiencies or tank parameters indicate that T_k^2 can lie between 0 and 0.5 depending upon tube design. For the worst case, the power coupled to the receiver will be of the order of two percent of the main line power although it can be much lower. To determine the total power coupled to the receiver during transmission, coupling from mistuning and unequal outputs from each klystron must be added to the power coupled to the receiver from mismatch. If a differential phase error of, for example, 12° is made during tuneup of the klystrons because the tank circuits thereof are not tuned to the same frequency, about 1.0 percent of the main line power will be coupled to the receiver. If each tube has a difference in power output of about 1 db, this will result in about a 0.25 percent contribution of power to the receiver. Total leakage power may be considered coherent, hence, for the worst possible (and unlikely) combination of factors contributing to the undesirable coupling of power to the receiver discussed hereinabove, the total power coupled to the receiver during transmission will reach a maximum of only about 8.4 percent of the main line power. However, by use of proper auxiliary circuitry and tuneup monitors well known in the art, the amount of power coupled to the receiver may be maintained at a substantially lower value. In any event, it may now be obvious that the receiver protective device need only control at most less than ten percent of the main line power, which line power may be many times greater than that of present-day duplexers. In a two-tube arrangement as described hereinabove, failure or disconnection of one of the klystrons places one-half of the other klystron's output in the receiver arm **34**. Hence, for tuneup of klystrons, it is recommended that either the protective means for the receiver be able to withstand this load or, preferably, that an R.-F. switch be utilized to protect the duplexer during the tuneup procedure.

During the receiving interval, the electron stream of each klystron is cut off and T_k will approach unity. The degree with which T_k approaches unity is determined by the ratio of loaded to unloaded Q of the tank circuit if

the output tank resonant frequency is not changed by the electron beam. At resonance,

$$|T_k| = \left|1 - 2\frac{Q_L}{Q_0}\right|$$

where Q_L is the loaded Q of the tank circuit and Q_0 is the unloaded Q of the tank circuit. The loss of received signal from this source is

$$L_r = 1 - |T_k|^2$$

For typical klystrons,

$$\frac{Q_L}{Q_0}$$

is approximately equal to .01, so that T_k equals .98, and the loss of signal will be approximately four percent or .2 db. Larger values of

$$\frac{Q_L}{Q_0}$$

may be tolerated if the electron beam causes any appreciable shift of the output tank resonant frequency. From the above, it may now be seen that the reflection coefficient of the output tank in the receive condition will not correspond to the reflection coefficient of the tank at resonance, but to some value which can be several times as great. Although reflection coefficient amplitude differences are unlikely, if the T_k of one klystron equals .98 and the T_k of the other klystron equals 1.0, there will be a loss of signal of .01 percent. Errors of 10° in output tuning will also result in less than one percent loss, hence the major loss of received signal arises when the tank T_k is less than unity. However, T_k is normally sufficientiy close to unity that satisfactory reception may be obtained.

A very satisfactory arrangement may be obtained by replacing the magic T's with 3 db directional couplers such as, for example, of the short-slot hybrid type described by H. J. Riblet on pages 180–184 of the February 1952 issue of the Proceedings of the IRE. Obviously, if the magic T's of FIG. 1 are replaced by couplers having an inherent 90° phase shift, the phase shifters **22—43** are not necessary and may be omitted. The present invention may be applied to more than a pair of amplifiers, the restriction being that the number of amplifiers shall equal 2^n where n is an integer, each of the amplifiers in FIG. 1 being replaced, for example, with parallel combinations of amplifiers.

With reference now to FIG. 2, there is shown by way of example a complete drive and coupling arrangement of eight amplifiers for very high power duplexing. Each amplifier **17—18** of FIG. 1 has been replaced respectively by four amplifiers **51—52—53—54** and **55—56—57—58** comprising four parallel combinations of two amplifiers each. The input electrodes of each parallel combination of amplifiers are connected respectively to the coplanar arms of four separate hybrid junctions **59—60—61—62**, the H plane arms of which are connected respectively to the coplanar arms of two hybrid junctions **63—64** which, in turn, have their H plane arms connected respectively to the coplanar arms **15—16** of the hybrid junction **11**. The E plane arms of the aforementioned hybrid junctions **59—60—61—62—63—64** are terminated in suitable dissipative loads. The output terminals of the aforementioned eight amplifiers are connected respectively to the coplanar arms of four hybrid junctions **65—66—67—68** which, in turn, are respectively coupled through their H plane arms to two hybrid junctions **69—70**, the H plane arms of which are coupled to the coplanar arms **38—39** of hybrid junction **32**. The E plane arms of hybrid junctions **65—66—67—68—69—70** are terminated in suitable dissipative or dummy loads. This arrangement can be carried out with any number of amplifiers equal to powers of 2, such as 2, 4, 8, 16, etc. amplifiers.

