Measuring RF power

Joe Carr explains presents a backgrounder to RF power and describes a number of circuits for measuring it.

Radio-frequency power measurements are made for a variety of purposes In this pair of articles, several different topics will be discussed: the nature of the power being measured, methods of measuring power, error sources in RF power measurement, and typical commercial instruments used for RF power measurements

The assumption is that the RF power is being measured to determine the output level produced by a radio transmitter, or some associated circuit or device.

What is Power?

Electrical power is defined as energy flow per unit of time. The internationally accepted standard unit of power is the *watt*, abbreviated to W of course, which is defined as an energy flow of one joule per second.

Other electrical units are defined in terms of the watt One volt for example is one watt per ampere of current flow. The watt is the product of the electrical potential and the current flowing,

$$P = V \times I$$

Other expressions of power include,

$$P = I^2 \times R$$

and,

$$P = \frac{V^2}{R}$$

Where P is power in watts, V is electrical potential in volts, I is current in amperes and R is resistance in ohms

Decibel notation of power units

It is common practice to express power relationships in terms of decibel notation, which allows gains and losses to be added and subtracted, rather than multiplied and divided, somewhat simplifying the arithmetic.

For relative power levels,

$$dB = 10\log\left[\frac{P1}{P2}\right] \tag{4}$$

And for absolute power levels 50Ω load,

$$dBm = 10\log\left[\frac{P_w}{0.001}\right] \tag{5}$$

or,

$$dBm = 10\log P_{mw} \tag{6}$$

where dBm is power level relative to one-milliwatt in a 50Ω load, $P1$ and $P2$ are two power levels (same units), P_W is power in watts and P_{mW} is power in milliwatts.

Types of RF power measurement

Measuring RF power is essentially the same as measuring low frequency AC power, but certain additional problems present themselves

For a continuous wave, or CW, signal, the issue is relatively straight forward because the signal is a series of equal amplitude sine waves. For on-off telegraphy, the problem gets somewhat more difficult because the waves are not constant amplitude. The RF power depends on the ratio of on time to off time.

In the case of the sine wave, a peak reading instrument, such as a diode detector, can be calibrated for root-

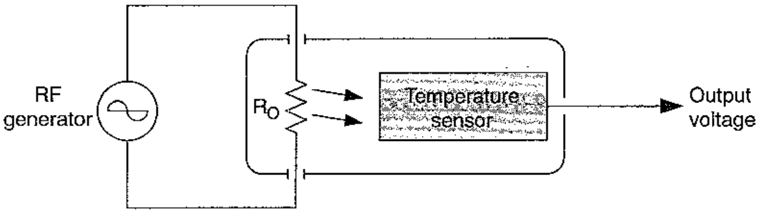


Fig 1. Simple bolometry/ calorimetry approach to measuring RF power.

Table 1. Power relationships between various modulation waveforms. System impedance is 50 Ω. Waveforms are compared with 100W RMS unkeyed CW power.

Waveform Description	PEV	PEP (PEV^2/Z$_o$)	Heating power
Continuous wave (CW)	70.7	100W	100W
Amplitude modulation (100%)	141.4	400W	150W
Amplitude modulation (75%)	122.3	300W	127W
Single-sideband (one-tone)	70.7	100W	100W
Single-sideband (two-tone)	70.7	100W	50W
Single-sideband (voice)	70.7	100W	(Note 1)
TV black level	70.7	100W	60.1W
Pulse (10% duty cycle)	70.7	100W	10W
Multiple carriers (Note 2)	282.8	1600W	400W

NOTES:

