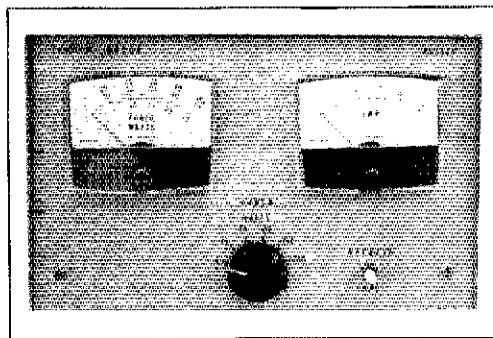


The Tandem Match—An Accurate Directional Wattmeter

This accurate directional wattmeter measures power from 1.5 to 1500 W and SWR over a range from 1:1 to 50:1.

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This article describes construction of a new type of directional wattmeter that can accurately measure power output and *standing wave ratio* (SWR) over a wide range of power. I originally started working on this project because I was unhappy with the performance of affordable directional wattmeters. The performance of the Tandem Match is as good as, or better than, any commercially available directional wattmeter designed for amateur use.

Most SWR meters are very inaccurate at low power levels because of non-linearities of the detector diodes. This design uses a compensating circuit to cancel the diode nonlinearity. A direct SWR readout provides a handy way of adjusting an antenna matching network for minimum SWR to the transmitter. There is no need for mental gymnastics to guess what the minimum SWR is in the event that transmitter output varies substantially with SWR.

Design Principles

Directional wattmeters for Amateur Radio use consist of three basic elements: a directional coupler, a detector, and a signal processing and display circuit. The directional coupler separates the signal into its forward and reflected components. The ideal directional coupler would provide a signal proportional to the forward and reflected voltage independent of frequency, and could then be used to measure forward and reflected power over a wide frequency range. The best designs today will work over two decades of frequency. If the unit is to operate without being switched, the directional coupler must provide both the forward and reflected voltages simultaneously.

The detector circuit provides a dc output voltage proportional to the ac input

voltage. Most directional wattmeters use a single germanium diode as the detector element. A germanium diode is used to minimize the diode nonlinearity at low power levels. The diode nonlinearity will still cause measurement errors in the SWR unless it is compensated before the display circuit. Most directional wattmeters do not work well at low power levels because of this diode nonlinearity.

The signal processing and display circuit computes and displays the SWR. There are a number of ways to perform this function. Meters that display only the forward and reflected power require the operator to compute the SWR separately. Many instruments require that the operator adjust the meter to a reference level while measuring forward power, then switch to measure reflected power with the SWR displayed on a special scale. Several units have been described that directly compute the SWR using analog signal processing circuits.¹⁻⁴

Let's take a brief look at several popular circuits for accomplishing the above functions. I will also compare and describe the circuits used in the Tandem Match. The design specifications used in the Tandem Match are shown in Table 1.

Circuit Description

Directional Coupler Circuits

A directional coupler consists of an input port, an output port and a coupled port. The device takes a portion of the power flowing from the input port to the output port and directs it to the coupled port, but *none* of the power flowing from the output port to the input port is directed to the coupled port. There are several terms that

define the performance of a directional coupler

- *Insertion loss* is the amount of power that is lost from the signal flowing from the input port to the output port.

- *Coupling factor* is the amount of power (or voltage) that appears at the coupled port relative to the amount of power (or voltage) flowing from the input port to the output port.

- *Isolation* is the amount of power (or voltage) that appears at the coupled port relative to the amount of power (or voltage) flowing from the output port to the input port.

- *Directivity* is the isolation less the coupling factor.

All of these factors important in determining the performance of a directional wattmeter. Insertion loss should be minimized so that the coupler doesn't dissipate a significant amount of the transmitted power. The flatness of the coupling factor as a function of frequency determines how accurately the directional wattmeter can determine the forward and reflected power over a range of frequencies. Directivity will dictate the minimum SWR that can be measured. A directional coupler with 20-dB directivity will measure a 1:1 SWR as 1.22:1, but one with 30-dB directivity will measure a 1:1 SWR as 1.07:1.

The most commonly used directional coupler for Amateur Radio is the design originally described by Bruene in a *QST* article.⁵ See Fig 1. I built a coupler of this type in one of my early attempts to make an accurate directional wattmeter. My measurements of its performance showed that over the range of 3 to 30 MHz, the coupling factor was flat to within ± 1 dB, and the directivity was approximately

¹Notes appear on page 26.

Table 1
Performance Specifications for the Tandem Match

Power range:	1.5 to 1500 W.
Frequency range:	1.8 to 54 MHz.
Power accuracy:	Better than $\pm 10\%$ (± 0.4 dB).
SWR accuracy:	Better than $\pm 5\%$.
Minimum SWR:	Less than 1.05:1.
Power display:	Linear, suitable for use with either an analog or digital meter.
SWR display:	Linear, suitable for use with either an analog or digital meter.
Calibration:	Requires only an accurate voltmeter. No calibrated RF source is required.

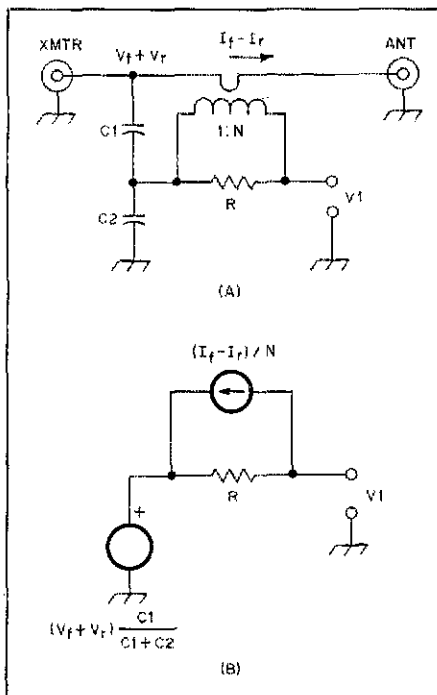


Fig 1—Simplified diagram of the Bruene directional coupler. At A, one of the unidirectional segments. At B, an equivalent circuit.

20 dB. Both of these factors limit the accuracy of this coupler, both for measuring power and determining low SWR. However, it is a relatively simple directional coupler, and it works well over a wide frequency range if high precision is not required.