It will be readily apparent to those skilled in the art that the principle of operation as described with reference to the embodiment shown in FIG. 1 is applicable to the embodiment as shown by way of example in FIG. 2 so long as the amplifiers have equal phase shifts, equal output amplitude and equal output impedances or tank reflection coefficients of equal amplitude and phase.

FIGS. 3 and 4 show the electric-vector relationships during transmission and reception for short-slot hybrids having inherent 90° phase shifts.

With reference now to FIG. 3, the output F_O from a suitable low level driver (not shown) enters the input arm of hybrid **11** where the hybrid action splits F_O and provides a quadrature phase relation at the input electrodes of power amplifiers **17** and **18**. Both signals are amplified without relative phase change and are combined in hybrid **32** to cancel in the receiver arm and add in the antenna arm. The signal F_O from the driver is split equally to drive the klystrons, but with a 90° phase difference as indicated immediately hereinabove, all as shown in FIG. 3. In hybrid **32**, the two signals from the amplifiers add in the antenna arm and subtract in the receiver arm as shown in FIG. 3. As pointed out hereinbefore, this condition holds only if the amplifiers have substantially identical gain, phase shift and output impedance. The addition and subtraction of signals in hybrid **32** as indicated in FIG. 3 takes place because of the power-split conditions of short-slot hybrids or their equivalent require that the 90° phase shift also apply to energy entering from either arm. Therefore, the signal from amplifier **17**, for example, has a relative phase shift of +90° in the antenna arm and a relative phase shift of 0° in the receiver arm whereas the signal from amplifier **18** has a relative phase shift of +90° in the antenna arm and +180° in the receiver arm. It therefore follows that if the signals from amplifiers **17—18** have equal amplitudes they will cancel in the receiver arm and add in the antenna arm.

With reference now to FIG. 4, which shows the electric-vector relationships during reception, returned energy F_R from the antenna splits equally to amplifiers **17—18** which have substantially identical output impedances. Due to the substantially identical output impedances of the amplifiers, the received energy incident on the output electrodes of the amplifiers is reflected back without relative phase change in such a manner that none is reflected back to the antenna arm and both signals incident on the output electrodes add in the receiver arm of hybrid **32**. An auxiliary duplexer **71** comprised of hybrids **72** and **73** is utilized to provide a match sufficient to insure the proper division of power by hybrid **32** and to present a matched load for both the transmit and receive conditions. The matched input for these conditions is a normal characteristic of the short-slot hybrid duplexer. A signal entering leg **1** of hybrid **72** from the receiver arm of hybrid **32** during transmission is terminated and absorbed by the non-reflective load in leg **2**. The aforementioned received signal in the receiver arm of hybrid **32** is coupled to leg **1** of the auxiliary duplexer **71** where the hybrid action of hybrid **72** splits the signal to provide two quadrature signals at the TR tubes **74**. These quadrature signals are insufficient to fire the TR tubes and are coupled to legs **3** and **4** of hybrid **73**. The quadrature signals are coupled to the receiver in the following manner. Due to the hybrid action of hybrid **73**, the signal incident in leg **3** from the TR tubes, for example, is coupled to the receiver and the line termination in leg **4** and has a relative phase angle of +180° at the receiver and a relative phase angle of +270° in leg **4**. The signal incident in leg **4** from the TR tubes is coupled to the receiver and the line termination in leg **4** and has a relative phase angle of +180° at the receiver and a relative phase angle of +90° in leg **4**. It therefore follows that the received signals from the TR tubes **74** add at the receiver and subtract in leg **4** and that the auxiliary duplexer **71**, although not essential, provides a desirable match load for hybrid **32** for both transmit and receive conditions.

It may now be evident that the present invention utilizes microwave amplifiers in combination with microwave hybrids to substantially extend the power handling capacity of duplexers and is particularly useful for very high power transmission. An added advantage of the invention is that protective means for the receiver such as TR tubes or the like can be used with a transmitted power of at least ten times the tube's normal rating with a receiver loss increase of about .2 db or less. If desired, automatic balancing circuits well known in the art may be utilized to bring about isolations of as much as 30 db.