Note 1: Depends on voice modulation characteristics

Note 2: Four 100W RMS CW carriers

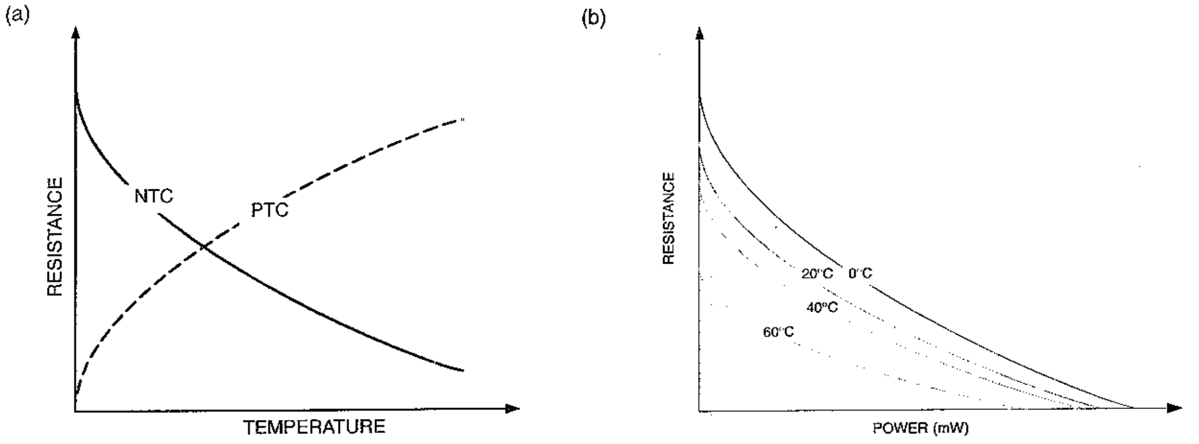
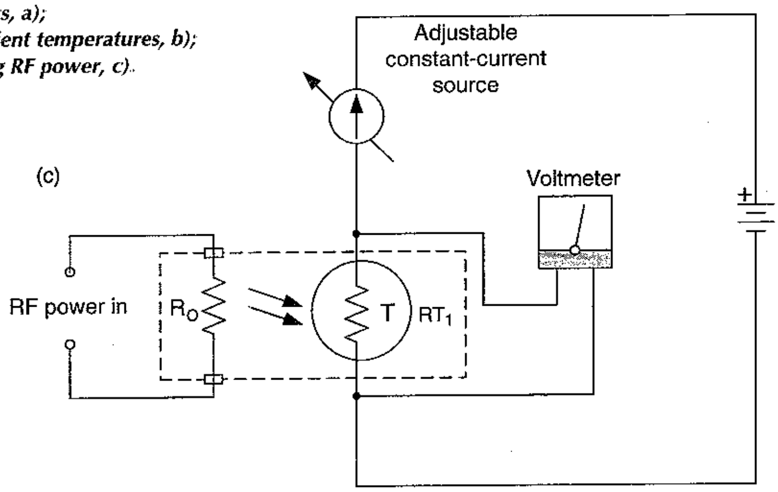


Fig. 2 Thermistor R-versus-T characteristics, a); R-versus-P characteristics at different ambient temperatures, b); and thermistor sensor mount for measuring RF power, c).



mean-square (RMS) power by the simple expedient of dividing the indication by the square root of two, which is 1 414

If the meter is inherently RMS reading – it is, for example, a thermally based instrument – then the power measurement of the complex waveform is inherently RMS.

Table 1 shows the power relationships for assorted modulation waveforms. The figures are arbitrarily based on the peak envelope voltage (PEV) in each waveform, a 50Ω system impedance, and are compared with 100W RMS unkeyed CW power

Methods for measuring RF power

RF power meters use a number of different approaches to making the measurement Some instruments measure the current or the voltage at a resistive load, and depend on the equations I^2R or E^2/R

Other methods are based on the fact that power dissipated in a resistive load is converted to heat, so the temperature change before and after the RF power is applied can be used as the indicator of RF power. This approach has the advantage of finding a DC equivalent RMS power.

Figure 1 shows the basic scheme. A load resistor, R_o, with a resistance equal to the system impedance, is enclosed in an isolated environment with some sort of temperature sensor.

Theoretically, you could place a dummy load resistor in a workshop room, and then use a glass mercury thermometer and stop watch to measure the rise in temperature and elapsed time to find the power. That's hardly practical though.

The basic idea is to find a sensor, such as a thermistor or thermocouple, that will convert the heat generated in the load resistor to a DC, or low-frequency AC, signal that is easily measured with ordinary electronic instruments.

In the case shown in Fig. 1, the temperature sensor produces a voltage output that is proportional to the applied RF power level.

Thermistor RF power meters

A thermistor is a resistor that changes its electrical resistance with changes in temperature. Although all conductors exhibit some 'thermistor behaviour' actual thermistors are usually made of a metallic oxide compound

Figure 2a) shows the resistance versus temperature curve for a typical thermistor device. A negative temperature coefficient, or NTC, device will decrease resistance with increases in temperature A positive temperature coefficient device, or PTC, device is the opposite: resistance rises with increases in temperature

Bolometers

Figure **2b)** shows a family of resistance versus self-heating power curves for a single thermistor operated at different temperatures

The resistance is not only nonlinear, which makes measurements difficult enough in its own right, but also the shape and placement of the curve varies with temperature. As a result, straight thermistor instruments can be misleading.

