Theory Of The Quarter Wavelength (3db) Hybrid

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1 Theory Of The 3db Hybrid

The information presented in this paper is intended only as an overview. It should provide a good working knowledge of 90° hybrids while employing minimal math during the analysis.

A quarter wavelength 3db hybrid is a section of transmission line that contains two equal center conductors. See Figure 1-1.

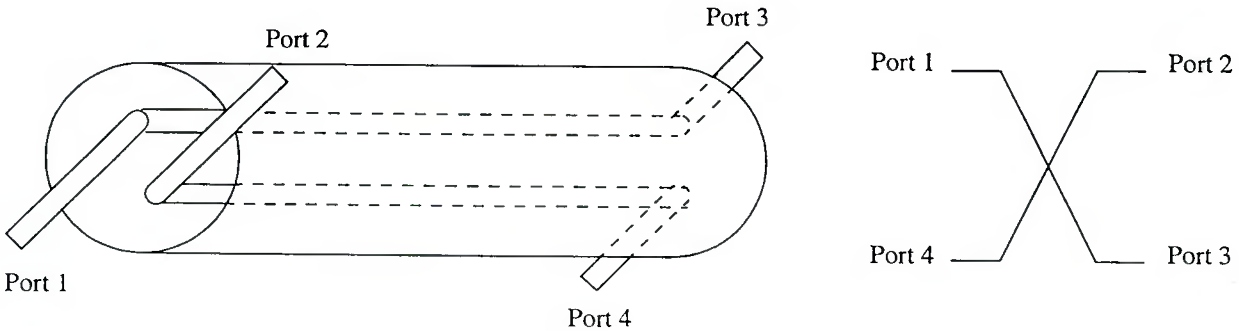

Figure 1-1 View of a 3dB Hybrid (Physical Construction) and Symbol (shown on the right)

For convenience, the center conductors are crossed at the end to make the standard connection easier. The ports are numbered 1 through 4. Figure 1-1 shows the symbol (right side of drawing) and Figure 1-2 shows the outline of a typical VHF hybrid with 3 1/8 inch connectors.

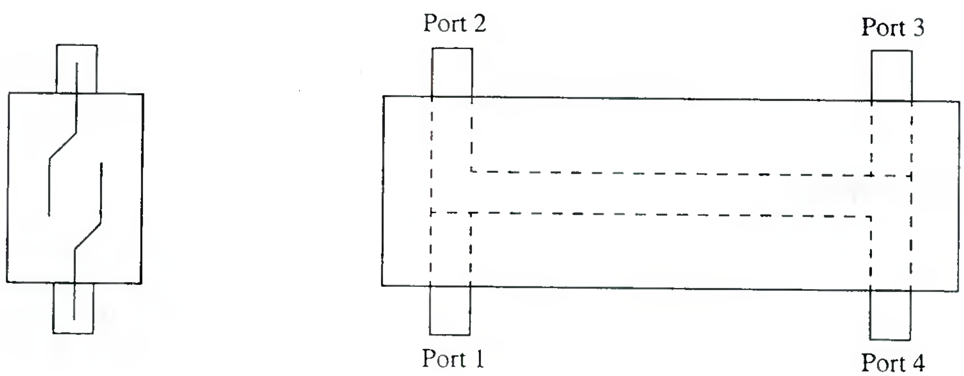

Figure 1-2 End View (left) and Outline Drawing (right) of a 3dB Hybrid

1.1 Review of a Directional Coupler

The concept of a 3db hybrid is not new. Consider the standard directional coupler shown in Figure 1-3. It is much like a 3db hybrid except that the power is not split equally. It is a section of transmission line that has a smaller second conductor. We will assume that this coupler has an isolation of 30db. If one volt is applied to the input port, the output of the coupled port will read approximately 32 millivolts. The load (at output port) will see approximately 0.9995 volts. The coupled port will respond only to power going from generator to load as long as its reject load is in place.

If the millivolt meter and the reject load are switched, the millivolt meter will read only reflected power (power going from load to generator). The level will be 30db below the actual value of reflected power.

To nail down some terms, the insertion loss is the power that is taken from the output load to provide the output for the coupled port. In the above example, the insertion loss is 0.004db.

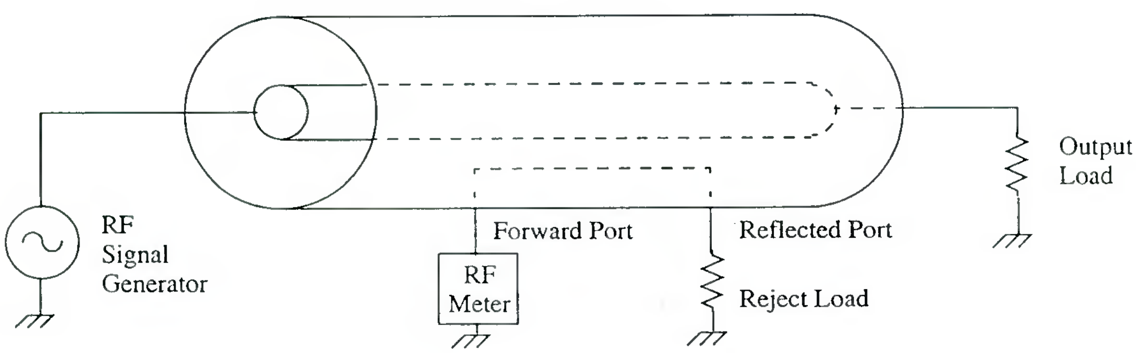

Figure 1-3 View of a Directional Coupler

The isolation is the level at the coupled port compared to that applied by the generator. The isolation of our example is 30db.

1.2 Splitting Hybrid

Figure 1-4 shows a 3db hybrid connected as a splitter. In terms of a directional coupler, port 1 is the input port, port 3 is the output port, port 2 is the coupled port, and port 4 is the reject load. In this case the insertion loss is 3db and the isolation is 3db. Remember that a 3db loss represents one-half power. Thus the input power is split equally with half appearing at port 2 and the other half appearing at port 3.

The reject load sees no power as long as the output loads have a good match. If the match of one but not both output loads is poor, the reflected power will split equally between the generator and the reject load. If both output loads are mismatched, the reflected power can appear at the generator, the reject load, or both depending on the relative phase and amplitude of the two reflected signals. This will make more sense later when we look at the 3db hybrid as a combiner.

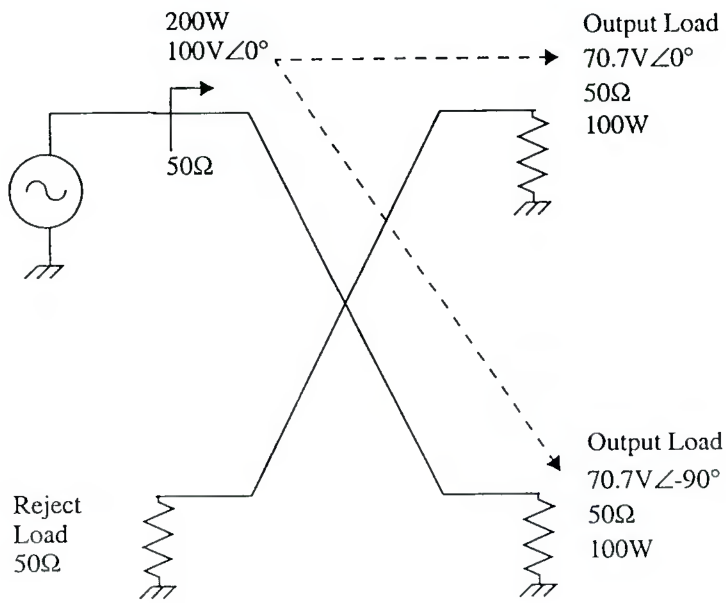

Figure 1-4 The 3db Hybrid used as a Splitter.

1.2.1 Voltage And Phase Relationships of a Splitting Hybrid

In Figure 1-4 if the voltage at port 1 is 100 V at a reference angle of 0° then the voltage at port two is 70.7 V ∠.0°. The voltage at port 3 is 70.7 V ∠.-90°. The 90° phase lag occurs because the length of the hybrid is one quarter wavelength (90°) between ports 1and 2 to port 3 and 4. It takes little time to progress from port 1 to port 2 (directly across). This time is unimportant to this discussion so the phase angle remains unchanged. It takes 90° to progress from port 1 to port 3 (diagonally across the hybrid). The important thing to keep in mind is the relative 90° difference of phase at port 2 and port 3. The output voltage is determined by the following equations:

If Power out = 1/2 power in, then Voltage out = 0.707 voltage in.

Using the formulas $P = \frac{E^2}{Z}$

100 V produces 200 W at the 50Ω input and 70.7 volts produces 100 W at each of the two 50Ω outputs.

1.3 Combining Hybrids

A 3dB hybrid may be used to combine the outputs of two amplifiers to satisfy the system power requirements. To accomplish this, the output of the RF source is split, with each output being used to drive one amplifier. Care must be taken to deliver the same voltage level at the required phase angle to the input of each amplifier.

When used as a combiner, two signals are applied to port 1 and port 4 such that both voltages are equal and port 4 lags port 1 by 90° of phase, see Figure 1-5. When these conditions are met, all of the power of both amplifiers will add in the output load and cancel in the reject load. If the applied voltages are not equal or the phase difference is not 90°, the power will divide between the output load and the reject load.

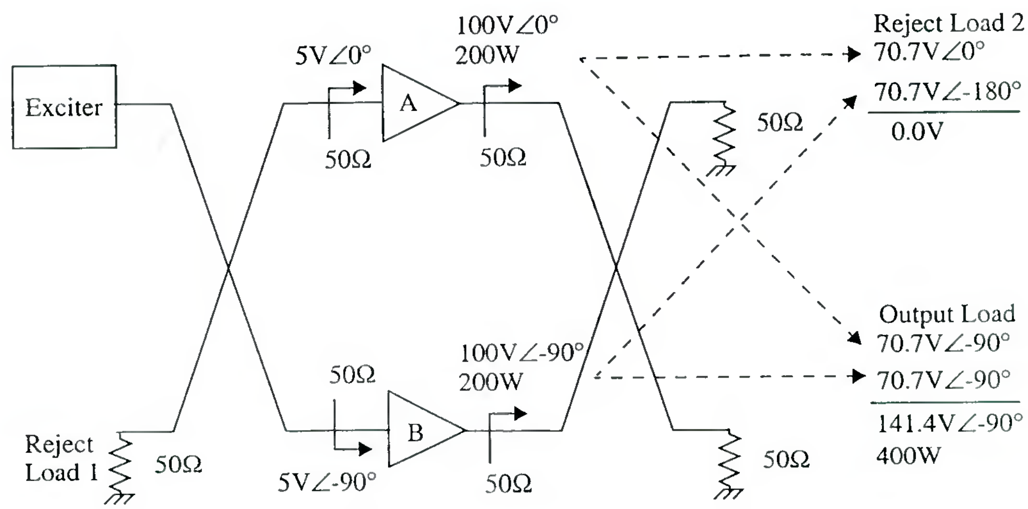

Figure 1-5 3db Hybrid Used as a Combiner

1.3.1 Analysis of the Combining Operation

Refer to Figure 1-5. The output voltage of amplifier A (100 V ∠.0°) is applied to port 1. At port 2, directly across, the voltage that appears as a result of the voltage applied to port 1 is 70.7 V ∠.0° (half power). The voltage that appears at port 3 as a result of the voltage applied to port 1 is 70.7 V ∠-90°. Remember that it takes time equal to 90° of phase to travel diagonally across the hybrid.

THe output voltage of amplifier B (100 V ∠.-90°) is applied to port 4. The voltage at port 2 as a result of the voltage applied to port 4 is 70.7 V ∠−180°. The voltage applied to port 4 had a phase angle of -90° and lost another 90° of phase in its diagonal transit across the hybrid.) As a result of the voltage applied to port 4, the voltage at port 3 is 70.7 V ∠.-90°. No additional time is lost going directly across the hybrid.

At port 2 the two voltages appearing are 70.7 V ∠.0° and 70.7 V ∠–180°. Note that they cancel since they are equal in amplitude and 180° out of phase.

.At port 3 the voltages are both 70.7 V ∠.-90°. They will add to provide 141.4 V ∠.-90°. This is twice the power of either source. (Remember if Power out = 2 Power in, then voltage out = 1.414 voltage in.)

1.3.2 Combining With Unequal Voltage

With unequal voltages applied, but at the proper 90° phase difference, the voltage at the reject load is 84.8V∠0° from amplifier A and 70.7V ∠-180° from amplifier B, see Figure 1-6. The signals do not cancel even though they are 180° out of phase because of the unequal voltages at the reject load.

The power at the output (484 W at port 3) is not quite equal to the sum of the two input powers (488 W). It is lower by the amount of power appearing in the reject load (4 W).