The coupler used in the Tandem Match consists of a pair of toroidal transformers connected in tandem. This configuration has been used for years and has been described in several articles.^{6,7} As long as the coupling factor is 20 dB or greater, this coupler can be used to separate both forward and reflected power. Fig 2 shows this coupler configuration.

I have made a number of measurements of the performance of this type of directional coupler. The particular configuration used in the Tandem Match works well over the frequency range of 1.8 to 54 MHz, with a nominal coupling factor of 30 dB. Over this range, the insertion loss is less than 0.1 dB. Figs 3 and 4

show plots of coupling factor and directivity as a function of frequency. Over the frequency range of 1.8 to 30 MHz the coupling factor is flat to within ± 0.1 dB, and increases to only ± 0.3 dB at 50 MHz. Directivity exceeds 35 dB from 1.8 to 30 MHz and exceeds 26 dB at 50 MHz.

The low-frequency limit of the directional coupler is determined by the inductance of the secondary windings of the transformers. Inductive reactance of the secondary windings should be greater than 150 Ω to avoid excessive insertion loss. The high-frequency limit of the directional coupler is determined by the length of wire used in winding the transformers. When this length approaches a significant fraction of a wavelength, the performance of the directional coupler deteriorates. A 20-dB coupling-factor version of this design should work up to 150 MHz because of the

shorter length of wire required in the transformer secondaries.

Detector Circuits

Most amateur directional wattmeters use a single germanium diode as the detector. Germanium diodes are used because of their low forward voltage drop. However, this voltage drop is still significant, and an uncompensated diode detector will underestimate the detected power. A directional wattmeter that directly displays power will usually compensate for the diode non-linearity by using a meter scale that takes these effects into consideration.

The effect of underestimating detected power becomes worse at lower power levels. Under these conditions, the ratio of the forward power to the reflected power will be overestimated because the reflected power is always less than the forward power. This results in an instrument that underestimates the SWR, particularly as the power level is reduced. A directional wattmeter can be checked for this effect by measuring the SWR at several power levels, as SWR should be independent of power level.

The Tandem Match uses a feedback circuit to compensate for diode nonlinearity. A simplified diagram of the detector is shown in Fig 5. When used with the 30-dB directional coupler, the output voltage of this circuit tracks the square root of the power over a range from 10 mW to 1.5 kW. A comparison between the

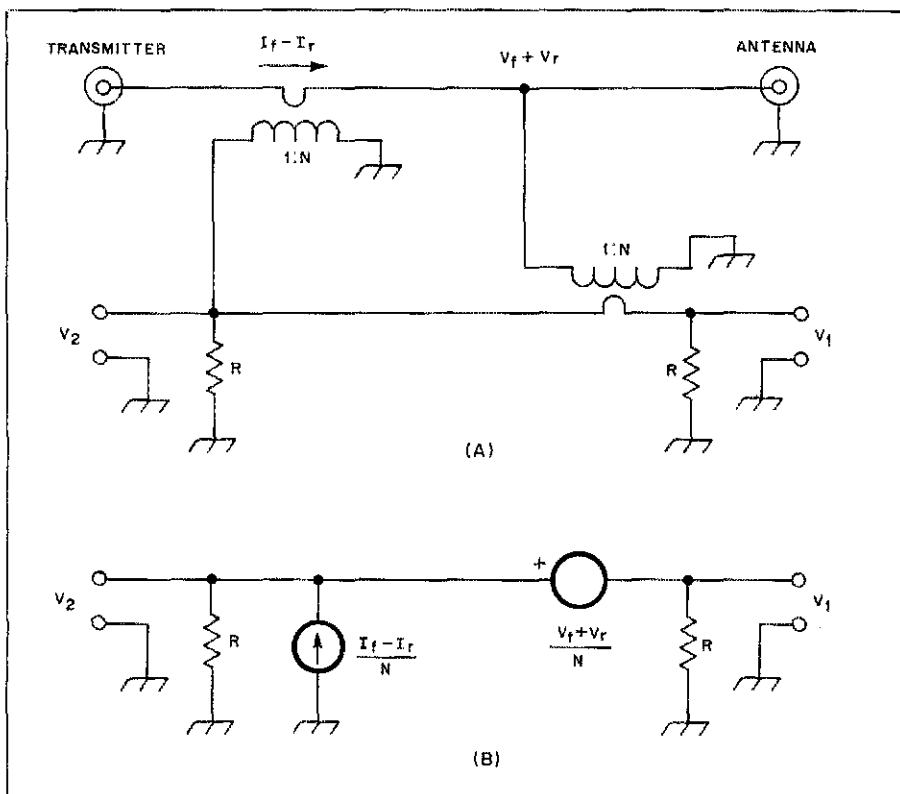


Fig 2—Simplified diagram of the Tandem Match directional coupler. At A, a schematic of the two transformers. At B, an equivalent circuit.

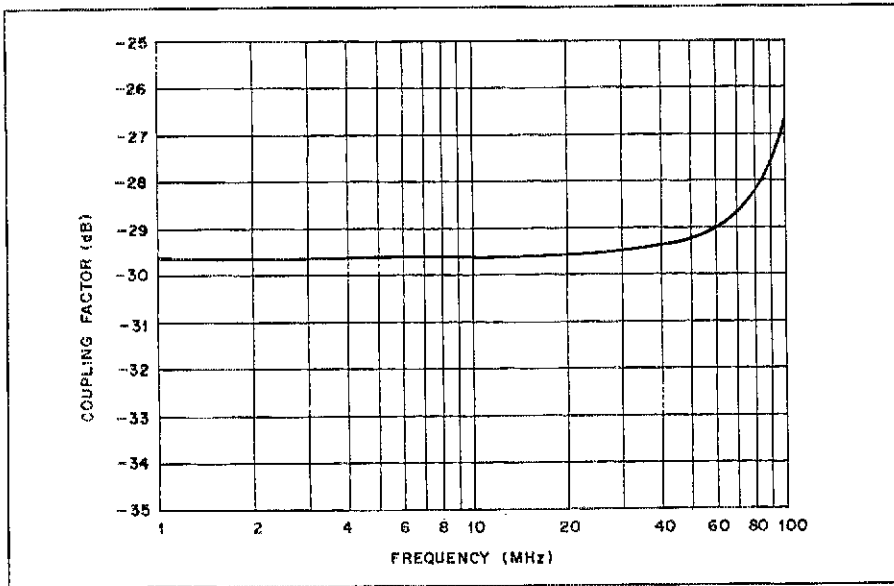


Fig 3—A plot of coupling factor for the Tandem Match directional coupler.