Bolometry is a method that takes advantage of this problem to create a more accurate RF power measurement system.

Self-heating power is caused by a DC bias flowing in the thermistor. Figure **2c)** shows how self-heating can be used in bolometry. Thermistor RT_1 is adjusted to a specified self-heating point when no RF power is applied to the dummy load R_O. The resistance of thermistor RT_1 can be read from the voltmeter because the current from the constant-current source remains the same once it is adjusted to a set point.

When RF power is applied to the dummy load, heat radiated from the load causes the resistance of RT_1 to decrease. The bolometer current source is then adjusted to decrease the bias until the resistance rises back to the value it had before power was applied This point is indicated by returning the meter reading to the same point as before

The change of bias power required to restore the thermistor to the same resistance is therefore equal to the power dissipated in the dummy load.

Self-balancing bridge instruments

The Wheatstone bridge circuit, **Fig. 3**, is used in a number of instrumentation circuits. In the null condition, when V_O is zero, the ratios of the resistors are equal: $R_1/RT_1=R_2/R_3$.

It is not strictly necessary that $R_1=RT_1=R_2=R_3$, only that $R_1/RT_1=R_2/R_3$. If one of the resistors is a thermistor, then the temperature can be measured by the unbalance of the bridge. Similarly, if the thermistor resistance is such that the equality $R_1/RT_1=R_2/R_3$ is satisfied, then you can infer the resistance of the thermistor by the null condition.

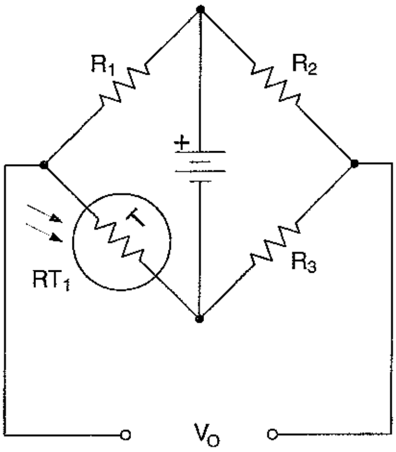


Fig. 3. Wheatstone bridge circuit with a thermistor in one arm.

The self-balancing – also known as autobalancing or autonull – bridge shown in **Fig. 4** uses a Wheatstone bridge thermistor to perform bolometry measurement of RF power. The thermistor mount sensor assembly contains a dummy load and a thermistor, R_T. The null condition is created when $R_1/R_T=R_2/R_3$.

The self-balancing bridge uses a differential amplifier A_1 to perform the balancing. A differential amplifier produces an output voltage proportional to the difference in two input voltages.

When the Wheatstone bridge is in balance, then the output of the differential amplifier is zero. The bias for the Wheatstone bridge, hence the thermistor in the bolometer sensor, is derived from the output of the amplifier.

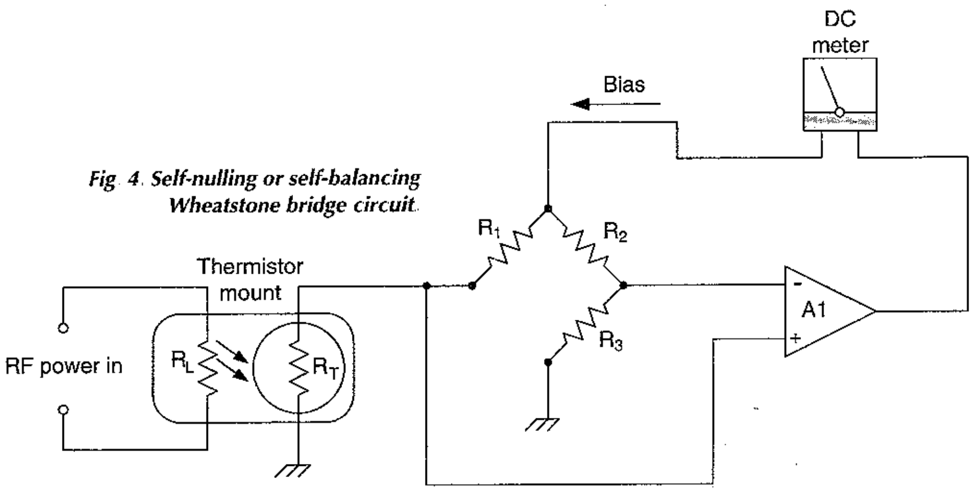


Fig. 4. Self-nulling or self-balancing Wheatstone bridge circuit.