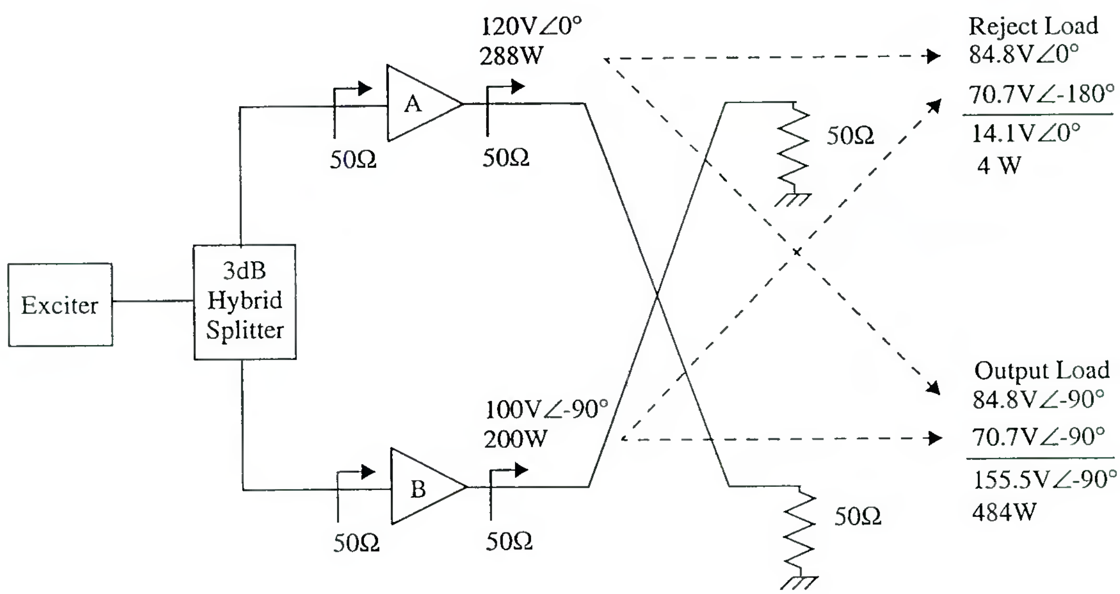

Figure 1-6 Combining with Unequal Voltages

1.3.3 Combining With Improper Phases

Refer to Figure 1-7. The applied voltages (from amplifiers A and B) are equal in amplitude, but do not have the required 90° phase difference. At the reject load, the voltages are equal but not 180° out of phase and therefore do not cancel. In Figure 1-7, both amplifiers are delivering 100 V but the two voltages are only 60° out of phase.

The resultant voltage at the reject load (port 2) is approximately 36.6V∠-75°, see vector diagram on left side of Figure 1-8.

At the output port (port 3) the voltages are not quite in phase and do not totally add. Their vector sum based on the above example is approximately 136.6V∠-75°, see vector diagram on right side of Figure 1-8.

Looking at power, 200 W is applied at port 1 and port 4 for a total of 400 W input. At the output (port 3), 373 W is present with the other 27 W appearing at the reject load (port 2).

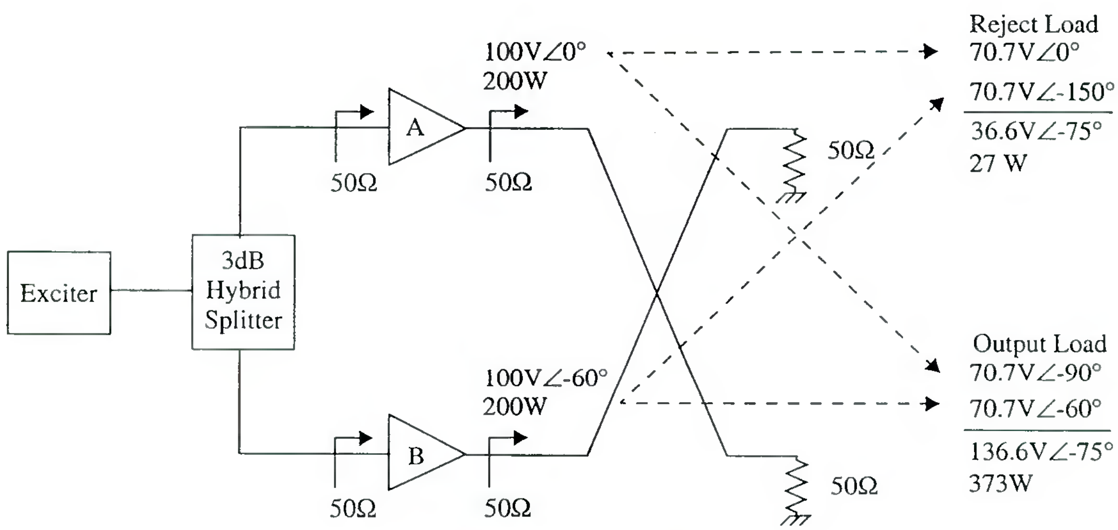

Figure 1-7 Combining With Improper Phase Relationship

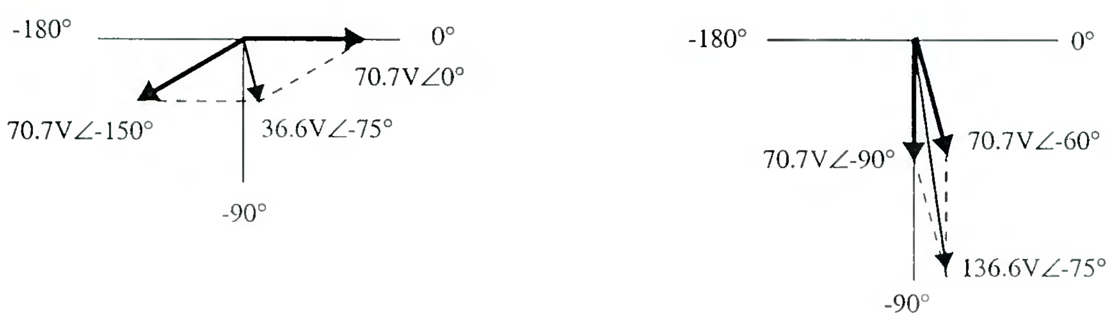

Figure 1-8 Vector Diagram, Reject Load Voltage (left) and Output Voltage (right)

1.3.4 Combining With Equal Voltages And Phases

In Figure 1-9, if the outputs of amplifiers A and B (applied to ports 1 and 4 respectively) are the same voltage at the same phase, the outputs at port 2 and port 3 will have the same voltage at a phase angle of 45° behind the inputs (see vector diagram Figure 1-10).

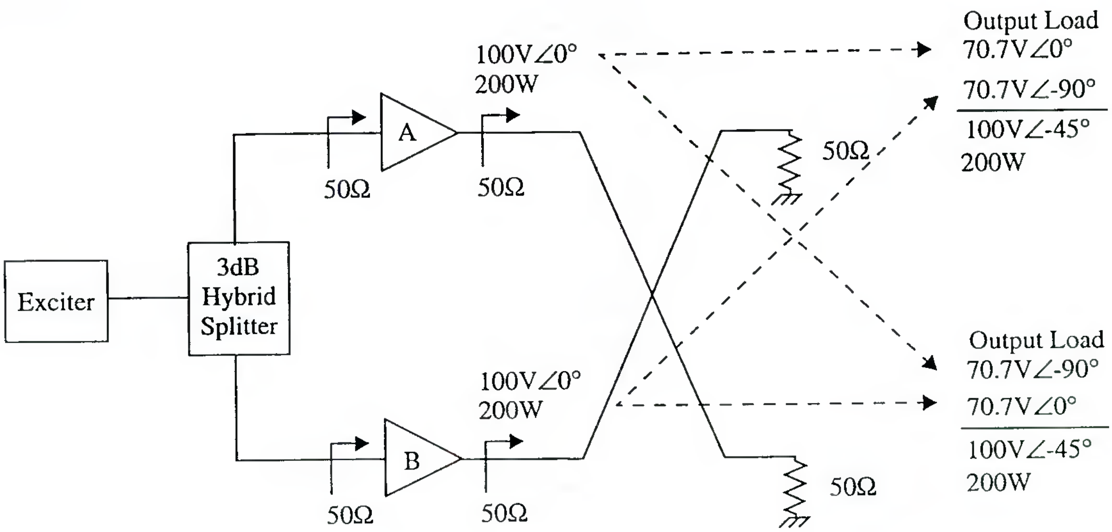

Figure 1-9 Combining With Equal Input Voltages at Same Phase Angle

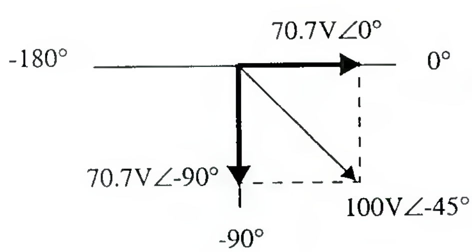

Figure 1-10 Vector Diagram (Combining With Equal Input Voltages At Same Phase Angle)

1.4 3db Hybrid Parameters

.Parameters of a 3db hybrid that concern of Field Personnel are the input VSWR, the split ratio, isolation between outputs. and the reject isolation.

A 3db hybrid is a symmetrical device. Any port can be the input and any port can be the output. The numbers are usually assigned to take advantage of the best combination of parameters for the application. The hybrid can be flipped so that another port is the input, Figure 1-11 shows the hybrid installed with port 1 as the input. The hybrid can be installed based on the most favorable parameter after testing.

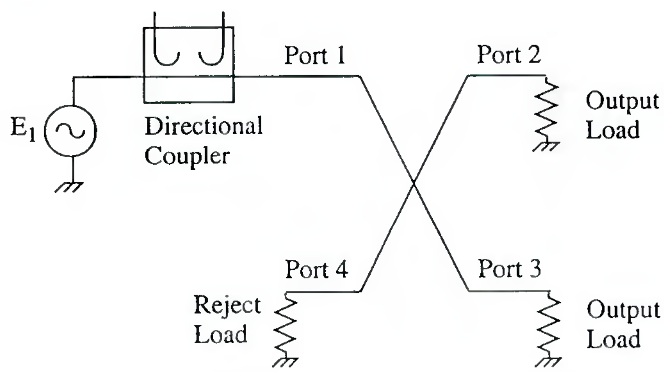

Figure 1-11 Hybrid Testing

1.4.1 Testing Hybrids

Apply a small signal from an RF signal generator to port 1 through a directional coupler. Terminate the other-ports-with high quality loads, see Figure 1-11. These loads should have a return loss of -35db or better. (A VSWR of 1.035 represents a -35db return loss.)

TEST 1. Input VSWR measured at the directional coupler at port 1. The input VSWR should be better than 1.1 to 1 (-26db return loss).

TEST 2. The split ratio of port 2 and port 3. The RF from these ports can be measured by substituting a 50 ohm millivolt meter (or other low power RF measuring device which has a 50 ohm input) in place of one load at a time on port 2 and 3. The voltages should be within 0.ldb of each other.

TEST 3. The isolation. Substitute the 50 ohm millivolt meter in place of the load at port 4 and read the RF voltage. it should be at least 30db lower than the voltage applied to port 1. Isolation port 2 to port 3 may -be, checked by rotating the hybrid 180° (Figure 10B). Basically the measured isolation port 2 to port 3 should be approximately equal to that of port 1 to port 4.

1.5 USES OF THE 3DB HYBRIDS

3dB hybrids are used in multiple applications because of their broad bandwidth and excellent combining characteristics in spite of input voltage or phase imbalances. Only a few of the many applications are covered in this report.

1.5.1 Parallel Amplifiers

When it is desirable to operate parallel final amplifiers to achieve greater power output. Two 3db hybrids (Hy 1 and Hy 2) are used to split the common drive signal and combine the output signals of the two amplifiers. We assume the amplifiers have equal gain and delays.

Hy 1 receives 7.07V∠0° from the exciter or IPA amplifier. It splits the signal into two equal parts to drive amplifiers A and B.
Amplifier A gets 5V∠0° from port 2 of Hy 1 and delivers 100V∠0° to port 1 of Hy 2.
Amplifier B gets 5V∠-90° from port 3 of Hy 1and delivers 100V∠-90° to port 4 of HY 2.

Reject load #2 (port 2 of HY 2) gets 70.7V∠0° from amplifier A and 70.7V∠-180° from amplifier B. The two voltages are opposite in phase and cancel leaving zero volts in the reject load.

In the output load (port 3of HY 2) both voltages are 7.07V/--90. The sum of these two voltages is 141.4V∠-90°, which is 400 W.

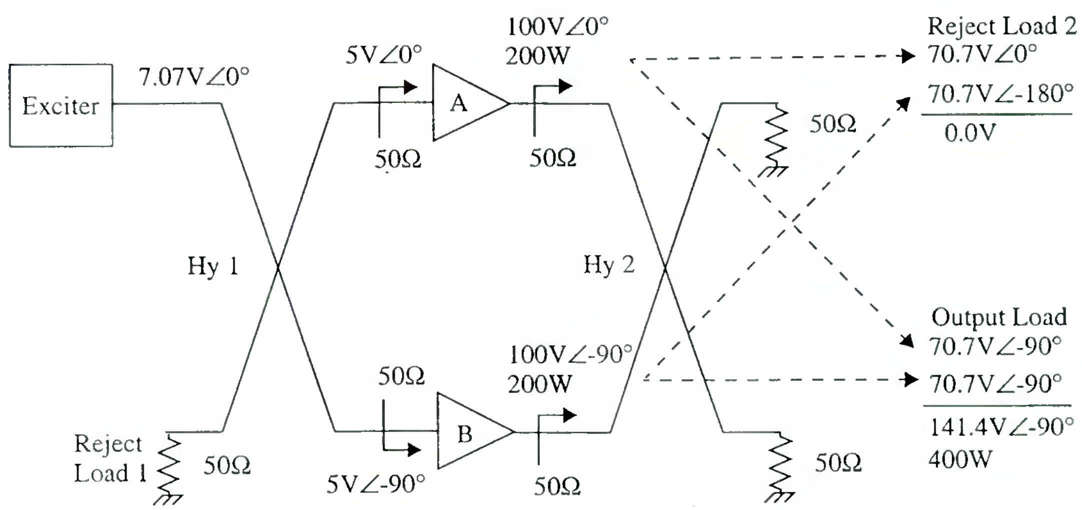

Figure 1-12 Operating Parallel Amplifiers

1.5.1.1 Adding Phase and Gain Adjustments

The outputs of the two amplifiers must have the same voltage (power) and be at the correct phase to ensure proper combining into the output load. With parallel amplifiers this necessitates controls to balance power and adjust phase.