While preferred embodiments of the present invention have been described, it is realized that modifications may be made and it is desired that it be understood that no limitations on the invention are intended other than may be imposed by the scope of the appended claims.

What is claimed is:

1. In a microwave duplexer circuit the combination comprising: a plurality of nonreciprocal space-charge amplifiers for amplifying microwave signals, said amplifiers providing substantially equal phase shifts and output signals having substantially equal amplitudes, each said amplifier having an input electrode and an output electrode; a first hybrid junction having four terminals, one terminal being connected to a dissipative load and the conjugate terminal being adapted to receive an input signal; means connected between the input electrode of each said amplifier and the other conjugate terminals of said first hybrid junction for coupling substantially equal portions of said input signal to said input electrodes and any portion of said input signal reflected back to said hybrid junction to said dissipative load; a second hybrid junction having four terminals, one terminal being connected to an antenna and the conjugate terminal being connected to a receiver; and means connected between the output electrodes of each said amplifier and the other conjugate terminals of said second hybrid junction for coupling the output of said amplifiers to said antenna, said amplifiers having substantially equal output impedances whereby the output of each said amplifier is coupled to the antenna and radiated as a single signal and energy received from free space by the antenna is first coupled to the said output electrodes, reflected back to the second hybrid junction and coupled to the receiver.

2. In a microwave duplexer circuit the combination comprising: a plurality of nonreciprocal space-charge amplifiers for amplifying microwave signals, said amplifiers providing substantially equal phase shifts and output signals having substantially equal amplitudes, each said amplifier having an input electrode and an output electrode; a first hybrid junction having four terminals, one terminal being connected to a dissipative load and the conjugate terminal being adapted to receive an input signal; first means connected between the input electrode of each said amplifier and the other conjugate terminals of said first hybrid junction for coupling substantially equal portions of said input signal to said input electrodes and any portion of said input signal reflected back to said hybrid junction to said dissipative load; a second hybrid junction having four terminals, one terminal being connected to an antenna and the conjugate terminal being connected to a receiver; second means connected between the output electrodes of each said amplifier and the other conjugate terminals of said second hybrid junction for coupling the output of said amplifiers to said antenna, said amplifiers having substantially equal output impedances whereby the output of each said amplifier is coupled to the antenna and radiated as a single signal and energy received from free space by the antenna is first coupled to the said output electrodes, reflected back to the second hybrid junction and coupled to the receiver; and switching means operatively disposed between said receiver and said second hybrid junction for preventing currents greater than a predetermined amount from reaching the receiver.

3. The combination as defined in claim 2 wherein the switching means has a power rating of about one-tenth the transmitted power.

4. The combination as defined in claim 3 wherein the number of amplifiers is 2^n where n is an integer and said amplifiers are klystrons; said first and second means each include an even number of hybrid junctions that is two less than the number of klystrons and an equal number of said klystrons are connected respectively to each pair of said other conjugate terminals of said first and second hybrid junctions.

5. In a microwave duplexer circuit the combination comprising: 2^n nonreciprocal klystrons where n is an integer greater than 2 for amplifying microwave signals, said klystrons having substantially equal phase shifts and output signals of substantially equal amplitudes, each said klystron having a cathode, a control electrode and an anode; a first hybrid junction having first and second conjugate terminals and third and fourth conjugate terminals, said first terminal being coupled to a dissipative load and said second terminal being adapted to receive an input signal; means connecting one-half of said control electrodes to said third terminal and the other half of said control electrodes to said fourth terminal whereby substantially equal portions of said input signal are coupled to said control electrodes and said input signal reflected back to said first hybrid junction is coupled to said dissipative load; a second hybrid junction having fifth and sixth conjugate terminals and seventh and eighth conjugate terminals, said fifth terminal being coupled to an antenna and said sixth terminal being coupled to a receiver; means connecting one-half of said anodes to said seventh terminal and the other half of said anodes to said eighth terminal for combining the outputs of said klystrons to form two signals, which signals are combined and coupled to said antenna, said klystrons having substantially equal output impedances whereby energy received from free space by the antenna is first coupled to the said anodes, reflected back to said second hybrid junction and coupled to the receiver; and switching means disposed between said second hybrid junction and said receiver operative to protect said receiver during transmission.