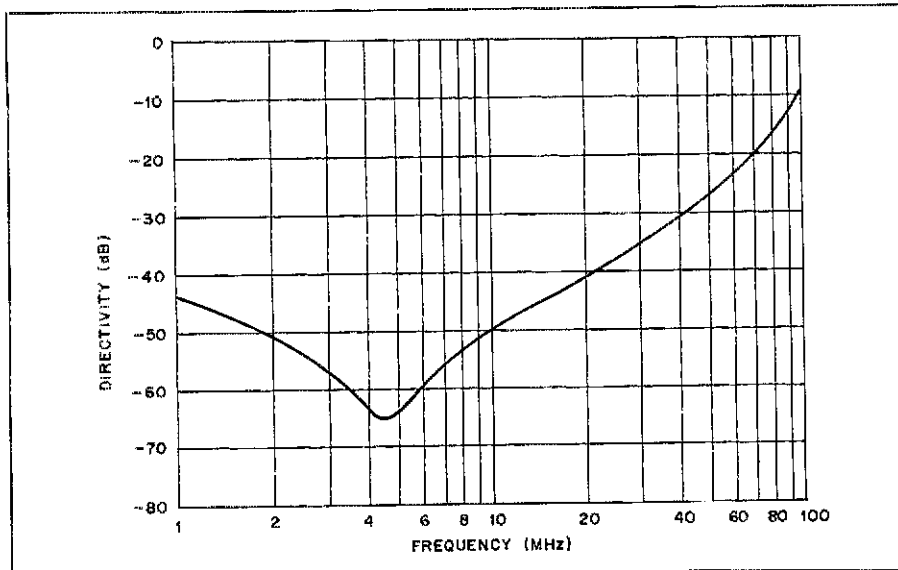


Fig 4—A plot of directivity for the Tandem Match directional coupler.

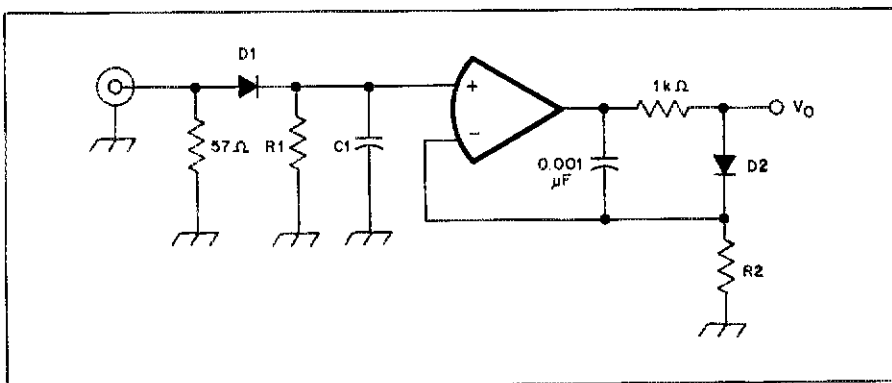


Fig 5—Simplified diagram of the detector circuit used in the Tandem Match. The output voltage, V_o is approximately equal to the input voltage. D1 and D2 must be a matched pair. The op amp should have a low offset voltage (<1 mV), a low leakage current (<1 nA), and be stable over time and temperature. The resistor and capacitor in the feedback path assure that the op amp will be stable.

accuracy of this detector using Schottky barrier diodes and a detector using a germanium diode is shown in Fig 6. The compensated diode detector tracks the peak input voltage down to an input level of 30 mV, while the uncompensated diode detector shows significant errors at peak inputs of 1 V and less.

The circuit uses the voltage across the feedback diode D2 to compensate for the voltage drop across the detector diode, D1. The diodes must be a matched pair. The average current through D1 is determined by the detector-diode load resistor, R1. The peak current through this diode is several times larger than the average current; therefore, the current through D2 must be several times larger than the average current through D1 to compensate adequately for the peak voltage drop across D1. This is accomplished by making the feedback-diode load resistor, R2, several times smaller than R1. The voltage at the output of the compensated detector will be approximately the peak RF voltage at the input.

A computer simulation was used to optimize this ratio. The simulation assumed that the detector diodes were Schottky barrier types and that the detector-diode load resistor was 1 megohm. A ratio of R1 to R2 of 5:1 appeared to be near optimal. A larger ratio resulted in excessive peaking in the low power range, and a smaller ratio resulted in a faster roll off at the lower power levels. Experimental data tended to confirm these results.

Signal-Processing and Display Circuits

The signal-processing circuitry calculates and displays the power measurement and SWR. A block diagram of the Tandem Match is shown in Fig 7. This circuit differs from conventional directional wattmeters in several respects. Most directional wattmeters display the forward power. This measurement is very close to the power delivered into the transmission line as long as the SWR is low. However, as the SWR increases, the forward power becomes an increasingly poor measure of the power being delivered to the load. At an SWR of 3:1, a forward power reading of 100 W implies that only 75 W is being delivered to the load, assuming that the transmission line has no losses. (The reflected power reading will be 25 W.) The Tandem Match directly displays the power being delivered into the transmission line. This is the quantity which must be optimized to result in maximum radiated power.