Refer to Figure 1-13. Two attenuators and a line stretcher have been added to direct the outputs of the amplifiers through Hy 2 to the output load. This is necessary because multiple real world amplifiers (even solid state amplifiers) will have slight gain and phase differences between them. This is especially true of vacuum tube amplifiers, where input tuning has a large affect on phase, and output tuning has a large affect on gain.

Equal output power is obtained in each amplifier by adjusting attenuator AT1 and/or AT2 for minimum power at reject load 2 (port 2 of HY 2). The reject load wattmeter is for this purpose.

The two attenuators may be separate devices installed as shown in Figure 1-13, or the gain control of the IPA or driver stage or the automatic power control (APC) of amplifiers A and B may serve the function.

Proper phase of the amplifier's output signal is obtained by adjusting the line stretcher for minimum power at reject load 2. The line stretcher changes the length of line feeding one amplifier and thus its input phase. A fixed length of line is added to the input of the other amplifier as a coarse phase, to set the output of the two amplifiers at the required 90° phase difference with the line stretcher set at mid range.

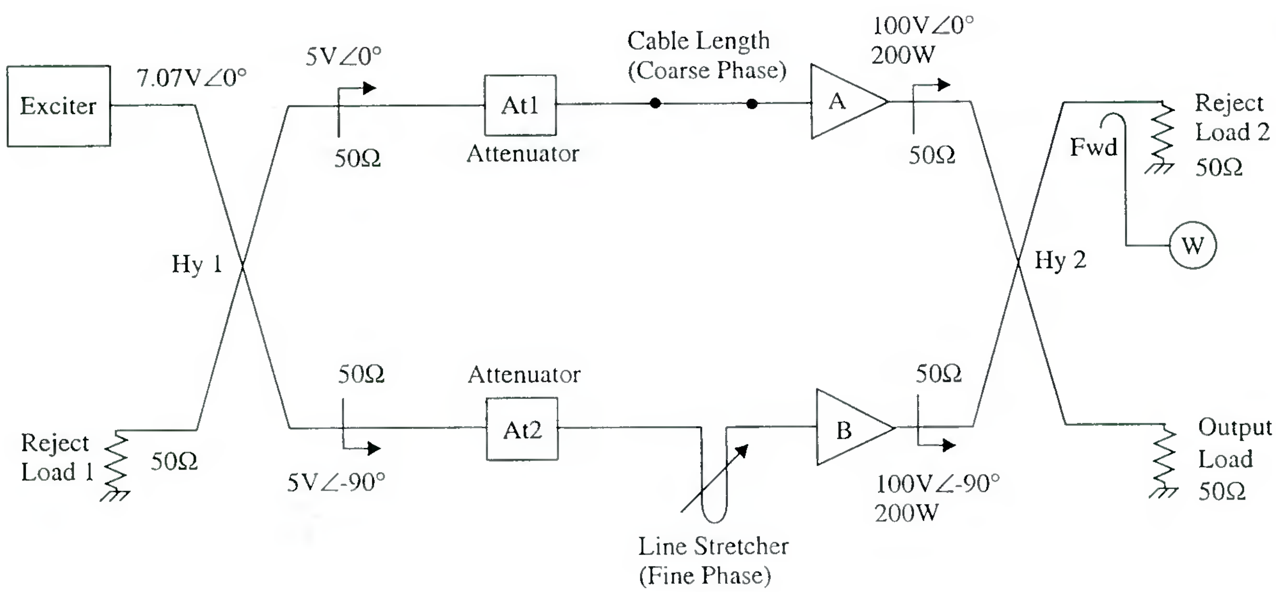

Figure 1-13 Phase and Gain Adjustments Added to the Combining System

1.5.1.2 Power Balance With a Second Line Stretcher

A convenient method for controlling power split and phasing of parallel amplifiers can be created by the use of two 3db hybrids and two line stretchers, as shown in Figure 1-14.

Hy 1 divides the power into two equal components that are 90° out of phase. By using proper lengths of cable between ports 2 and 1 of Hy 1 and Hy 2 (the coarse adjustment), and the line stretcher (LS1) between ports 3 and 4 of the same hybrids, the signals at ports 1 and 4 of Hy 2 will be equal in phase and amplitude. This will cause the output of HY 2 (ports 2 and 3) to be equal phase and equal amplitude.

If (LS1) is varied, the relative phase of the signals at the inputs of HY 2 will no longer be the same. This will cause the power levels at the outputs of HY 2 to be uneven. Thus (LS1) is the power balance control for the parallel amplifiers replacing the attenuators. This has the advantage of much less power loss than would be encountered if attenuators are used.

LS2 junctions as the phase adjustment for the amplifiers. The required 90° phase difference between the amplifiers inputs is established by the proper cable length between ports 2 and 1 of hybrids 2 and 3 and line stretcher 2 between ports 3 and 4 of the same two hybrids.

The length of each phasing cables is selected to put its respective line stretcher at its mid range while maintaining proper combined operation of the two amplifiers.

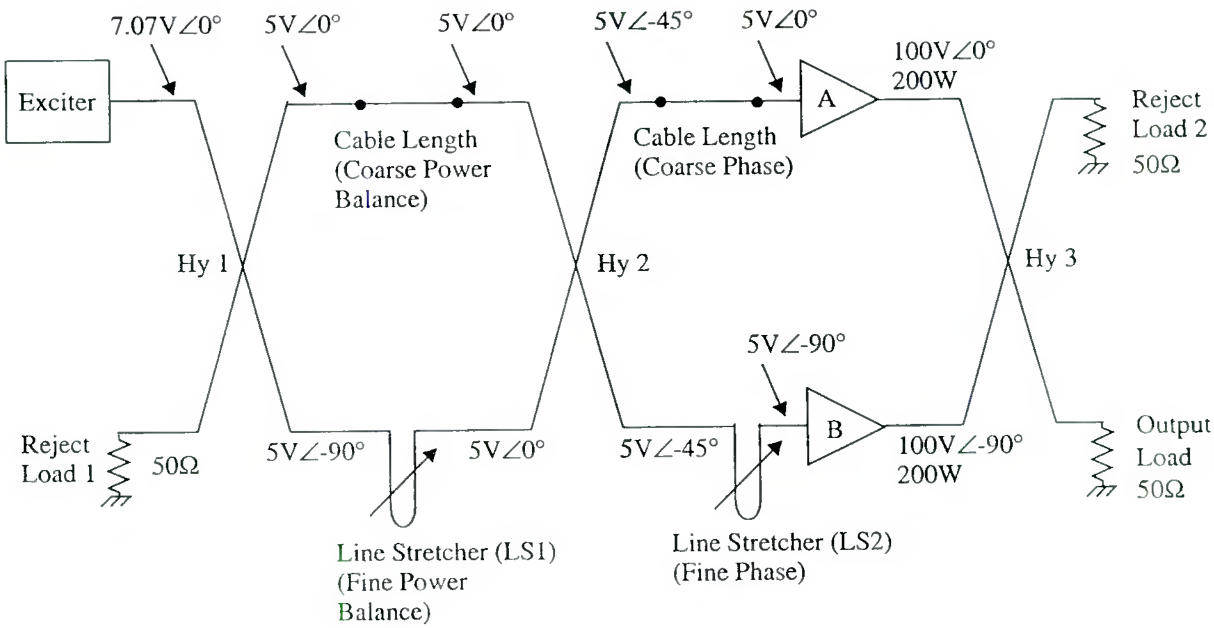

Figure 1-14 Attenuators Replaced With Another Line Stretcher and Hybrid

1.5.2 The Non Reflecting, Voltage Controlled Attenuator

A problem exists with variable RF attenuators if the-input and output impedance is not matched. A VSWR can occur that will cause a reflection into the generator detuning or damaging it. By the use of two 3db hybrids and two PIN diodes, an attenuator with constant input and output impedance can be built. Any reflection from the PIN diodes while they are attenuating will end up in reject load #1.

In the circuit in Figure 1-15 if no forward bias is applied to the PIN diodes, they have a high RF impedance and will not ground the signal. All of the signal will go to the output load.

Assume that a forward bias (in the case of Figure 1-15, a positive voltage applied from the battery and potentiometer) is applied to the PIN diodes through the control voltage input. The diodes will develop a low RF resistance and ground the RF signal through capacitor C. The RF impedance of a PIN diode is inversely proportional to the forward bias current flowing through it.

The action of the hybrids should be understood by now, so only a brief explanation will be attempted. The signal applied to port 1 of HY 1 is split into two equal parts with port 3 lagging port 2 by 90°. The signal is passed to HY 2 such that the amplitudes are still equal but port 4 of HY2 lags port 1 of HY2 by 90°. This causes the signal the output load to add and cancel in the reject load of HY 2.

When the PIN diodes are forward biased and attenuating the signal they create an.impedance mismatch. This will cause some of the signal to be reflected back into Hy1 The reflected signal (Er) from D 1 to port 2 of HY1 will be at a phase angle of 0°. The phase of the reflected signal (Er) from D2 to port 3 of HY 1 will be -90°. It is assumed that common forward bias on the PIN diodes will reflect the same amount of RF voltage back to HY1. The reflected signal will add in reject load #1 (port 4 of HY1) and cancel at port 1 (the input port).

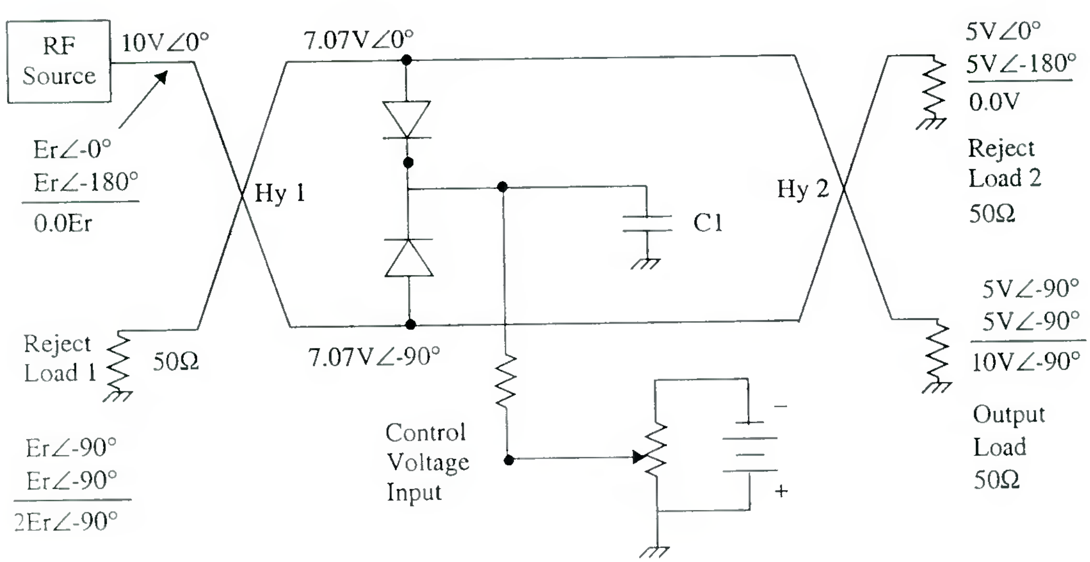

Figure 1-15 Non Reflecting Attenuator

1.5.3 Variation of the Non Reflecting, Voltage Controlled Attenuator

This version of the non reflecting attenuator has the advantage of using one hybrid instead of two. It is often used on printed circuit boards when a voltage controlled attenuator is required.

In the circuit in Figure 1-16, the signal from the RF source is applied to port 1 of the hybrid. The hybrid splits the signal into two components, which are applied to the combinations of R1, D1 and R2, D2. If no forward bias is applied to the PIN diodes, they have a high RF impedance. R1 and R2 will provide a perfect 50Ω load for the two signals, resulting in no reflection and no signal at the output load.

A forward bias (in the case of Figure 1-16, a negative voltage applied from the battery and potentiometer) is applied to the PIN diodes through the control voltage input. When the PIN diodes are forward biased the parallel combination of the resistor and the diode will cause the load impedances at ports 2 and 3 of the hybrid to go below 50Ω. This will cause some of the signal to be reflected back into Hy1. It is assumed that common forward bias on the PIN diodes will cause the same amount of RF voltage to be reflected back to ports 2 and 3 of HY1. The reflected signal will add in the output (port 4 of HY1) and cancel at the input (port 1). Therefore, greater forward bias (control voltage) results in less attenuation (more output) and less forward bias causes greater attenuation.

This circuit has a typical attenuation range of -5 to -45 dB.