A change in the resistance of the thermistor unbalances the bridge, and this moves the amplifier's differential input voltage away from zero. The amplifier output voltage goes up, thereby changing the bias current in an amount and direction necessary to restore balance. Thus, by reading the bias current, the power level that changed the thermistor resistance can be inferred.

Because the thermistor will have a different characteristic curve at different ambient temperatures, it is necessary to either control the ambient temperature, or correct for it. It is very difficult to control the ambient temperature. Although it is done, it is also not terribly practical in most cases. As a result, it is common to find RF power meters using two thermistors in the measurement process, **Fig. 5**.

One thermistor is mounted in the thermistor sensor mount used to measure RF power, while the other is used to measure the ambient temperature. The readings of the ambient thermistor are used to correct the readings of the sensor thermistor.

Thermocouple RF power meters

The thermocouple is one of the oldest forms of temperature sensor. When two dissimilar metals are connected together to form a junction, and the junction is heated, then the potential across the free ends, V_T, is proportional to the temperature of the hot junction. This phenomenon is called the Seebeck effect.

A thermocouple RF ammeter is constructed using thermocouples and a small value resistance heating element, **Fig. 6**. The meter will have a small wire resistance element in close proximity to a thermocouple element. The thermocouple is, in turn, connected to a DC meter.

When current flows through the resistance heating element, the potential across the ends of the thermocouple changes proportional to the RMS value of the current. Thus, the RF ammeter measures the RMS value of the RF current.

If the RF ammeter is used to measure the current flowing from an RF source to a resistive load, then the product I^2R indicates the true RF power. These meters can measure RF current up to 50 or 60MHz, depending on the instrument.

Thermocouples and thermistors share the ability to measure true RF power. Although thermocouple RF ammeters have been used since the 1930s, or earlier, the use of thermocouples in higher frequency and microwave power meters started in

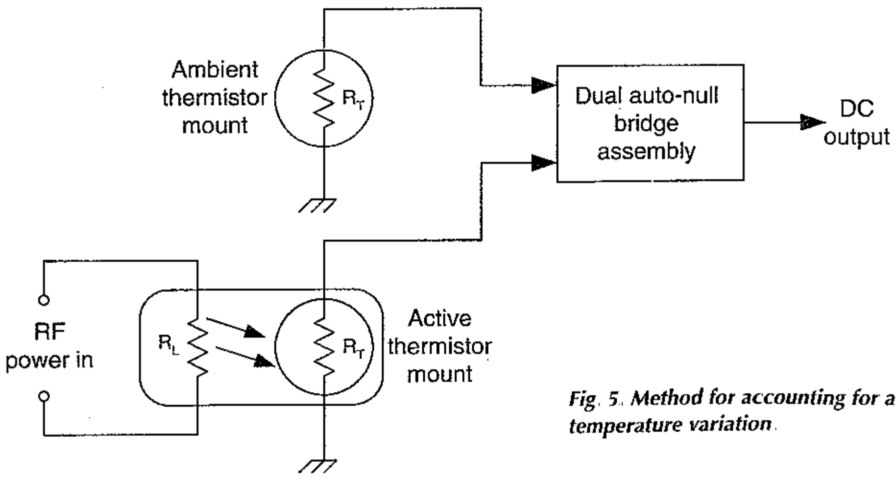


Fig. 5. Method for accounting for ambient temperature variation.

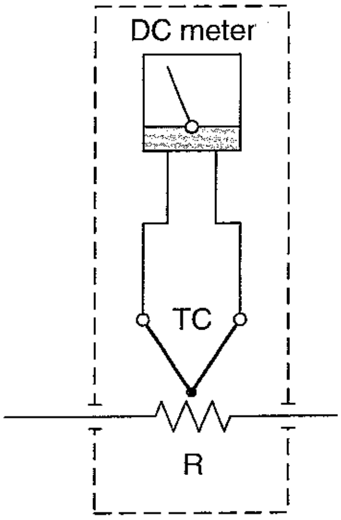


Fig. 6. The thermocouple RF ammeter is useful for measuring frequencies to about 60MHz.