The Tandem Match also directly computes and displays the SWR of the transmission line on a linear scale. The direct display of SWR provides a convenient method of adjusting an antenna matching network. The antenna matching network is adjusted to minimize the displayed SWR. The displayed SWR is not affected by changes in the transmitter output power and the antenna system can be

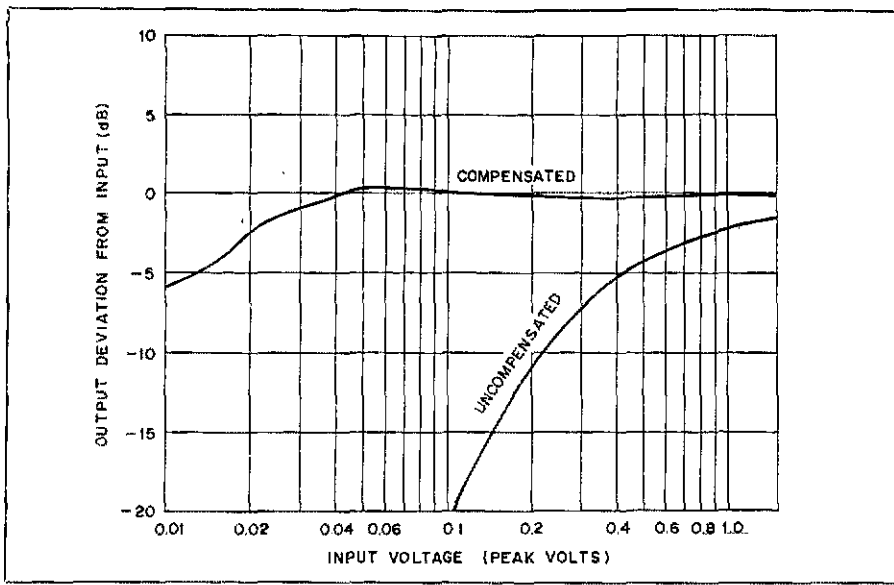


Fig 6—Comparison of accuracy for a compensated and uncompensated diode detector. The top line shows measurement error as a function of peak RF input voltage for the compensated detector using a matched pair of Schottky barrier diodes. The bottom line shows measurement error for an uncompensated 1N34A germanium diode detector. Measurements were made at a frequency of 10 MHz.

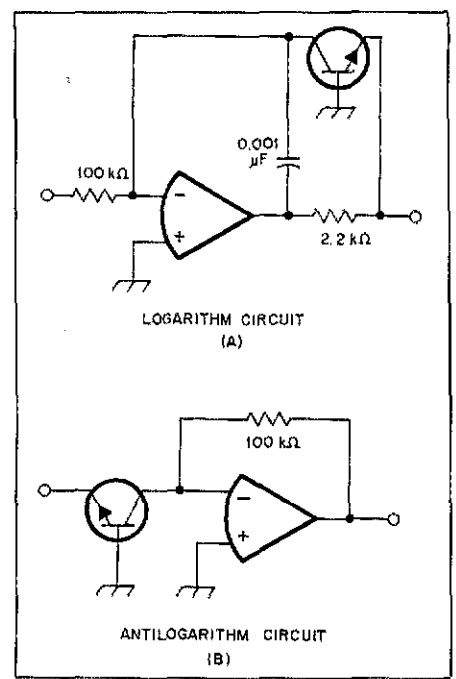


Fig 8—Simplified diagrams of the logarithm circuit at A and the antilogarithm circuit at B.

tuned with an output power of only a few watts. People are amazed at how easy it is to tune an antenna system using the direct SWR display from the Tandem Match.

The heart of the signal-processing circuit is the analog logarithm and antilogarithm circuits shown in Fig 8. The circuit is based on the fact that the collector current in a silicon transistor is proportional to the

exponential (antilogarithm) of its base-emitter voltage over a range of collector currents from a few nanoamperes to a few milliamperes when the collector base voltage is zero.⁴ Variations of this circuit are used in the squaring circuits to convert voltage to power and in the divider circuit used to compute the SWR. With good op amps, this circuit will work well for input

voltages of less than 100 mV to greater than 10 V.

Construction

Up to this point, we have examined some of the circuitry of the Tandem Match. The