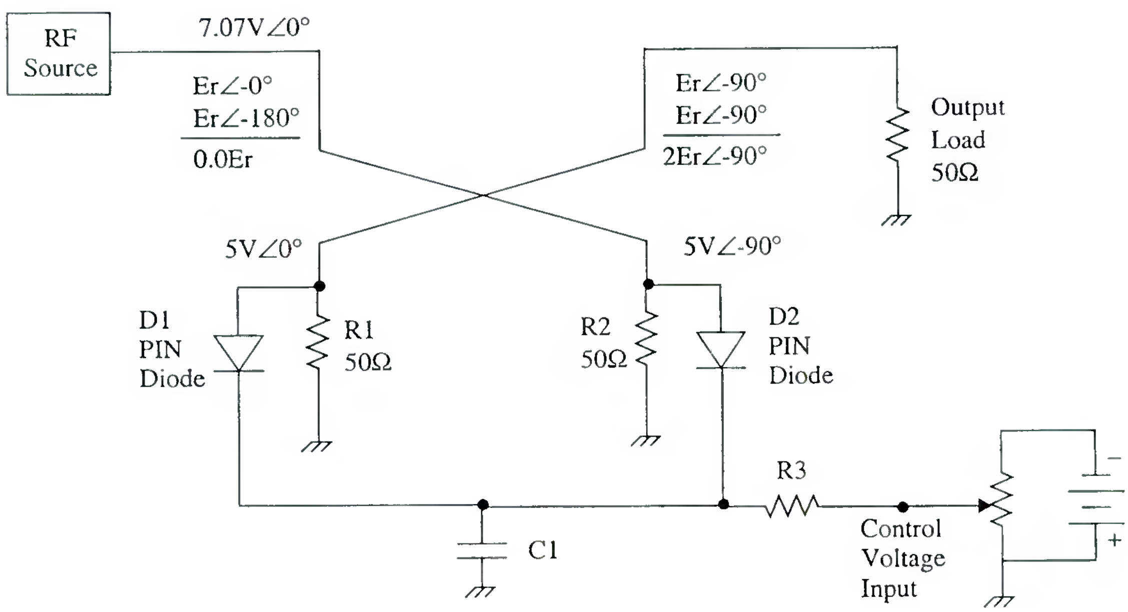

Figure 1-16 Another Non Reflecting Attenuator

1.5.4 Non Reflecting, Voltage Controlled Phase Shifter

The non reflecting, voltage controlled phase shifter uses one hybrid. It is often used on printed circuit boards when a voltage controlled phase shifter is required. A typical application is for this circuit to replace the line stretchers in multiple power amplifier transmitter systems, with the required control voltage provided by manual or automatic means.

In the circuit in Figure 1-17, the signal from the RF source is applied to port 1 of the hybrid. The hybrid splits the signal into two components, which are applied to the varicap diodes, D1 and D2. The diodes are located at the outputs of the hybrid and, due to the capacitive load they present, always reflect 100% of their signal back to the hybrid.

A reverse bias (in the case of Figure 1-17, a positive voltage applied from the battery and potentiometer) is applied to the varicap diodes through the control voltage input. This causes the capacity of the diodes to change, which results in a variable phase shift to the RF signals they reflect. The common forward bias is applied to the diodes results in both having the same capacity and phase shift. Since the voltage applied to the diodes had a 90° phase difference, the reflected signal will also have the same 90° phase difference. This causes the reflected signals to add in the output (port 4 of HY1) and cancel at the input (port 1).

Varying the reverse bias (the control voltage) produces a variable phase shift from the input to the output.

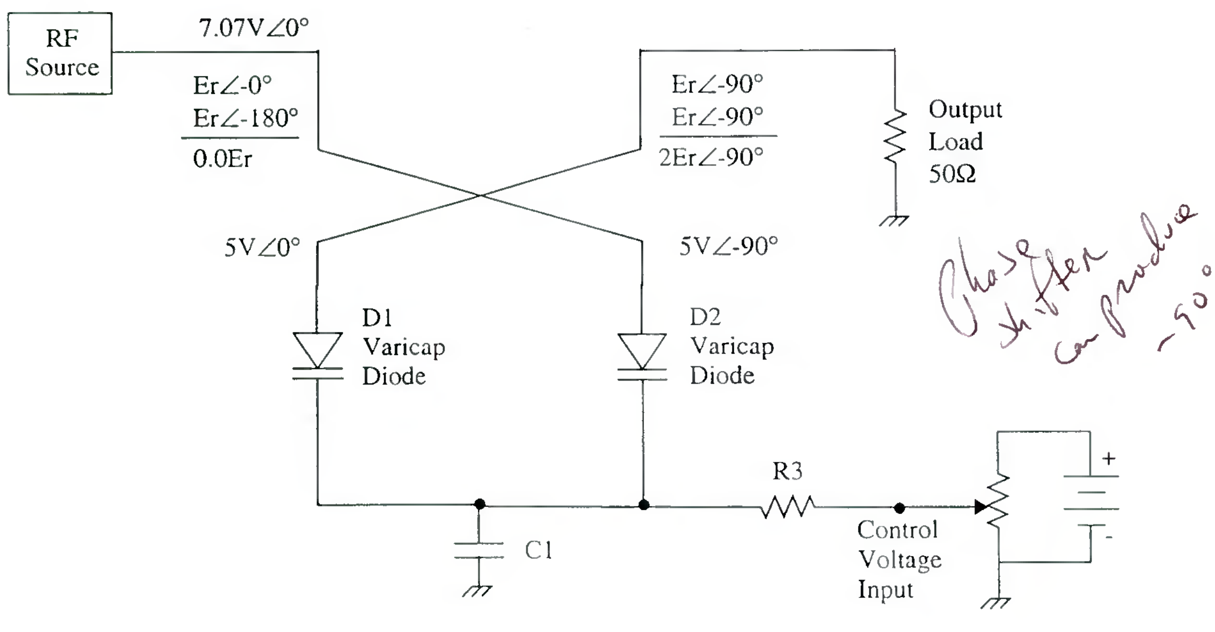

Figure 1-17 Non Reflecting, Voltage Controlled Phase Shifter

1.5.5 The Hybrid Diplexer

Many TV antennas require two separate feeds of equal power with a phase shift of 90° or 0° between lines. This can be accomplished easily using a 3db hybrid as a diplexer. The 3db hybrid outputs will each have half of the total input power of each transmitter and will be 90° out of phase. The hybrid diplexer will act like a splitting hybrid for the visual and aural transmitter.

If the visual signal in Figure 1-18 is 1000V∠0° at port 1, it will be 707V∠0° at port 2 and 707V∠-90° at port 3. The aural transmitter will see no visual power, it's position will be that of a reject load for the visual transmitter.

The aural signal, 316V∠0°, is applied at port 4. The signal at port 3 will be 223V∠0°. At port 2 the signal will be 223V∠-90°. No aural signal will be seen at port 1. The visual transmitter will act as reject load for the aural transmitter.

A reflection from either transmission line will divide equally between the visual and aural transmitter. A reflection from both lines can appear in the visual transmitter, the aural transmitter, or both depending upon phase and power level of both reflected signals. The effect of the visual to aural reflection will be the most noticeable. This is because of the greater visual power. It is characterized by an increase of aural VSWR as the visual power is increased. A signal from one transmitter reflecting into the other is referred to as cross coupling of reflected signals.

The faulty transmission line or antenna can usually be isolated by terminating one, the other or both of the output ports of the 3db hybrid in a 50 ohm load capable of handling the power.

1.5.5.1 Multiplexing Two Television Transmitters

The hybrid diplexer can be used to multiplex adjacent channel digital and aural television transmitters into one wide band antenna. Refer to Figure 1-18 The digital transmitter is connected in place of the aural transmitter and the analog television transmitter is connected in place of the visual transmitter. The visual and aural of the analog transmitter must have been combined, either by way of a common mode transmitter or through the use of a notch diplexer.

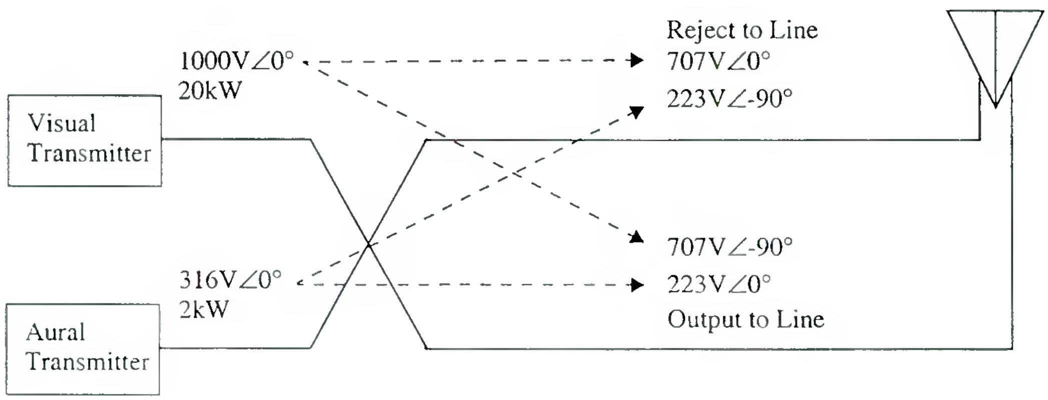

Figure 1-18 The Hybrid Diplexer

1.5.6 Notch Diplexer

A notch diplexer has the advantage of combining both visual and aural transmitter into one transmission line.

In Figure 1-19, the visual transmitters power is split by HY1 and combined by HY 2 in port 3. The visual signal cancels in the aural transmitter, port 2 of HY 2. For the visual transmitter, Hy1 is a splitting hybrid with ports 2 and 3 the outputs. Hy2 is a combining hybrid with ports 1 and 4 as inputs and port 3 as the output.

In Figure 1-20, the notch diplexer is shown without the resonant cavities (equivalent series resonant circuits). This will help explain the aural path and the visuals isolation from the aural. The aural signal is applied to HY 2 at port 2 and splits into two equal parts at ports 1 and 4. The signal at port 4 is 90° behind the signal at port 1.

Here is where the series resonant cavities in Figure 16C come into play. Without them, these two signals would go to ports 2 and 3 of Hy 1 where they would combine in the reject port (and cancel in port 1, the visual transmitter).

Now refer to Figure 1-21. The series resonant cavities between the hybrids are high Q circuits and they are tuned to the aural frequency. The aural cavities (cavity 1 and 2 in Figure 1-21) appear as a very low impedance (mismatch) to the aural signal. This causes the aural signal to reflect back to ports 1 and 4 of HY 2 in the same relative phase. The voltage at port 1 of HY 2 is $707V\angle 0°$ and the voltage at port 4 of HY 2 is $707V\angle -90°$. These reflected signals cancel at port 2 of Hy2 (the aural transmitter output port and add in the antenna port.

The series resonant cavities cause group delay at the upper end of the visual pass band, but, except for a slight roll off at the upper end of the video pass band, have little effect on the amplitude response of the visual transmitter. The group delay caused by the notch diplexer must be corrected by a notch diplexer equalizer (a series of all pass networks). The visual signal flow of Figure 1-19 is still valid.

1.5.6.1 Notch Diplexer Adjustments

Always consult the manufacturers literature or representative before adjusting the notch diplexer

In practice, the only adjustments that are normally made in the field are the frequency of the resonant cavities. The tuning of the resonant cavities should be checked with the diplexer operating into the station load. Adjustment should only be made after operating temperatures have been achieved. Only small adjustments should be made permitting system to stabilize after each adjustment. If drastic changes occur when operating into the antenna, a further check of the transmission line and/or antenna is in order.

For some notch diplexers, probes are available that can be screwed into the diplexer lines in the vicinity of the resonant cavities. For these diplexers, both visual and aural transmitters are operated at full power, and the cavities adjusted for minimum aural carrier, as viewed from these special probes by a spectrum analyzer.

The general method of adjustment is to operate only the aural transmitter. The series resonant cavities are then tuned for minimum visual VSWR, aural VSWR and reject load power. Normally the visual VSWR from the aural transmitter will be quite low. The aural VSWR might not null at the same place that minimum reject load power occurs. If this happens, a compromise is necessary to decide which parameter should be the lowest. Normally both are quite low, but if a null occurs where one or the other is too high (VSWR of over 1.3, or 5% aural power in reject) other problems in the diplexer and/or output system might exist.

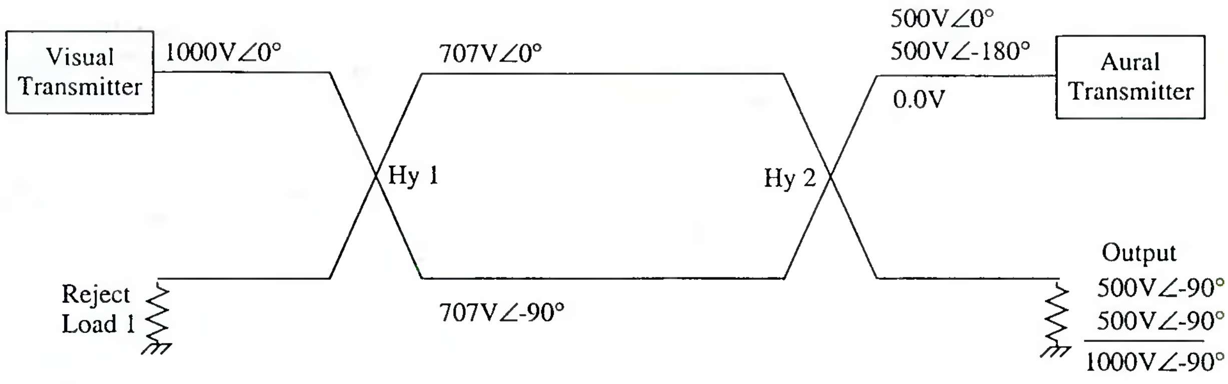

Figure 1-19 Notch Diplexer Visual Signal Flow (Aural cavities not shown).