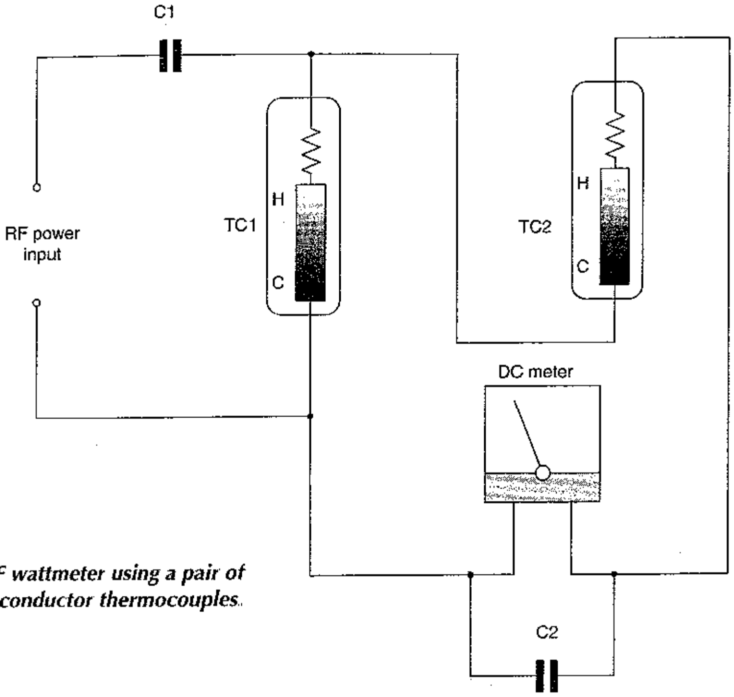
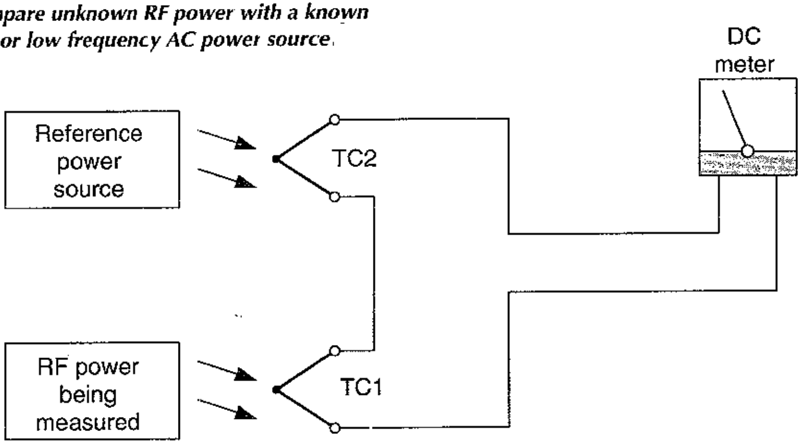


Fig. 7. RF wattmeter using a pair of semiconductor thermocouples.

Fig. 8. Using two thermocouples to compare unknown RF power with a known DC or low frequency AC power source.



the 1970s Thermocouples are more sensitive than thermistor sensors, and are inherently square-law devices.

Figure 7 shows a solid-state thermocouple sensor that can be used well into the microwave region Two semiconductor thermocouples are connected such that they are in series for DC, and parallel for RF frequencies Thus, their combined output voltages are read on the DC voltmeter. Because of the capacitors, however, they are in parallel for RF frequencies, and if designed correctly will make a 50Ω termination for a transmission line.

Thermocouples suffer the same reliance on knowing the ambient temperature as thermistors. **Figure 8** shows a method for overcoming this problem. A pair of thermistors is used One is used either in a bolometry circuit or as a terminating sensor to measure the unknown RF power The other sensor is used to measure a highly controlled reference power source.

Depending on the implementation, the reference power might be DC, low frequency AC or another RF oscillator with a highly controlled, accurately calibrated output power level.