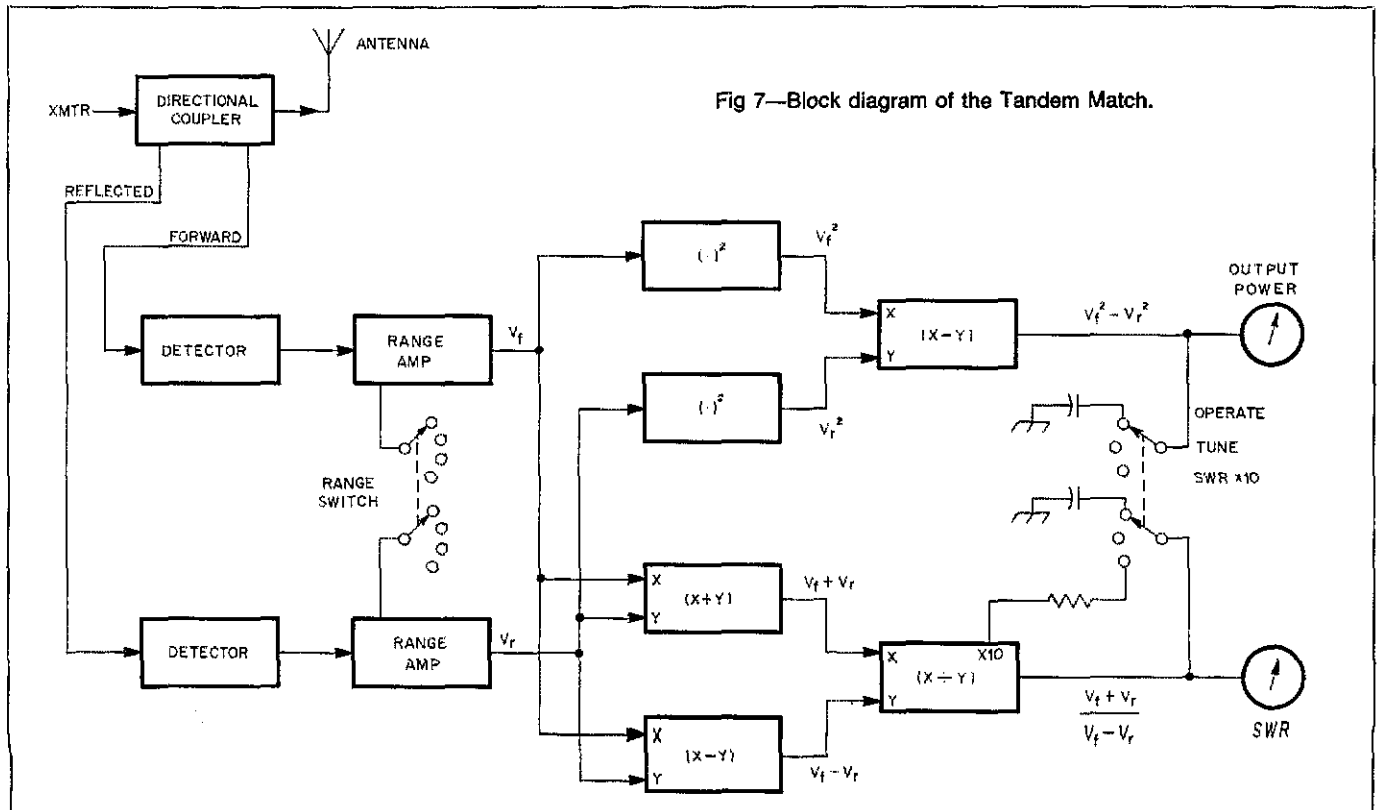


Fig 7—Block diagram of the Tandem Match.

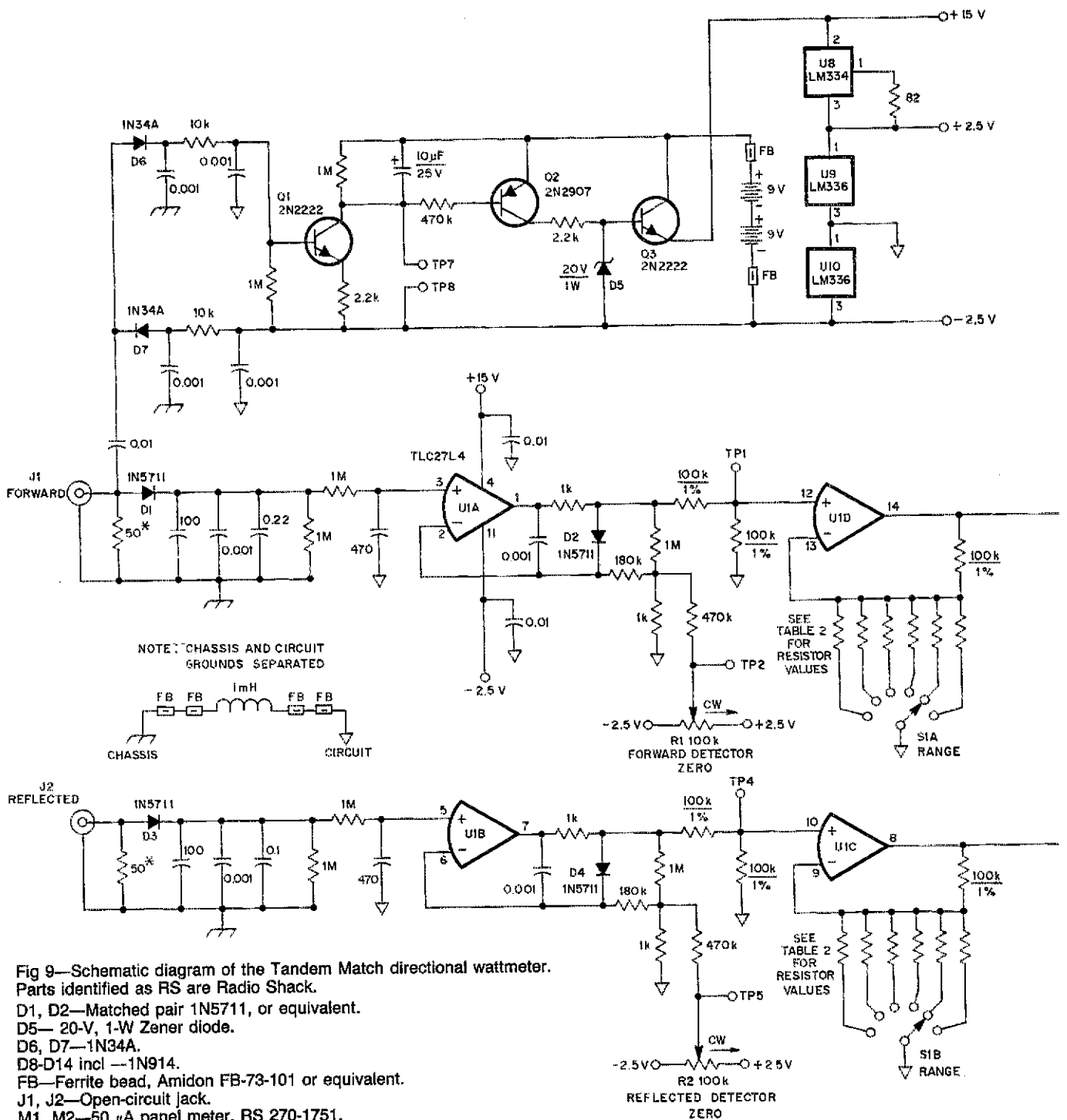


Fig 9—Schematic diagram of the Tandem Match directional wattmeter. Parts identified as RS are Radio Shack.

- D1, D2—Matched pair 1N5711, or equivalent.
- D5—20-V, 1-W Zener diode.
- D6, D7—1N34A.
- D8-D14 incl.—1N914.
- FB—Ferrite bead, Amidon FB-73-101 or equivalent.
- J1, J2—Open-circuit jack.
- M1, M2—50 μ A panel meter, RS 270-1751.
- Q1, Q3, Q4—2N2222 or equivalent.
- Q2—2N2907 or equivalent.
- R1, R2, R5—100 k Ω , 10-turn cermet Trimpot[®].
- R3, R4—10 k Ω , 10-turn cermet Trimpot.
- U1-U3 incl.—TLC27L4 or TLC27M4, RS 276-1750.
- U4—TLC27L2 or TLC27M2, RS 278-1749.
- U5-U7 incl.—CA3146.
- U8—LM334.
- U9, U10—LM336.

rest of this article describes the construction and calibration of the unit. The schematic diagram for the Tandem Match is shown in Fig 9. The finished unit is capable of

measuring power and SWR as accurately as any commercial directional wattmeter, yet requires only an accurate voltmeter for calibration. I have constructed several

versions of both the directional coupler and the detector circuit. They have all performed within their specifications.