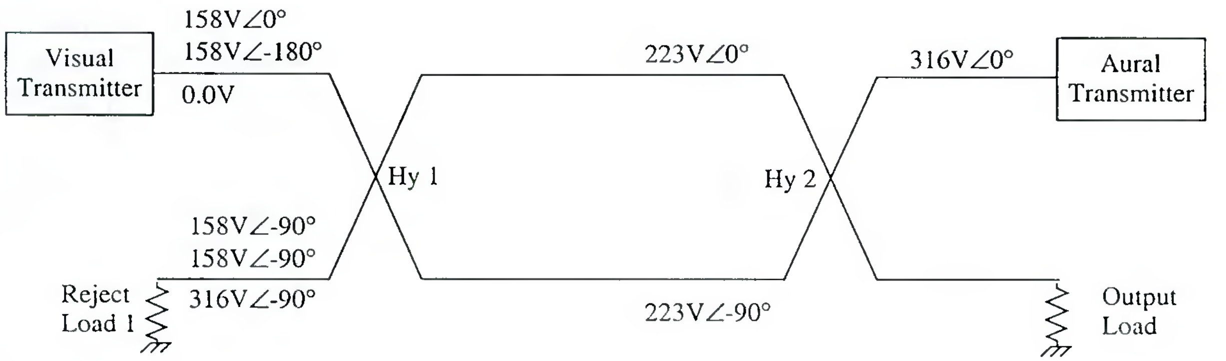

Figure 1-20 Notch Diplexer Aural Signal Flow Without Aural Cavities

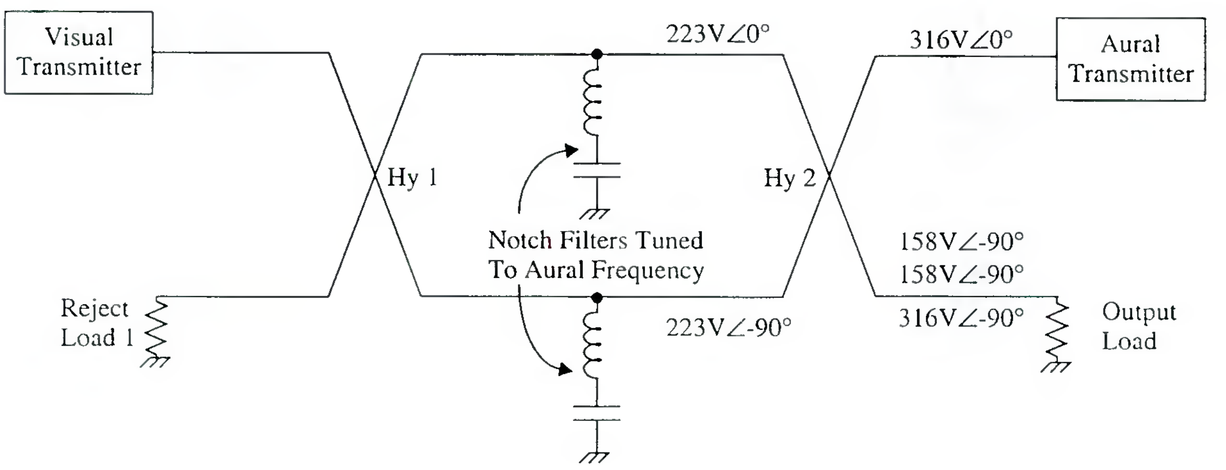

Figure 1-21 Notch Diplexer Aural Signal Flow With Aural Cavities

1.5.7 Constant Impedance Filter

A bandpass filter is intended to pass a band of frequencies and reject others. It usually reflects the components that it rejects back to the amplifier that supplied the signal to the filter. If amplifier performance is degraded by the reflected energy from the filter, the constant impedance filter provides a remedy.

Operation of a constant impedance (non reflecting) filter is similar to the The Non Reflecting, Voltage Controlled Attenuator, on page 1-12 and the Notch Diplexer, on page 1-16. The input signal is connected to port 1 or Hy1.

Refer to Figure 1-22. The signal from the input source is assumed to occupy a band of frequencies, some of which will pass through the cavity bandpass filters and others will be outside the bandpass of the filter and be rejected. Since the two filters are identical and each receives the same input signal voltage from Hy1, the signal passing through the cavities will each have the same amplitude. Likewise, the signals rejected by the cavities will have the same voltage. Also, each cavity is the same distance from the hybrids, therefore, the phase relationship of the two Eouts and the two Ers will be the same as that of the two signals that enter the cavities.

In Figure 1-22, the input signal (Ein) is split by Hy1 and the two resulting output signals (90° out of phase) enter the cavities. The portion that passes through the cavities (Eout) enters Hy2, which acts as a combining hybrid. The output signals of Hy2 cancel in reject load 2 and add in the output load. This accounts for most of the input power.

The portion of the signals rejected by the cavities (Er) reflects back into Hy1, which acts as a combining hybrid for them. These signals cancel at the input source (port 1 of Hy1) and add in reject load 1. Therefore, the input source sees none of the signal rejected by the cavities.

As an example, assume the input source is a 20 KW transmitter. Its output (Ein) is 1000V (into 50Ω). If 19.5 kW of the input passes through the cavities, their outputs (Eout) will be approximately 698V. The voltage presented to the output load will be 1.414Eout = 987V, which is 19.5 kW. The 500 W rejected by the cavities is represented by an Er of approximately 112V from each cavity. The voltage at reject load 1 will be 1.414Er = 158V, which is 500 W.

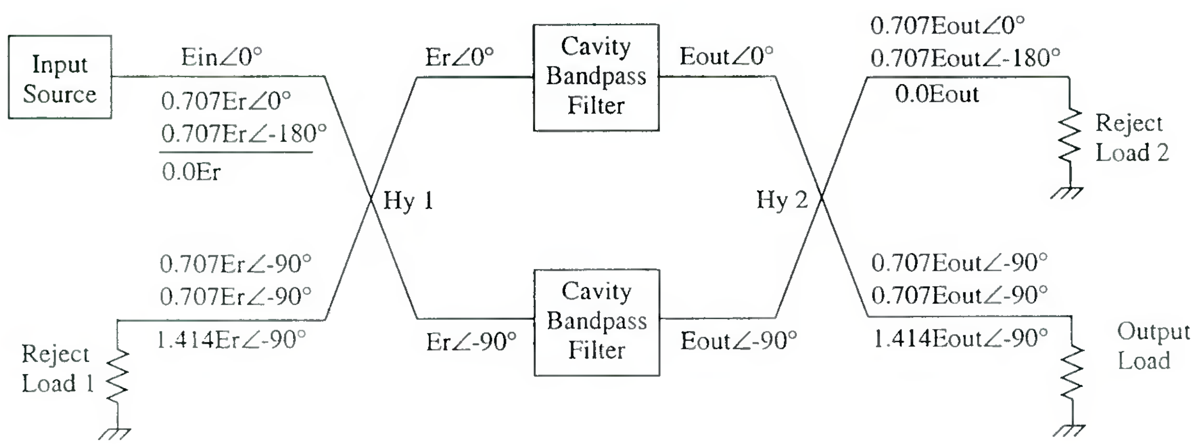

Figure 1-22 Constant Impedance Filter

1.5.7.1 Constant Impedance Filter as a Multiplexer

Refer to Figure 1-23. The outputs of two or more transmitters of different frequencies can be efficiently combined into a single signal through the use of one or more constant impedance filters as multiplexers.

To do this, the reject load of the constant impedance filter becomes the "wide band input," which will accept input signals outside the bandpass of the cavities. These signals reflect off the cavities, pass through Hy2, and combine in the output load. One transmitter, or the output of another multiplexer, can be connected into the wide band input.

The conventional input to the constant impedance filter is now the "narrow band input." The operating frequency at the narrow band input must be within the bandpass of the resonant cavities. Excellent isolation is achieved between the multiplexer output and inputs and between the two inputs.

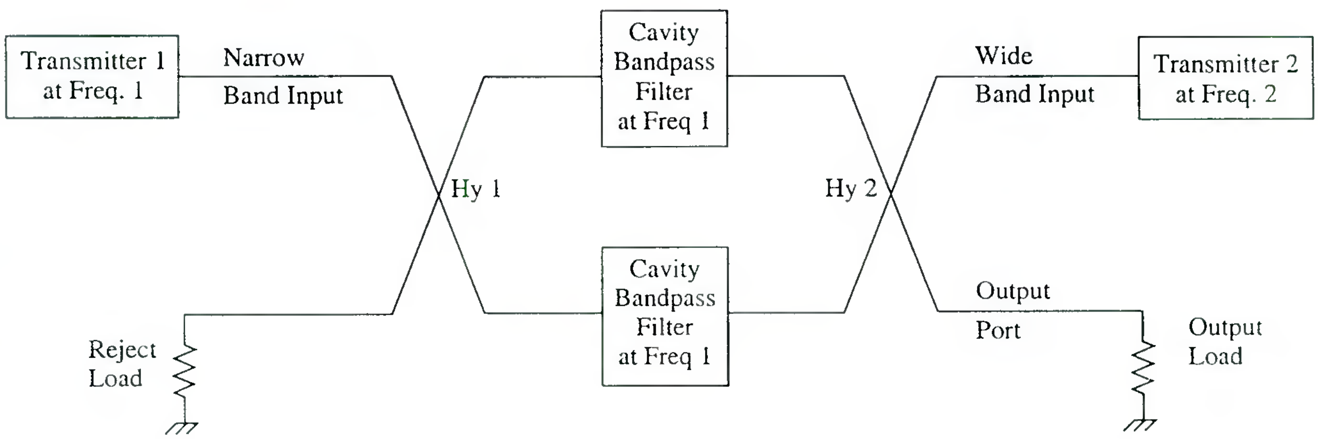

Figure 1-23 Constant Impedance Filter Used as a Multiplexer

1.5.7.1.1 Uses of the Constant Impedance Filter/Multiplexer

Since all digital television transmitters require an output filter to meet the adjacent channel intermod requirements, an increasingly common use the this multiplexer is to combine a digital television transmitter with another digital or analog television transmitter.

Two or more FM transmitters are often multiplexed into a single wideband antenna, as shown in Figure 1-24.

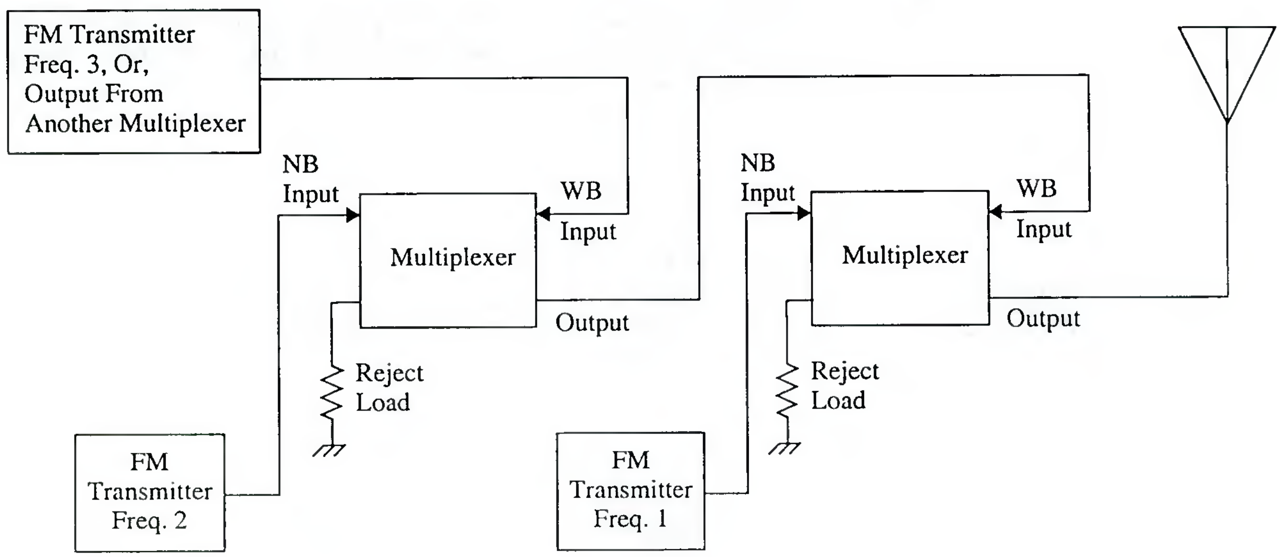

Figure 1-24 Multiplexing FM Transmitters

The Wilkinson Hybrid and its Derivations

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1 The Wilkinson Hybrid and its Derivations

Transmission lines can be used to create RF circuit combiners and splitters (hybrids) of several types. One of the basic types of splitter/combiners is the Wilkinson hybrid. Several other types of hybrids, including the Rat Race and the Gysel combiners, are derivations of the Wilkinson.