6. In a microwave duplexer circuit the combination comprising: 2^n nonreciprocal klystrons, where n is an integer greater than 2, for amplifying microwave signals, said klystrons having substantially equal phase shifts and output signals of substantially equal amplitudes, each said klystron having a cathode, a control electrode and an anode, a first hybrid junction having first and second conjugate terminals and third and fourth conjugate terminals, said first terminal being connected to a dissipative load and said second terminal being adapted to receive an input signal; first means including n—2 hybrid junctions coupling the control electrode of one-half of said klystrons respectively to said third and fourth terminals of said first hybrid junction whereby substantially equal portions of said input signal are coupled to said control electrodes and said input signal reflected back to said first hybrid junction is coupled to said dissipative load; a second hybrid junction having fifth and sixth conjugate terminals and seventh and eighth conjugate terminals, said fifth terminal being connected to an antenna and said sixth terminal being coupled to a receiver; second means including n—2 hybrid junctions coupling one-half of the anodes of one-half of said klystrons respectively to said seventh and eighth terminals of said second hybrid junction whereby the output of said klystrons are coupled to said antenna and energy received from free space by the antenna is coupled to the receiver, the anodes of said klystrons having substantially equal phase and amplitude reflection coefficients whereby said received energy is first coupled to the said anodes reflected back to said second hybrid junction without relative phase change and coupled to the receiver; and third means disposed between said sixth terminal and said receiver operative to protect said receiver.

7. The combination as described in claim 6 wherein said third means includes at least one TR tube and means to provide a matched load for said second hybrid junction for both transmitting and receiving conditions.

8. In a microwave duplexer circuit the combination comprising: 2^n nonreciprocal amplifiers where n is an integer for amplifying microwave signals, said amplifiers having substantially equal phase shifts and output signals of substantially equal amplitudes, each said amplifier having an input circuit and an output circuit; a first hybrid junction having first and second conjugate terminals and third and fourth conjugate terminals, said first terminal being coupled to a dissipative load and said second terminal being adapted to receive an input signal; first means including $n-2$ hybrid junctions coupling one-half of said input circuits to said third terminal and the other half of said input circuits to said fourth terminal for supplying substantially equal portions of said input signal to said amplifiers and said input signal reflected therefrom and back to said first hybrid junction to said dissipative load; a second hybrid junction having fifth and sixth conjugate terminals and seventh and eighth conjugate terminals, said fifth terminal being coupled to an antenna and said sixth terminal being coupled to a receiver; second means including $n-2$ hybrid junctions coupling one-half of said output circuits to said seventh terminal and the other half of said output circuits to said eighth terminal for combining the output signals of said amplifiers and coupling them to said antenna, said amplifiers having substantially equal output impedances whereby energy received from free space by the antenna is first coupled to said output circuits, reflected back to said second hybrid junction and coupled to receiver; and switching means disposed between said sixth terminal and said receiver operative to protect said receiver during transmission.

9. In a microwave duplexer circuit the combination comprising: a plurality of nonreciprocal klystrons for amplifying microwave signals, said klystrons having substantially equal phase shifts and output signals of substantially equal amplitudes, each said klystron having a cathode, a control electrode and an anode; a first hybrid junction having first and second conjugate terminals and third and fourth conjugate terminals, said first terminal being connected to a dissipative load and said second terminal being adapted to receive an input signal; means connecting one-half of said control electrodes to said third terminal and the other half of said control electrodes to said fourth terminal whereby substantially equal portions of said input signal are coupled to the said control electrodes and said input signal reflected back to said first hybrid junction is coupled to said dissipative load; a second hybrid junction having fifth and sixth conjugate terminals and seventh and eighth conjugate terminals, said fifth terminal being connected to an antenna and said sixth terminal being connected to a receiver; means connecting one-half of said anodes to said seventh terminal and the other half of said anodes to said eighth terminal for combining the outputs of said klystrons to form two signals, which signals are combined and coupled to said antenna, said klystrons having substantially equal output impedances whereby energy received from free space by the antenna is first coupled to said anodes, reflected back to said second hybrid junction and coupled to the receiver; and switching means disposed between said second hybrid junction and said receiver operative to protect said receiver against a small portion of the transmitted power during transmission.