Diode detector RF power meters

Rectifying diodes convert bi-directional alternating current

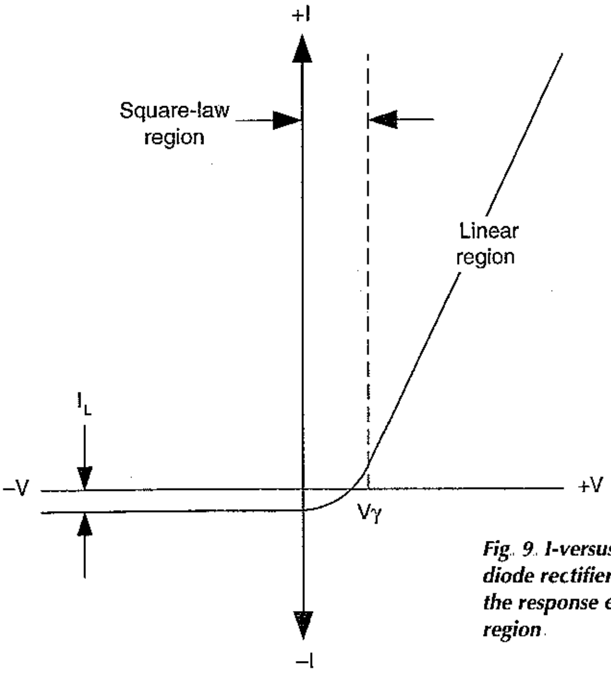


Fig. 9. I-versus-V curve of diode rectifier. Note that at Vγ, the response enters a linear region.

to unidirectional pulsating DC. When filtered, the output side of a diode is a DC level that is proportional to the amplitude of the applied AC signal.

Figure 9 shows the unidirectional action in the form of the *I-versus-V* curve When the applied bias is positive – i.e forward bias – the current begins to flow, but not proportionally. At some point between 200 and 300mV in germanium diodes or 600 and 700mV in silicon diodes, marked V_γ in Fig 9, the response enters a linear region This response is termed ohmic because it follows Ohm's law.

When the applied voltage reverse biases the diode, the current flow ceases, except for a very small leakage current, I_L. One indicator of the quality of diodes is that I_L is minimised on higher quality units

The nonlinear region of the *I-versus-V* curve is called the square-law region. In this region the rectified output voltage from the diode is proportional to the input power **Fig. 10**. This behaviour is seen from power levels of –70 to –20dBm.

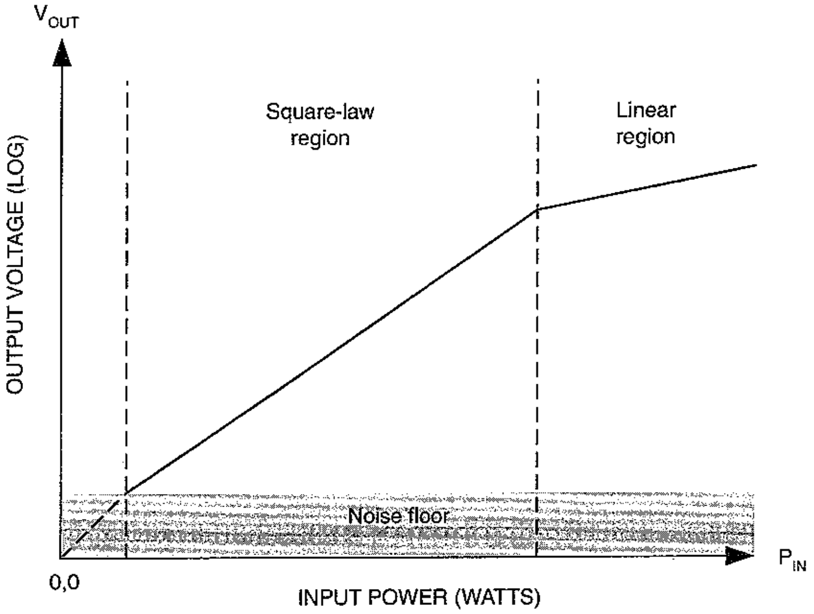


Fig. 10. Output voltage versus RF input power curve. In the square-law region, rectified output from the diode is proportional to input power.

In low-cost RF power measuring instruments, silicon and even germanium diodes are often used, but these are not highly regarded for professional measurements Low-barrier Schottky diodes are widely used up to well into the microwave region.

For higher frequencies in the microwave region, planar doped barrier (PDB) diodes are preferred. They work up to 18GHz or better, and power levels of –70dBm. It is claimed that PDB diodes are more than 3000 times more efficient than thermocouple detectors.

Circuits

Figures 11a) and **11b)** show two similar circuits using a diode detector. Resistor R_L in Fig. 11a) is a dummy load that has a resistance value equal to the characteristic impedance of the transmission line connecting the system – 50Ω for example

Diode D_1 is the rectifier diode, while capacitor C_1 is used to filter the pulsations at the rectifier output into pure DC. A problem with that circuit is that it is limited to power levels consistent with the native characteristics of the diode.