1.1 The Wilkinson Hybrid

The Wilkinson combiner is a device that is used to match the output impedance of two or more RF amplifiers to a load impedance (usually a transmission line). It has three advantages:

1 The output power of each amplifier is combined into one unbalanced output with minimal loss. The combiners normal output level is the sum of the individual amplifier outputs.

2 The second advantage of the Wilkinson combiner is good isolation between amplifiers. If one amplifier should happen to fail, the other one still functions into a perfect load. Its operation is not impaired by the failed amplifier, as would be the case if the two or more amplifiers were connected directly in parallel. In the case of two amplifiers, if one failed, the combiner output level would fall to 1/4 of its normal combined power (1/2 the power of one amplifier).

3 All of the amplifiers that are to be combined are operated in phase. The main advantages here is that it makes the RF cabling simpler, reducing the problems that might occur if the wrong cable were connected to the wrong amplifier. Another advantage is that when a reflected signal arrives back at the outputs of the combined amplifiers, it will change all of their operating parameters in the same way.

Note

In the quarter wavelength hybrid, where the amplifier outputs must be held 90 degrees out of phase to combine properly, the reflected signal will change the output parameters of each amplifier differently, stressing one amplifier more than the other.

The Wilkinson combiner can also be used as power splitter. It has the same advantages as when used as a combiner, low loss and good isolation between loads.

The normal operating condition of this combiner is that the amplifiers have a 50Ω output impedance and the load (output line) has a 50Ω input impedance. To accomplish this impedance matching and combining, this combiner takes advantage of the impedance inverting properties of a 1/4 wavelength section of transmission line. To operate properly, the amplifiers that feed this combiner must have the same power output levels, their output signals must be in phase, and each amplifier must see the same load impedance.

In Figure 1-1, the 50Ω load is fed by the output of the two 70.7Ω, 1/4 wavelength transmission lines. Since voltage and currents fed by each of the two 70.7Ω lines are in phase and at the same level, each line sees a 100Ω load impedance.

To understand this point, remember that the voltage at the two 70.7Ω line outputs and the 50Ω line input is the same, since this is the same point in the circuit. The 50Ω output line current is the sum of the currents of the two feed lines, therefore the current level of each feed line is 1/2 of the output current.

$$\text{If} \quad 50\Omega = \frac{\text{Eout}}{\text{Iout}} \qquad \text{then} \qquad \frac{\text{Eout}}{0.5 \times \text{Iout}} = 100\Omega$$

Applying the 70.7Ω line impedance and the 100Ω load impedance to the impedance matching formula for the 1/4 wavelength matching section, the result is a 50Ω source impedance for each 70.7Ω line. This 50Ω source impedance is the load impedance for each amplifier.

$$Z_S = \frac{Z_O^2}{Z_L} = \frac{70.7^2}{100} = \frac{4998}{100} = 49.98\,\text{ohms} \ \ (50\ \text{ohms})$$

Where: Z_S = the source impedance,
Z_O = the line impedance, and
Z_L = the load impedance.

The balancing resistor (R_{Bal}) that connects the outputs of each amplifier is invisible to the circuit, because the voltage at each end of the resistor (the amplifier's outputs) are in phase and at the same amplitude, therefore no current flows through the resistor. This gives R_{Bal} an apparent infinite resistance.

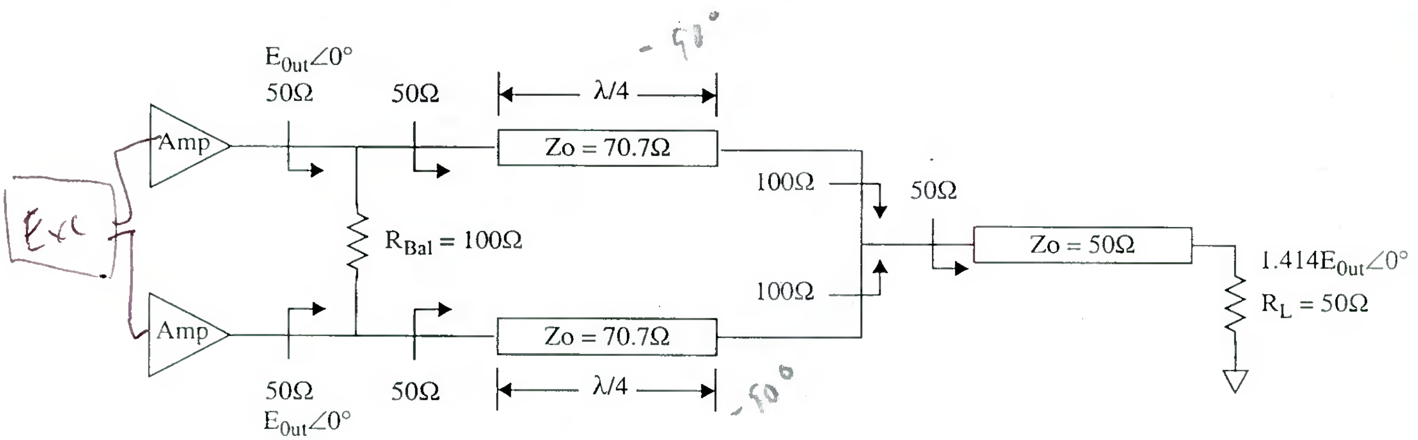


Figure 1-1 Two Way Wilkinson Hybrid (Used as a Combiner)

If one of the amplifiers should fail, the nature of this circuit makes that amplifiers output appear as a virtual ground, see Figure 1-2. This occurs if the actual amplifier output is shorted, open, or somewhere between.

This happens because the voltage that gets fed back to the bad amplifier arrives by two paths. One is through the 100Ω resistor and arrives in phase with the good amplifier's output voltage. The other path is through the two 1/4 wavelength lines. Since each 1/4 wavelength line gives the signal a 90 degree phase shift, it arrives at the output of the bad amplifier 180 degrees out of phase with the signal that comes through the 100Ω resistor.

Since the voltages are 180 degrees out of phase and equal in amplitude, they cancel leaving zero volts. Subsequently, the current flowing passed that point sees zero volts, and therefore that point (the bad amplifier output) becomes a virtual ground.

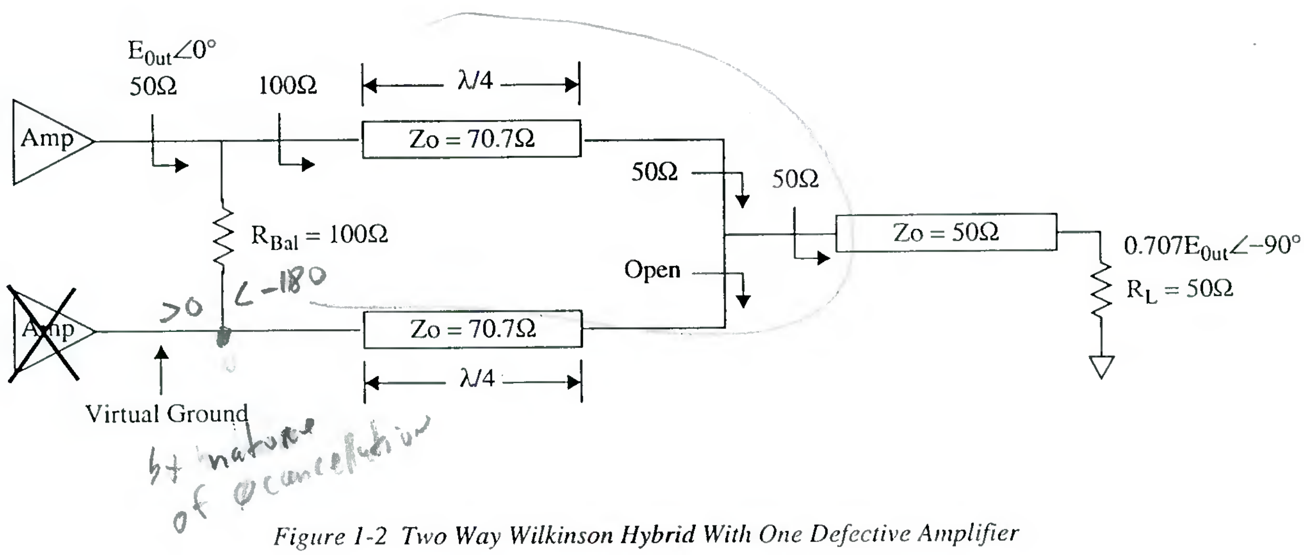


Figure 1-2 Two Way Wilkinson Hybrid With One Defective Amplifier

Since the bad amplifier end of its 70.7Ω line is at virtual ground (that end appears shorted) the other end, at the junction of the 50 and 70.7Ω lines, appears open. The 70.7Ω line from the good amplifier now sees a 50Ω load from the 50Ω output line. The inverting properties of the 70.7Ω line transforms the 50Ω load impedance at that junction to a 100Ω impedance at the end connected to the good amplifier. The good amplifier now sees a 100Ω impedance from the balancing resistor in parallel with a 100Ω impedance from its 70.7Ω line, therefore it sees a 50Ω (perfect) load. Under these conditions, half of the power of the good amplifier is dissipated in the balancing resistor and the other half is fed to the 50Ω load through its 70.7Ω impedance matching line.

For the two way Wilkinson combiner operating with one bad amplifier which still produces some output, the combiner output power can be calculated by the formula given below. For two or more combined amplifiers, use the formulas presented in Step 6, on page 1-4.

$$P_{out} = \frac{P_A + P_B}{2} + \sqrt{P_A \times P_B}$$

Where: P_{out} = Combined output power of both amplifiers.
P_A = output power of amplifier A
P_B = output power of amplifier B

If the bad amplifier produces 17.16% of its normal output power, the combined output of the good and bad amplifier equals the output of the good amplifier.

At this time it is worth while to observe that although the 70.7Ω line at the bad amplifier's output has a current flowing into it (from the 100Ω balancing load). The zero volt voltage level at this point means this line is accepting no power (P = E * I). At the other end of this line (the open end) there is voltage, but no current flows into the line at this end, thus no power is transported at this end of the line.

1.2 The N Way Wilkinson Combiner

The Wilkinson Combiner can combine any number of amplifiers, as long as the correct impedance of transmission line is available for the required 1/4 wavelength transmission line sections.

In Figure 1-3, a four way Wilkinson combiner is being designed, the following steps are used:

1 The load resistor R_L will probably be a transmission line with an impedance of 50Ω.

2 The load impedance (Zout) of each 1/4 wavelength matching section is found by the formula:

$$Zout = N \times R_L = 4 \times 50 = 200\Omega$$

Where: N = the number of amplifiers to be combined

3 The amplifier's output impedance (source impedance for each 1/4 wavelength matching section) is 50Ω.

4 The required 1/4 wavelength transmission line impedance (Z_0) is found by the formula:

$$Z_0 = \sqrt{Z_S \times Z_L} = \sqrt{50 \times 200} = 100\Omega$$

Where: Z_0 = impedance of λ/4 line
Z_S = source impedance of λ/4 line
Z_L = load impedance of λ/4 line.

5 The value of each balancing resistor is the same as the amplifier load impedance, and should have a power rating which equals the power output of one amplifier.

6 When one or more of the combined amplifiers has failed, the combined power output (Pout) of this configuration is found by the following two formulas:

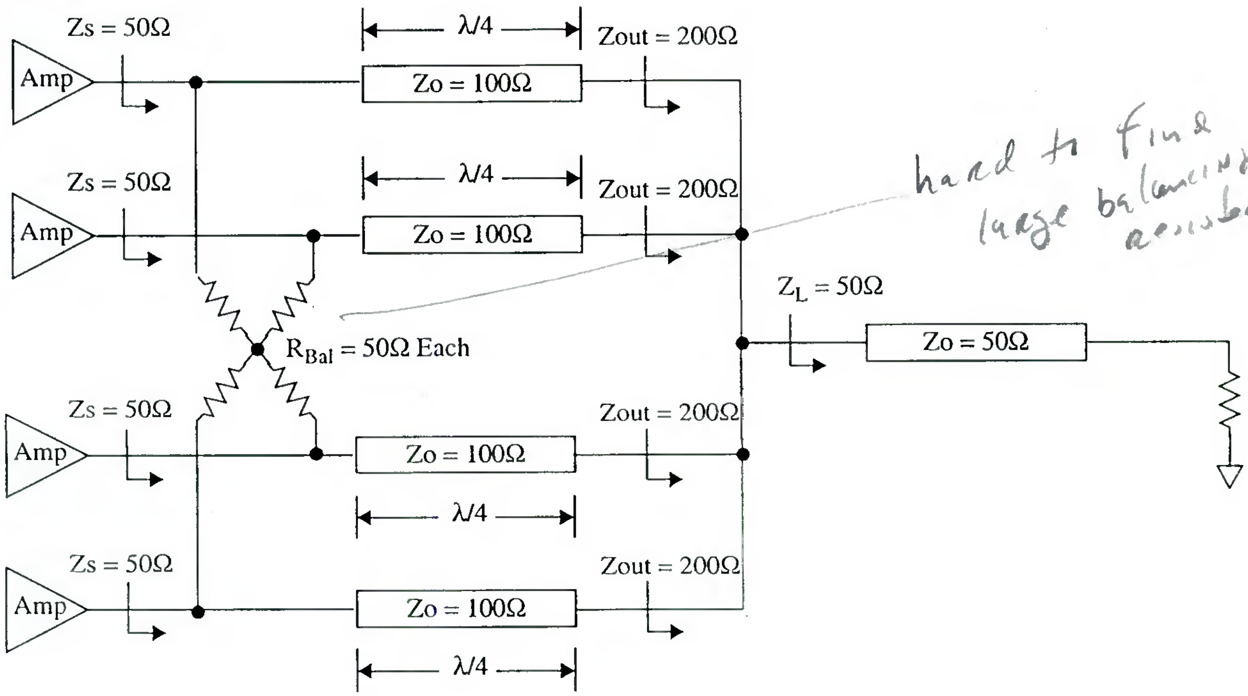
$$Pout = \frac{(e1 + e2 + \text{----} + en)^2}{n \times R_L}$$

Where: e1, e2, and etc. = output voltage of each amplifier
n = number of amplifiers
Output of one or more amplifier is different from the others.