The Tandem Match is designed to oper-

across the box to improve the directivity of the coupler. The RG-8X coaxial cable passes through holes in the PC board. The center conductor of the coaxial cable is connected to the center pin of the SO-239 connectors. The coaxial-cable shield is connected only at one end; the other end is open. This is very important—the shield must be connected only at one end or the directional coupler circuit will not work properly. The shield forms an electrostatic shield between the two sides of the transformer. Each transformer consists of 31 turns of no. 24 enamel wire on an Amidon T50-3 iron-powder core. The core is then slipped over the coaxial cable (including both the shield and the outer insulation.) The center conductor forms the primary of the transformer. The transformer is then connected as shown in Fig 10 with the wires running through separate holes in the copper-clad PC board. The secondary leads are twisted together and run to the SO-239 connector on the opposite side.

The directional coupler can be separated from the rest of the circuitry, if desired. In this event, run two coaxial cables from the directional coupler to the detector inputs to carry the forward and reflected power.

I have not used this directional coupler at power levels in excess of 100 W output and don't know if higher power levels will cause the enamel insulation to break down. If this is a problem, Teflon[®] insulated wire should work at power levels up to the legal limit. The wire size is not important, but the wire diameter, including insulation, must not exceed the size of no. 24 enamel-covered wire. I constructed one directional coupler using no. 28 Teflon-insulated wire, and it worked identically to one constructed with enameled wire.

Detector and Signal-Processing Circuits

The detector and signal-processing circuits were constructed on a piece of copper-clad Vectorbord[®]. These circuits use two separate grounds. It is extremely important that these grounds be isolated as shown in the circuit diagram. Failure to do this will probably result in RF disrupting the circuit operation because of RF currents flowing on the outside shield of the coaxial cable. The separate grounds prevent this current from getting into the op amp circuitry.

The directional coupler requires good 50-ohm loads. Each load is constructed on the back of a female UHF chassis connector. The load consists of four 200-ohm resistors connected from the center conductor of the UHF connector to each of the four holes on the mounting flange, as shown in Fig 11. The detector diode is then run from the center conductor of the connector to the 100-pF and 1000-pF bypass capacitors mounted right next to the connector. This load and detector combination has been measured to be flat to beyond 500 MHz.

The detector diodes must be matched.

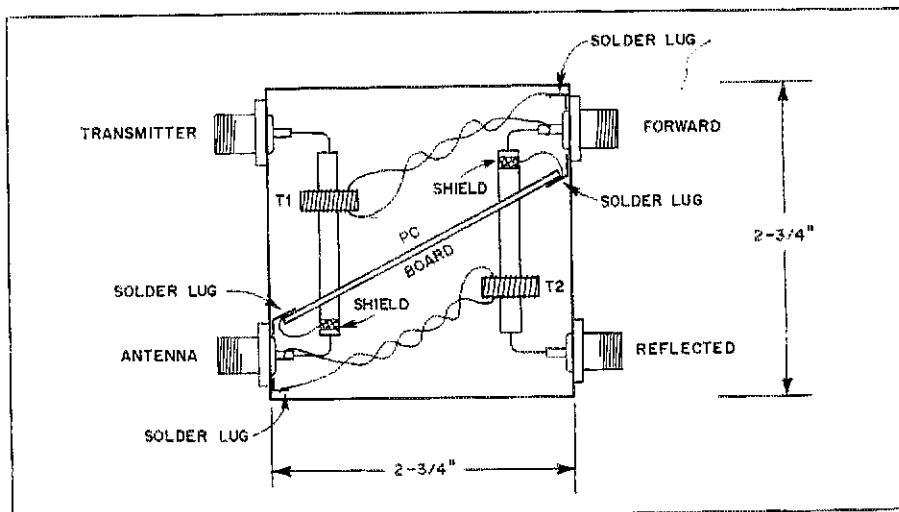


Fig 10—Construction details for the directional coupler.

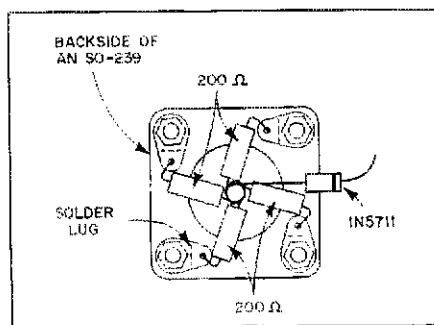


Fig 11—Mounting of parallel load resistors on SO-239 connector. Four 200-ohm resistors are mounted in parallel to provide a 50-ohm detector load.

This can be done at dc using the circuit shown in Fig 12. The meter must have a high input impedance, preferably 10 megohms or greater. Diodes which have a voltage drop within a few millivolts of each other can be considered matched. I found that diodes from the same batch were already matched.

I used 1N5711 Schottky barrier diodes because they were available. Any RF detector diode with a low forward voltage drop could be used. The important parameters are that the diodes must be a matched pair, the forward voltage drop of the diodes should be less than 300 mV, and the reverse breakdown voltage of the diodes must be greater than 30 V.

Germanium diodes could be used in this circuit, but there will be a degradation in performance. If germanium diodes are used, the resistance values for the detector-diode and feedback-diode load resistors should be reduced by a factor of 10.

The rest of the circuit layout is not critical. However, the lead lengths of the 0.001- and 0.01- μ F bypass capacitors should be kept short. The capacitors provide additional bypassing for the op amp circuitry.

The 1N34A diodes form a voltage

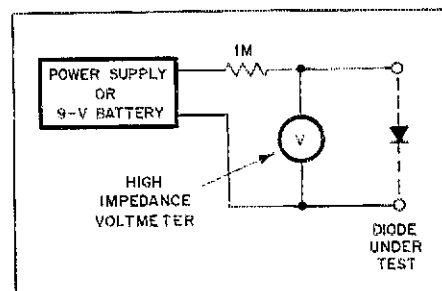


Fig 12—Diode matching test setup.

doubler which is used to detect the presence of a carrier. When forward power exceeds 1.5 W, Q3 is turned on and supplies power to the directional coupler. Power is held on for about 10 seconds after the carrier is last detected. Connecting TP7 to TP8 will force the unit on, even with no carrier present. Regulated references of +2.5 V and -2.5 V are generated by the LM334 and LM336. Using Zener diodes instead of these will significantly degrade the stability and accuracy of the directional wattmeter.