10. In a microwave duplexer circuit the combination comprising: a plurality of nonreciprocal klystrons for amplifying microwave signals, said klystrons having substantially equal phase shifts and output signals of substantially equal amplitudes, each said klystron having a cathode, a control electrode and an anode; a first hybrid junction having first and second conjugate terminals and third and fourth conjugate terminals, said first terminal being connected to a dissipative load and said second terminal being adapted to receive an input signal; means connecting one-half of said control electrodes to said third terminal and the other half of said control electrodes to said fourth terminal whereby substantially equal portions of said input signal are coupled to said control electrodes and said input signal reflected back to said first hybrid junction is coupled to said dissipative load; a second hybrid junction having fifth and sixth conjugate terminals and seventh and eighth conjugate terminals, said fifth terminal being connected to an antenna and said sixth terminal being connected to a receiver; means connecting one-half of said anodes to said seventh terminal and the other half of said anodes to said eighth terminal for combining the outputs of said klystrons to form two signals, which signals are combined and coupled to said antenna, said klystrons having substantially equal output impedances whereby energy received from free space by the antenna is first coupled to said anodes, reflected back to said second hybrid junction and coupled to the receiver; switching means disposed between second hybrid junction and said receiver operative to protect said receiver against a small fraction of the line current during transmission; and means disposed between said sixth terminal and said receiver for providing a substantially matched load for said second hybrid junction for both transmitting and receiving conditions.

11. The combination as defined in claim 10 wherein the switching means has a power rating of about one-tenth the transmitted power.

12. In a microwave duplexer circuit the combination comprising: a plurality of nonreciprocal klystrons for amplifying microwave signals, said klystrons having substantially equal phase shifts and output signals of substantially equal amplitudes, each said klystron having a cathode, a control electrode and an anode; a first hybrid junction having first and second conjugate terminals and third and fourth conjugate terminals, said first terminal being connected to a dissipative load and said second terminal being adapted to receive an input signal; means connecting one-half of said control electrodes to said third terminal and the other half of said control electrodes to said fourth terminal whereby substantially equal portions of said input signal are coupled to the said control electrodes and said input signal reflected back to said first hybrid junction is coupled to said dissipative load; a second hybrid junction having fifth and sixth conjugate terminals and seventh and eighth conjugate terminals, said fifth terminal being connected to an antenna and said sixth terminal being connected to a receiver; means connecting one-half of said anodes to said seventh terminal and the other half of said anodes to said eighth terminal for combining the outputs of said klystrons to form two signals, which signals are combined and coupled to said antenna, said klystrons having substantially equal output impedances whereby energy received from free space by the antenna is first coupled to said anodes, reflected back to said second hybrid junction and coupled to the receiver; and third means coupling said sixth terminal to said receiver operative to protect said receiver during transmission and provide a substantially matched load for said second hybrid junction, for both transmitting and receiving conditions, said third means comprising a third and fourth hybrid junction and a pair of transmit-receive tubes operatively disposed therebetween.

13. In a microwave duplexer circuit the combination comprising: a plurality of nonreciprocal klystrons for amplifying microwave signals, said klystrons having substantially equal phase shifts and output signals of substantially equal amplitudes, each said klystron having a cathode, a control electrode and an anode; a first hybrid junction having first and second conjugate terminals and third and fourth conjugate terminals, said first terminal being connected to a dissipative load and said second terminal being adapted to receive an input signal; means

connecting one-half of said control electrodes to said third terminal and the other half of said control electrodes to said fourth terminal whereby substantially equal portions of said input signal are coupled to said control electrodes and said input signal reflected back to said first hybrid junction is coupled to said dissipative load; a second hybrid junction having fifth and sixth conjugate terminals and seventh and eighth conjugate terminals, said fifth terminal being connected to an antenna and said sixth terminal being connected to a receiver; means connecting one-half of said anodes to said seventh terminal and the other half of said anodes to said eighth terminal for combining the outputs of said klystrons to form two signals, which signals are combined and coupled to said antenna, said klystrons having substantially equal output impedances whereby energy received from free space by the antenna is first coupled to said anodes, reflected back to said second hybrid junction and coupled to the receiver; and a short slot hybrid duplexer having four legs and

coupling said sixth junction to said receiver for protecting said receiver during transmission and providing a substantially matched load for said second hybrid junction during both transmission and reception, said duplexer comprising a third and fourth hybrid junction each forming a pair of said legs, one leg of each said pair being terminated at one end in a dissipative load and in communication at the other end with the other leg of the other pair, one of said other legs being coupled to said sixth terminal and the other to said receiver, and a transmit-receive tube disposed intermediate each terminated leg and the said other leg with which it is in communication.

References Cited in the file of this patent

UNITED STATES PATENTS

2,704,351	Dicke	Mar. 15, 1955
2,847,517	Small	Aug. 12, 1958