If the bad amplifier(s) have zero output, the formula below can be used.

$$Pout = Pt \times \left(\frac{Good}{Total}\right)^2$$

Where: Pt = total combined output power, all amplifiers operating properly.
Good = number of good amplifiers
Total = total number of amplifiers.



hard to find large balancing resistors

Figure 1-3 Four Way Wilkinson Combiner, Showing Normal Operation

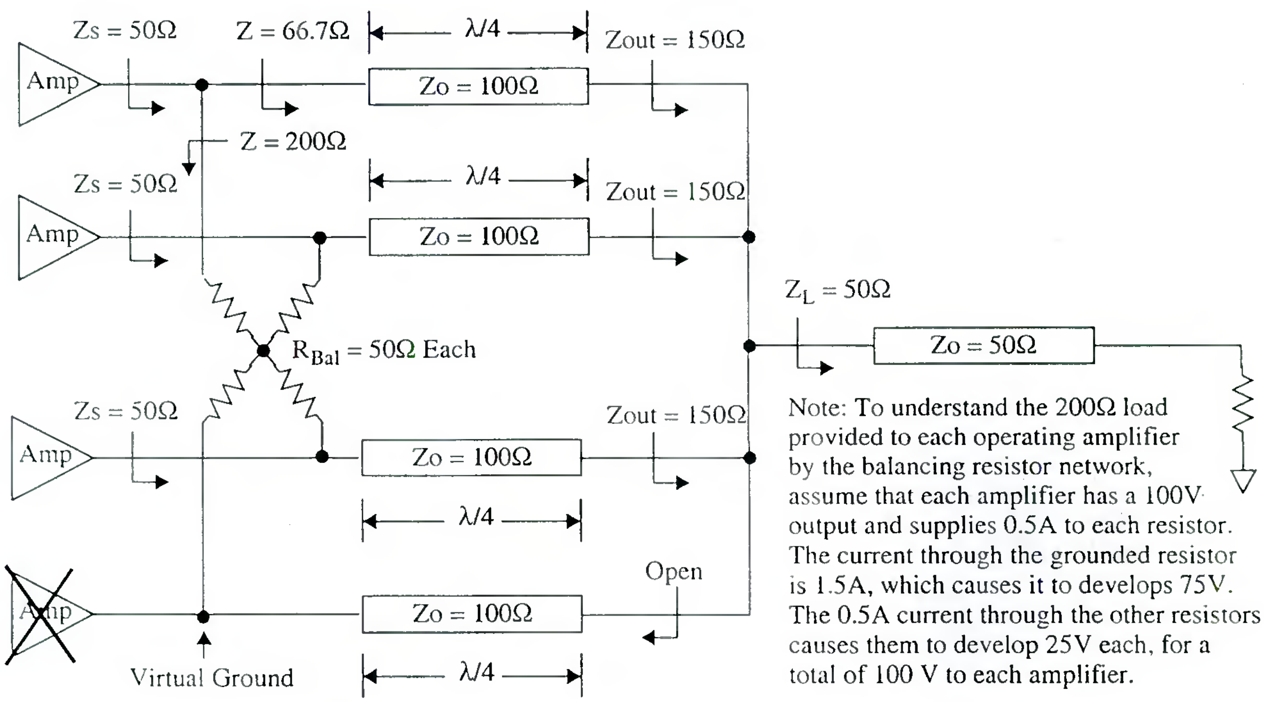


Figure 1-4 Four Way Wilkinson Combiner, Showing Operation With One Defective Amplifier

1.3 The Rat Race Combiner

This variation of the Wilkinson combiner is more popular when combining, high power amplifiers because it can use unbalanced high power test loads for balancing resistors. This resistor is called the reject load in the Rat Race combiner, but it does the same job as the balancing resistor. This represents a large savings if a balancing resistor of 1000 watt or greater rating is required.

In Figure 1-5, the outputs of two amplifiers are to be combined. They are connected to the output load (R_L) by two quarter wavelength, 70.7Ω lines. This part of the circuit forms a conventional Wilkinson combiner. The output load (R_L) is 50Ω, and each amplifier sees a 50Ω output load. The outputs of both amplifier outputs have the same voltage and are in phase. The output load receives a voltage which is 1.414 times greater than the output of either amplifier, therefore the combined output power is twice the power output level of either amplifier.

Each amplifier is connected to the 50Ω reject load by 70.7Ω transmission lines, but the length of these two lines are not the same. One has a length of 3/4 wavelength (270 electrical degrees) and the other has a length of 1/4 wavelength (90 electrical degrees). The voltages that arrives at the reject load from each amplifier has the same amplitude, but due to the differences of connecting line lengths, they are 180 degrees out of phase when they reach the reject load. These two voltages cancel setting the reject load total voltage at zero volts. The reject load is therefore at virtual ground during normal operation and it receives no power from either amplifier. The other end of the 70.7Ω lines appear as open circuits to the amplifiers, making the entire reject circuit (the reject load and its two lines) invisible to the two amplifiers.

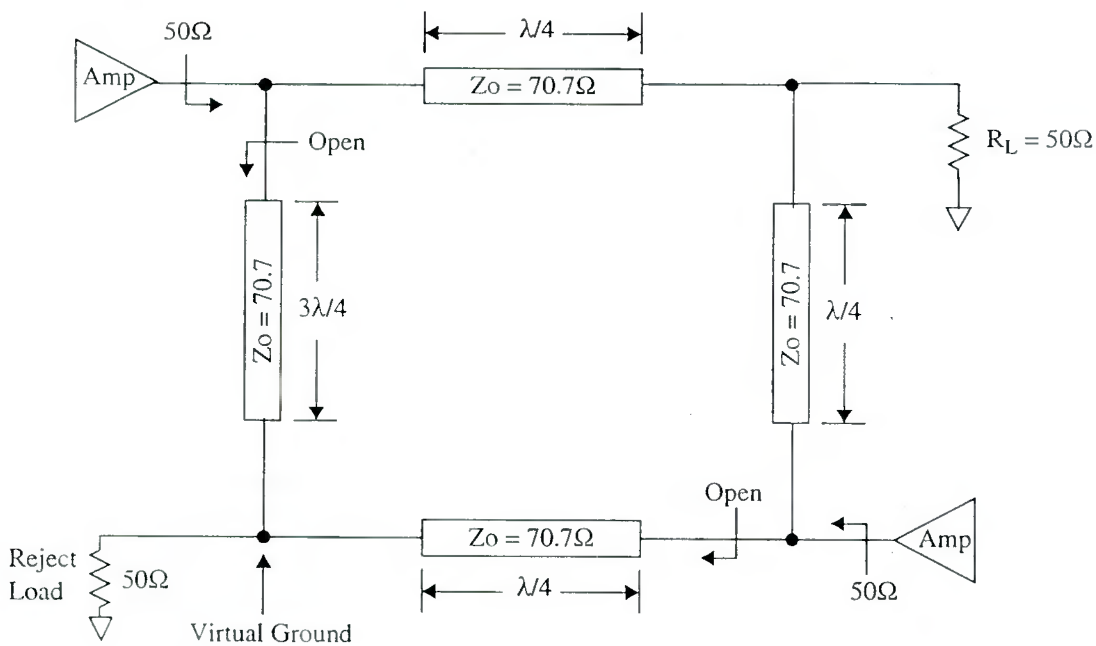


Figure 1-5 Rat Race Combiner, Showing Normal Operation

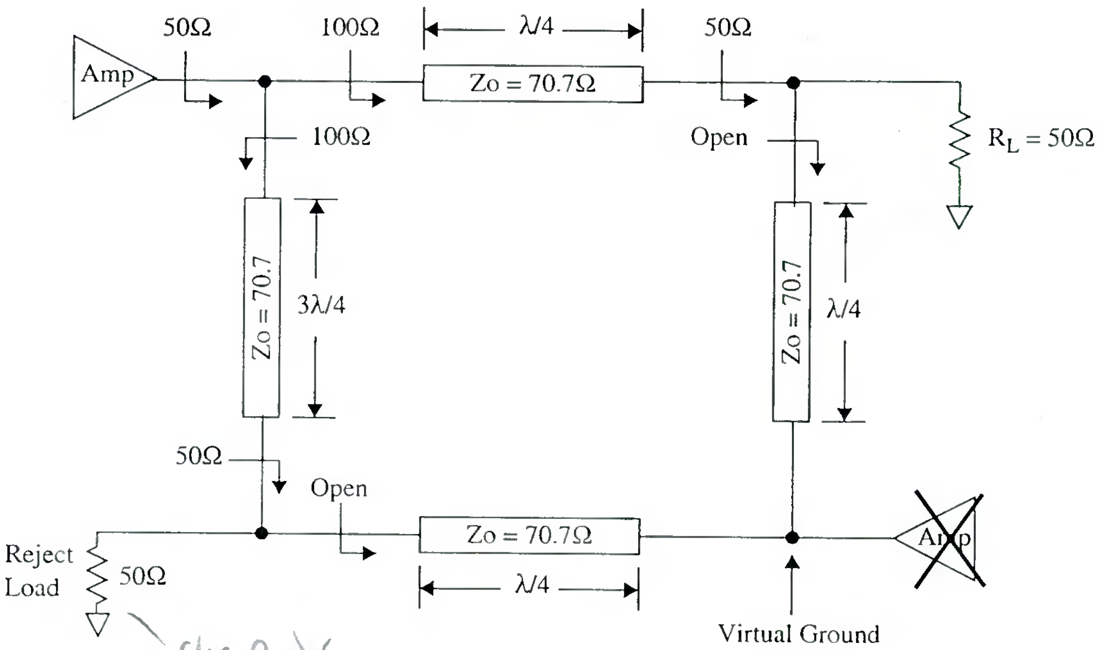
If one amplifier fails, producing zero output, the circuit places that amplifier output at virtual ground, see Figure 1-6. This represents a shorted termination for its two output lines, and they appear as open circuits to the reject and output loads, therefore, the other two lines see 50Ω loads. These lines invert the load impedance to 100Ω, which they present to the good amplifier. The two 100Ω impedances presented to the good amplifier give it a proper (50Ω) load, and its output power is split evenly between the reject and output loads.

It is easy to understand how a 3/4 wavelength line inverts impedance if it is thought of as a 1/2 wavelength line in connected in series with a 1/4 wavelength line. The 1/2 wavelength line presents a repeated load impedance to the 1/4 wavelength line, and the 1/4 wavelength line inverts it.

When operating with one failed amplifier, the output power can be calculated using the formulas given in step 6 of the N way Wilkinson combiner design procedure given above.

For the Rat Race combiner with one bad amplifier, the combiner output power can be calculated by the formula:

$$\text{Pout} = \frac{\text{Pa} + \text{Pb}}{2} + \sqrt{\text{Pa} + \text{Pb}}$$



cheap DC
as opposed to Bal R

Figure 1-6 Rat Race Combiner, Showing Operation With One Defective Amplifier

Figure 1-7 shows the Rat Race combiner of Figure 1-5 constructed from equivalent inductor/capacitor artificial transmission lines. This is useful at frequencies below 30 MHz, where the line length would be inconveniently long for 1/4 wavelength. Notice that 1/4 wavelength of 70.7Ω line is created with one series inductor of 70.7Ωs reactance connected to ground at each end through two capacitors of 70.7Ω reactances. In the same figure, 3/4 wavelength of 70.7Ω line is formed be one 70.7Ω series capacitor connected to ground at each end through a 70.7Ω inductor. Due to the narrow bandwidth of these artificial lines, they are not practical for use at frequencies above 30 MHz, but this circuit is valuable for analysis, and it has been used to combine high power A.M. broadcast band transmitter power amplifiers.