The four op amps in U1 compensate for the nonlinearity of the detector diodes. D1 and D2 must be a matched pair, as must D3 and D4. A RANGE switch selects the power range. The resistor values for the RANGE switch are shown in Table 2. I used a six-position switch because I had one handy. Full-scale input power gives an output at U1C or U1D of 7.07 V. The forward and reflected power detectors are zeroed with R1 and R2.

Forward and reflected voltages are squared by U2, U5 and U6 so that the output voltages are proportional to forward and reflected power. The gain constants are adjusted using R3 and R4 so that an input of 7.07 V to the squaring circuit gives an output of 5 V. The difference between these two voltages is used by U4B to yield an output that is proportional to the power deli-

Table 2
Range-Switch Resistor Values

Full-Scale Power Level (Watts)	Range Resistor (1% Accuracy) (kilohms)
1	2.32
2	3.24
3	4.02
5	5.23
10	7.68
15	9.53
20	11.0
25	12.7
30	14.0
50	18.7
100	28.7
150	37.4
200	46.4
250	54.9
300	63.4
500	100.0
1000	237.0
1500	649.0
2000	open

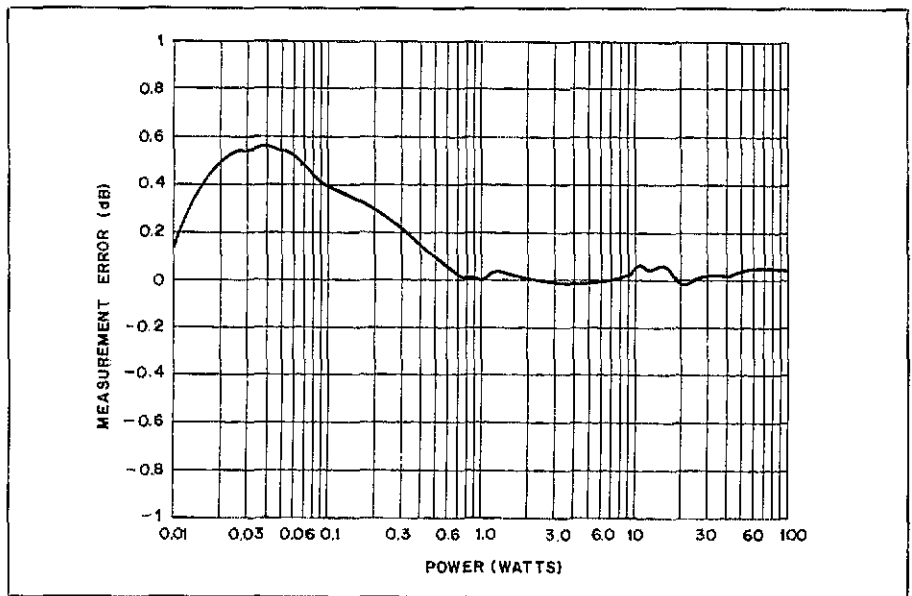


Fig 13—Power measurement accuracy for the Tandem Match. Measurement errors exist primarily in the low-power range.

vered into the transmission line. This voltage may be peak detected to hold and indicate the maximum power that occurs during CW or SSB transmissions.

Computation of SWR from the forward and reflected voltages is accomplished by U3, U4 and U7. When no carrier is present, Q4 forces the SWR reading to zero. This circuit considers no carrier present if the forward power is less than 1 to 2% of the full-scale setting of the RANGE switch. The SWR computation circuit gain is adjusted by R5. The SWR output varies from 1 V for an SWR of 1:1 to 5 V for an SWR of 5:1. The output may be peak detected to hold and indicate the maximum SWR reading during CW or SSB transmissions.

Transistor arrays (U5, U6 and U7) are used for the logarithm and antilogarithm circuits. Using transistor arrays guarantees that the transistors will be well matched. Individual transistors may be used, but the accuracy may be significantly degraded.

A three-position toggle switch is used to select the three operating modes. In the OPERATE mode, the power and SWR outputs are peak detected and held for a few seconds to allow the meters to be read during actual transmissions. In the TUNE mode, the meters display the instantaneous output power and SWR. This mode is used to adjust an antenna matching network. In the SWR \times 10 mode, the SWR full-scale reading is increased to 50:1. This mode is handy for adjusting an antenna matching network when one has no idea what the correct setting should be.

An external meter can be used to read both power and SWR values. The output power range is 0 to 5 V, with 0 V representing no output power and 5 V representing the RANGE switch full-scale value. Output

voltages above 5 V may be incorrect because of voltage limiting in some of the op amp circuits. The SWR range is also from 0 to 5 V, with 0 V representing no power present, 1 V representing an SWR of 1:1 and 5 V representing an SWR of 5:1. I have used a digital voltmeter to obtain more precise readings than possible with the analog meters. Alternatively, one could incorporate digital panel meters into this unit in place of the analog meters shown in the circuit diagram.

Calibration

The directional wattmeter can be calibrated to its full accuracy using only an accurate voltmeter. A digital voltmeter is preferred, but a good analog meter should also work. All calibration is done with dc voltages. The directional coupler and detector circuits are inherently accurate if they were correctly built. To calibrate the wattmeter, use the following procedure:

- 1) Set the mode switch to TUNE and the RANGE switch to 100 W full scale or less.
- 2) Jumper TP7 to TP8. This turns the unit on.
- 3) Jumper TP1 to TP2. Adjust R1 for 0 V at TP3.
- 4) Jumper TP4 to TP5. Adjust R2 for 0 V at TP6.
- 5) Adjust R1 for 7.07 V at TP3.
- 6) Adjust R3 for 5.00 V at TP9 or full scale reading on M1.
- 7) Adjust R2 for 7.07 V at TP6.
- 8) Adjust R4 for 0 V at TP9 or zero reading on M1.
- 9) Adjust R2 for 4.71 V at TP6.
- 10) Adjust R5 for 5.00 V at TP10 or full scale reading on M2.
- 11) Set RANGE switch to most sensitive

scale.

12) Remove jumpers from TP1 to TP2 and TP4 to TP5.

13) Adjust R1 for 0 V at TP3.