Figure 11b) shows the same circuit with a resistor voltage divider, R_1/R_2, to reduce the voltage associated with higher power levels to the characteristic of the diode. The actual voltage applied to the diode will be $V_{RL}\times[R_2/(R_1+R_2)]$. This circuit is similar to the metering circuit built into a number of low-cost amateur radio dummy loads in the past

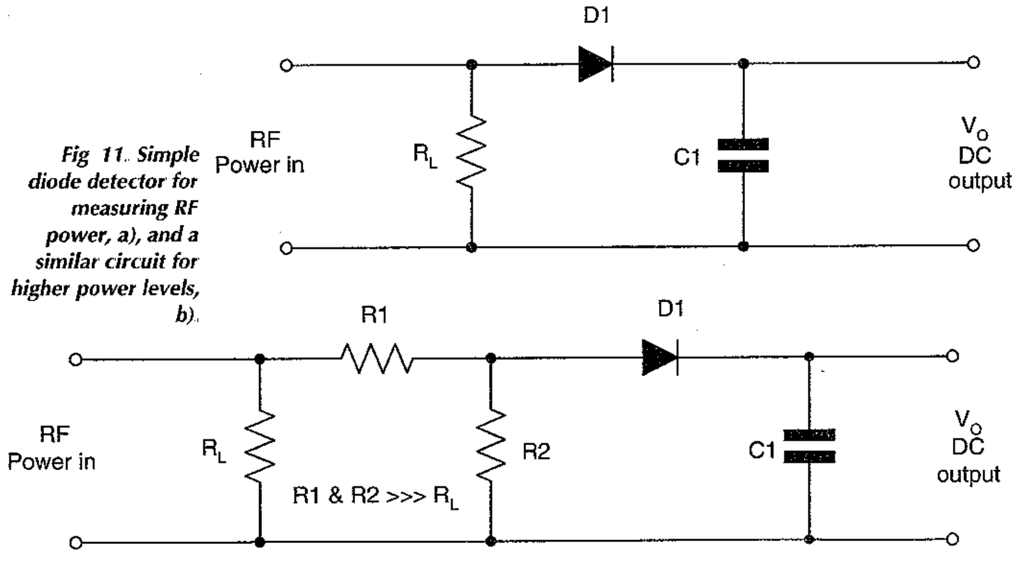


Fig 11. Simple diode detector for measuring RF power, a), and a similar circuit for higher power levels, b).

Practical in-line bridge circuits

Low-cost in-line RF power meters, **Fig. 12**, are available using a number of different forms of bridge circuit. These are superior to the classical Wheatstone bridge because they can

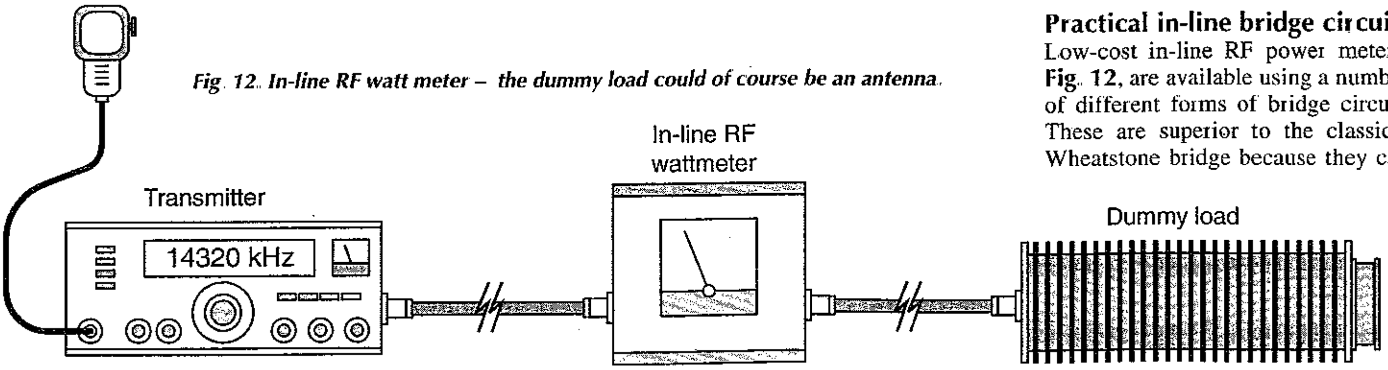


Fig. 12. In-line RF watt meter – the dummy load could of course be an antenna.

be left in-line while transmitting. Although the illustration in Fig. 12 shows a dummy load, it could just as easily use a radiating antenna.