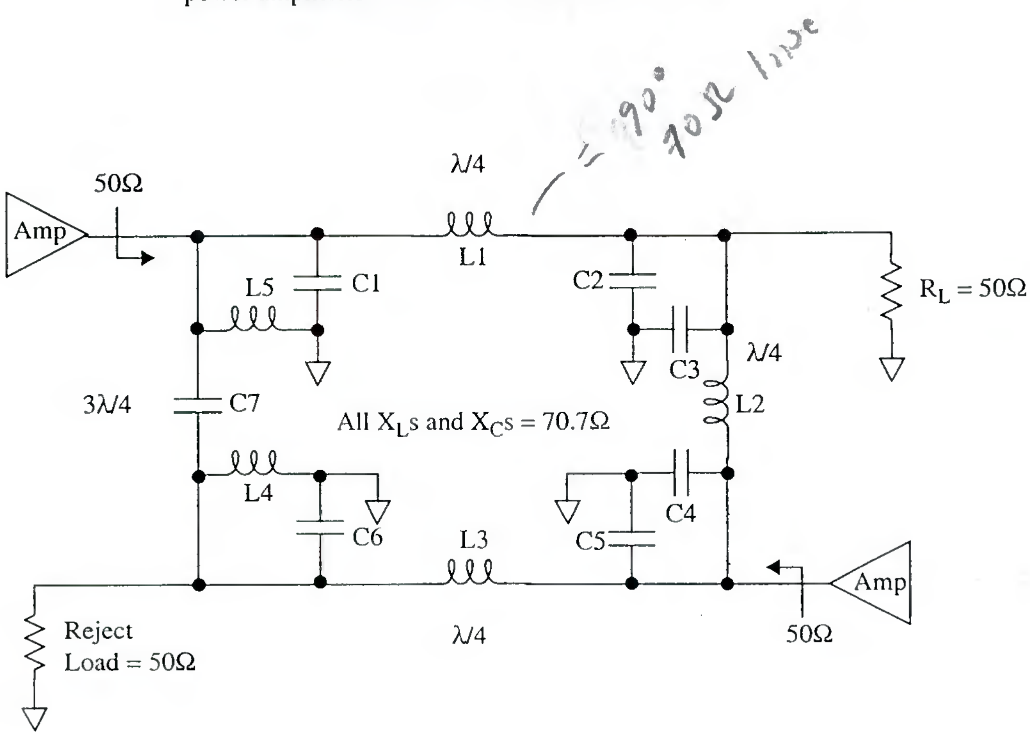


Figure 1-7 Rat Race Combiner Constructed of Artificial Transmission Lines

Figure 1-8 shows the circuit of Figure 1-7 with the grounded, left hand corner components combined. The parallel combination of 70.7Ω inductors and capacitors at each corner are combined and are therefore eliminated since their reactances cancel producing an infinite resistance to ground at that point. The right hand two 35.35Ω capacitive reactances are created by combining the two 70.7Ω capacitors that are connected to ground at those points in. This is the actual combiner circuit that is used in one pair of combined, high power AM transmitters.

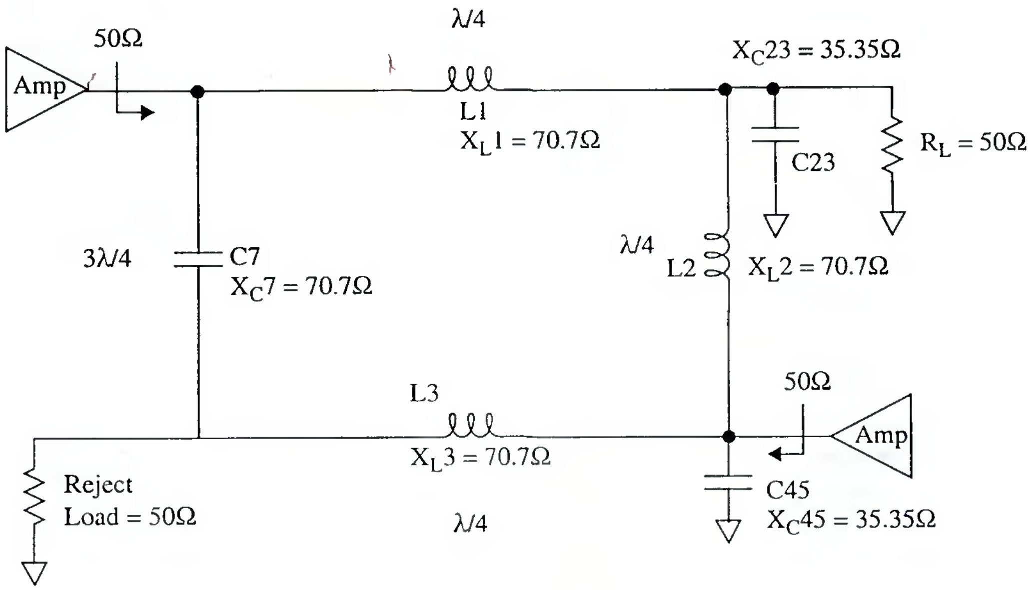


Figure 1-8 Rat Race Combiner With Corner Components Combined

1.4 The Gysel Combiner.

The Gysel combiner, shown in Figure 1-9, is still another modification of the Wilkinson combiner. The Rat Race combiner is limited to just two amplifiers, but the Gysel combiner can combine any number of amplifiers, being limited only by the availability of the correct impedance transmission line used to connect each amplifier to the output load (R_L). This limitation is minimized by the use of microstrip transmission line technique. Microstrip transmission lines are covered in another paper (Development of Microstrip Transmission Lines, by Doc Daugherty).

The output side of this circuit (the left side of Figure 1-9, within dotted box) including the amplifiers) functions like a conventional Wilkinson combiner, it is the right side that is of interest here. At the right side, all of the 1/4 wavelength, 50Ω transmission lines are joined together. Since each line feeds the same voltage to this junction, it appears as a virtual open during normal operation of this combiner. 1/4 wavelength away from this virtual open circuit, the 50Ω transmission lines present a short circuit to reject loads (R1 through R4), placing them at virtual ground. The 1/4 wavelength, 50Ω lines that connect each reject load to its amplifier appear as an open circuit to the amplifier. This makes the entire reject circuit (reject loads R1 through R4 and their eight transmission lines) invisible to the two amplifiers.

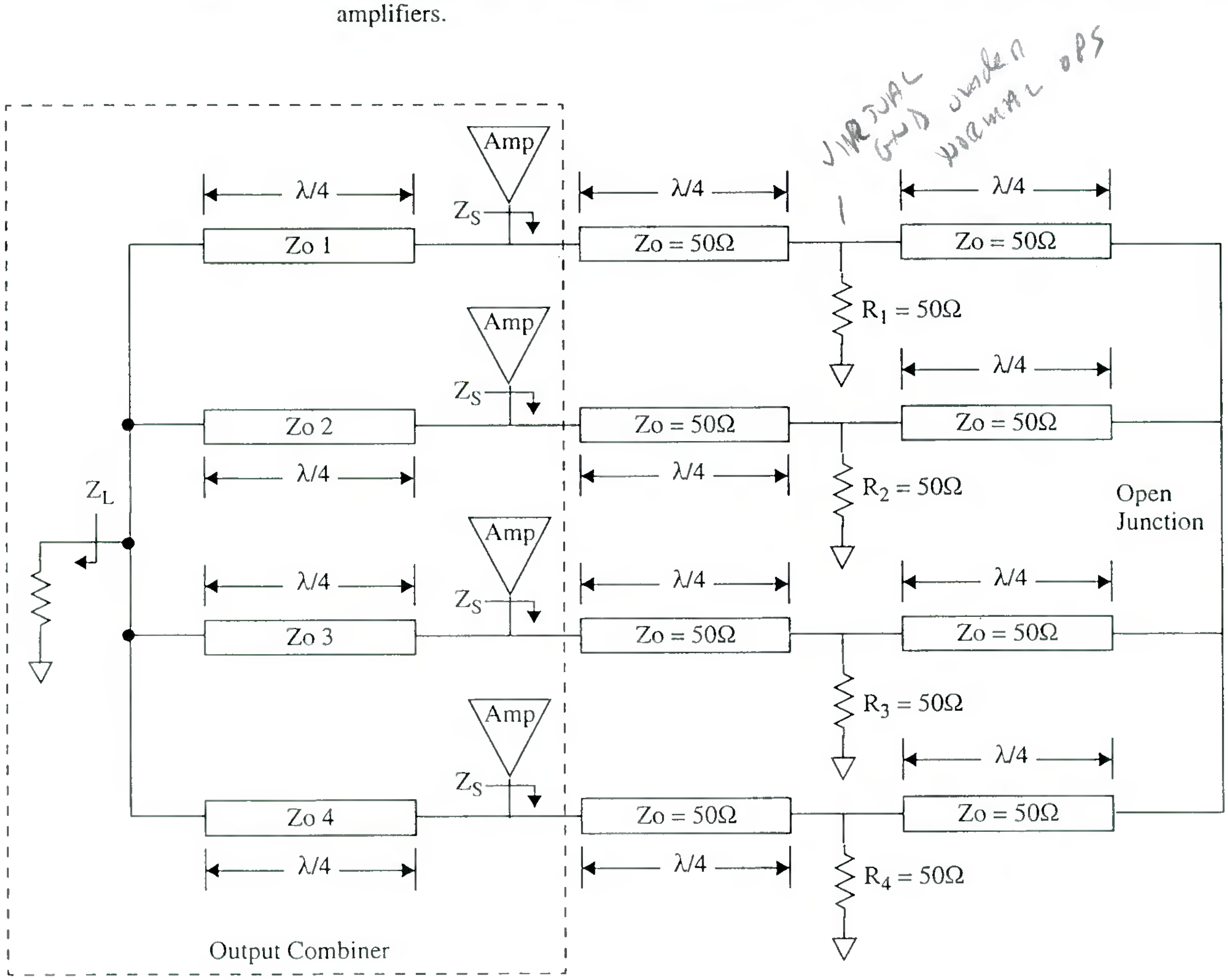


Figure 1-9 Gysel Combiner, Normal operation

If an amplifier fails, its output becomes a virtual ground, as with the other combiners studied. The impedance inverting properties of its two 1/4 wavelength output lines present open circuits to the output load and its reject load. The improper (higher) impedance presented to each good amplifier by the output circuit is brought back down to 50Ωs by the reject loads and their network of 1/4 wavelength, 50Ω interconnecting transmission lines.

When operating with one or more failed amplifiers, the output power can be calculated using the formulas given in step 6 of the N way Wilkinson combiner design procedure given above.

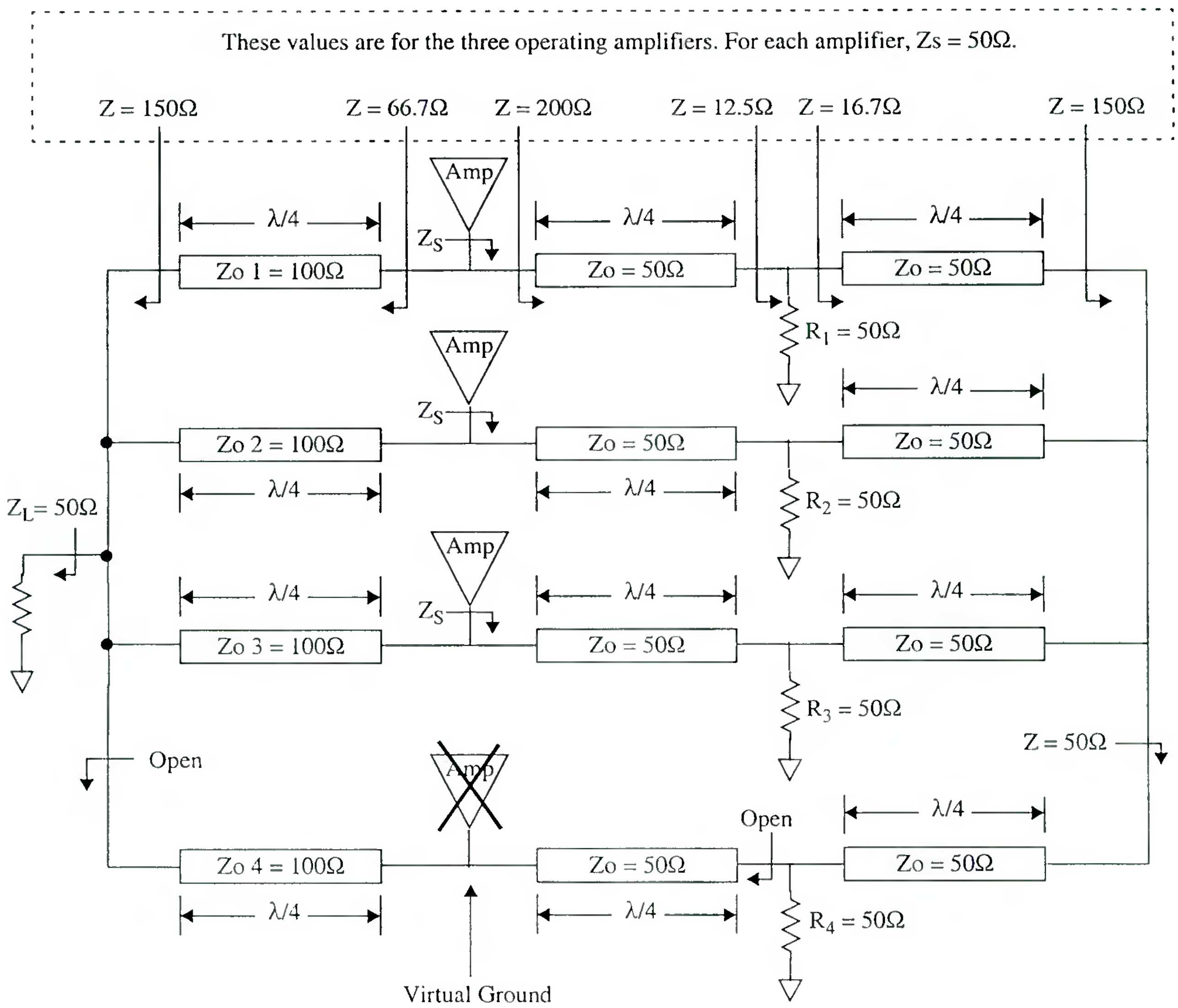


Figure 1-10 Gysel Combiner, Showing Operation With One Defective Amplifier