14) Adjust R2 for 0 V at TP6.

15) Remove jumper from TP7 to TP8.

This completes the calibration procedure. I have found that this calibration is as accurate as using expensive laboratory test equipment. The directional wattmeter should now be ready for use.

Accuracy

Some writers claim that their new gadget performs miracles, but there is seldom any proof to back up their claims. For this article, I was determined to demonstrate that the Tandem Match meets its accuracy specifications when tested with calibrated laboratory test equipment.

I compared the performance of this wattmeter against other well-known directional couplers and laboratory test equipment. The Tandem Match is as good as any amateur directional wattmeter I have tested. I checked the power measurement accuracy against a Hewlett-Packard HP-436A power meter. The HP meter has a specified measurement error of less than ± 0.05 dB. The Tandem Match tracked the HP meter to within ± 0.5 dB over a power range of 10 mW to 100 W, and to within ± 0.1 dB over a power range of 1 W to 100 W. Fig 13 shows the measured performance. The unit was tested only to 100 W because I do not have a transmitter with a higher power rating.

The performance in measuring SWR was equally good. Using the HP power meter and a calibrated directional coupler to compute the SWR, the Tandem Match tracked the test equipment to within $\pm 5\%$

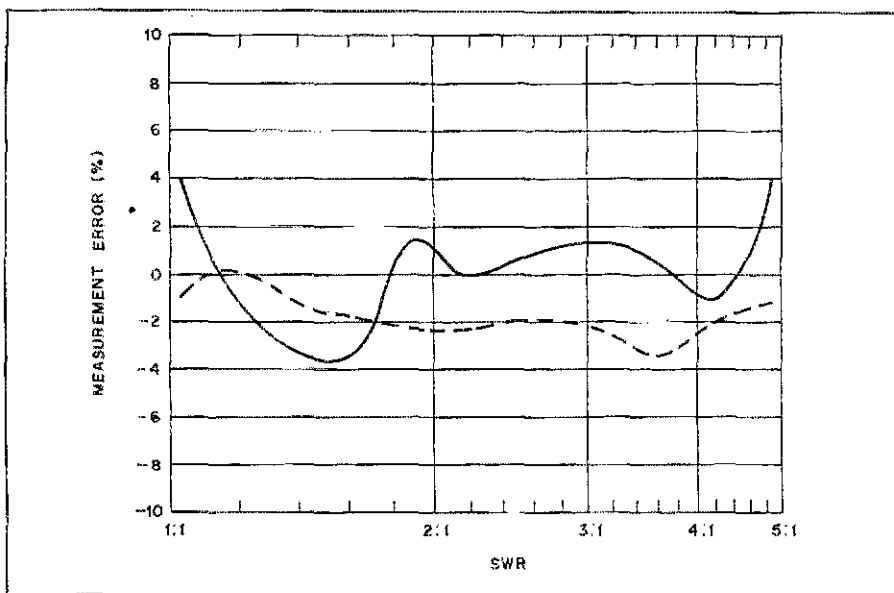


Fig 14—SWR measurement accuracy for the Tandem Match over the range of SWR values from 1:1 to 5:1. Measurements were made at 10 MHz. The dashed line was measured at 8 W forward power; the solid line was measured at 100 W forward power.

for SWR from 1:1 to 5:1. These measurements were made at power levels of 8 W and 100 W. Fig 14 reflects these results.

Operation

Operation of the Tandem Match is straightforward. The unit is connected in the 50-ohm line between the transmitter and the antenna matching network, or antenna if no matching network is used. The RANGE switch should be set for a range greater than the output rating of the transmitter, and the mode switch should be set to TUNE. When the transmitter is keyed, the Tandem Match will automatically turn itself on and measure the power delivered to the antenna and the SWR on the transmission line. If no carrier is present, the OUTPUT POWER and SWR meters will indicate zero.

The OPERATE mode is used to measure the peak power delivered to the antenna and the SWR when CW or SSB is transmitted. The peak detectors in the unit are not ideal, and there could be about a 10% variation from the actual peak power and SWR. However, this mode is convenient for monitoring these parameters during actual transmissions.

The SWR $\times 10$ mode is used to increase the SWR meter range to 50:1. This mode is sometimes necessary for initially adjusting a matching network if the SWR is very high. This range should be sufficient to cover any SWR value that occurs in amateur use. A 50-foot length of RG-8 that is left open circuited will display a measured SWR of 43:1 at 3.5 MHz exclusively because of the loss in the cable. Higher frequencies and longer cables will exhibit a smaller maximum SWR.

It is easy to use the Tandem Match to adjust a matching network. Adjust the transmitter for minimum output power, as long as it exceeds 1.5 W. With the carrier on and the mode switch set to TUNE or SWR $\times 10$,

adjust the matching network for minimum displayed SWR. The process is similar to dipping the plate current on a tube-type transmitter. Once the minimum SWR is obtained, the transmitter can be set to the proper operating mode and output power with the Tandem Match set to the OPERATE mode. The peak output power and SWR can then be monitored during operation.

Design Variations

There are several ways in which this design could be changed to enhance operation. The most important would be to add VHF/UHF operation capability. This can be accomplished by designing a new directional coupler that will work above the HF range. The existing detector circuit will work to at least 500 MHz.

For those who desire a low-power directional wattmeter, the directional coupler can be changed to a 20-dB coupling factor by decreasing the turns ratio of the transformers to 10:1. A low-power unit should be capable of measuring output power from 1 mW to about 150 W, and the unit should switch on at about 150 mW. This change should also increase the maximum operating frequency to about 150 MHz. If operation on 160 meters is desired, it may be necessary to change the toroidal core material to obtain sufficient reactance at 1.8 MHz to minimize the insertion loss.

The unit can be made to operate with coaxial cable having characteristic impedances other than 50 ohms. It will be necessary to change the detector terminating resistors to result in the value of the characteristic impedance of the coaxial cable used. Because the detector circuit measures voltage, not power, the range resistors must also be changed to obtain the proper power levels.

The detector circuitry can be used to directly measure low RF power levels in

50-ohm circuits. Power is fed directly to the forward detector, and the power is read from the POWER OUTPUT meter. Over the power range from 10 μ W to 1.5 W, the detector is quite linear.

Acknowledgments

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