Micromatch. One form of in-line RF power meter is the micromatch circuit of **Fig. 13**. This device is similar to a Wheatstone bridge in which the antenna impedance represents one arm, and a pair of capacitive reactances X_{C1} and X_{C2} represent two other arms.

Output voltage of the bridge is rectified by D_1, and filtered by R_2/C_3, before being applied to a microammeter. Note that this may be any meter from 100µA to 1mA full-scale.

The bridge consists of X_{C1}, X_{C2}, R_1 and R_L – the antenna or load resistance. The null condition exists when $X_{C1}/X_{C2}=R_1/R_L$. For 50Ω antenna systems the ratio R_1/R_L is 1/50, so a value of C_2 around 15pF is needed to produce the correct C_1/C_2 ratio.

For a 75Ω system, about 10pF is

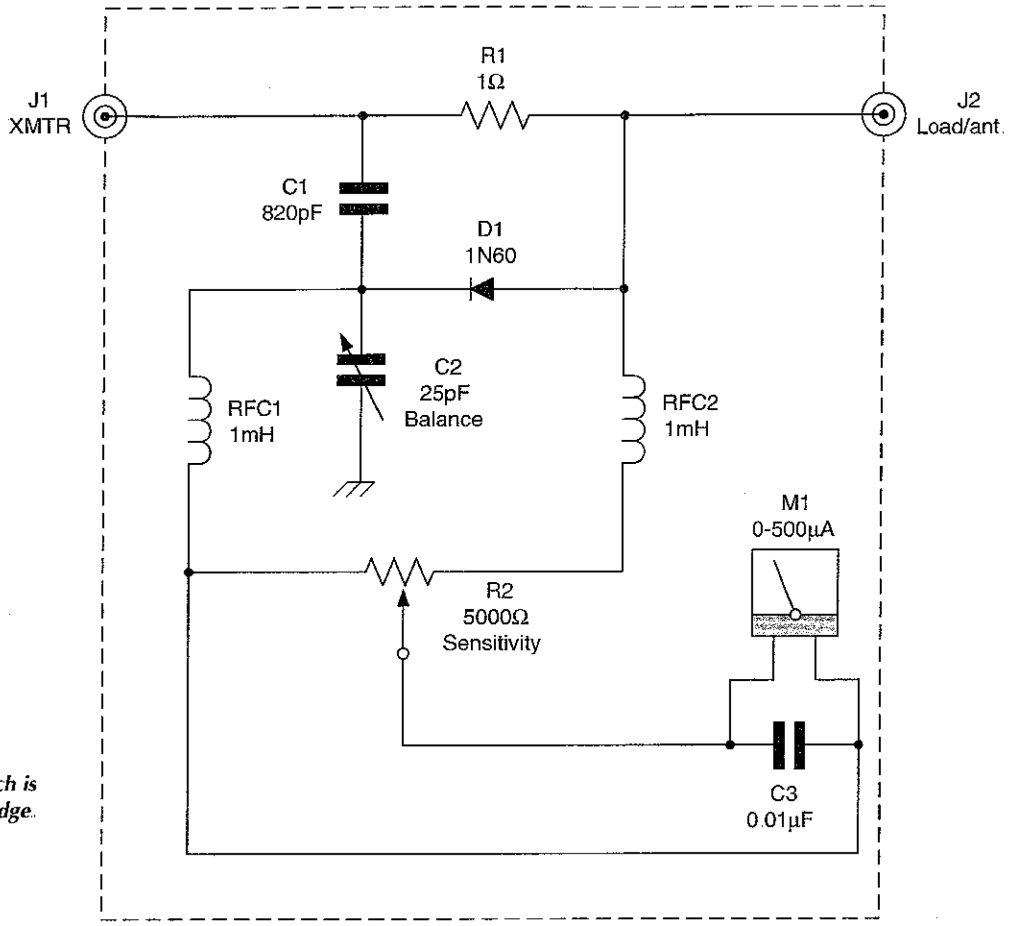


Fig. 13. Micromatch RF watt meter, which is similar to a Wheatstone bridge.

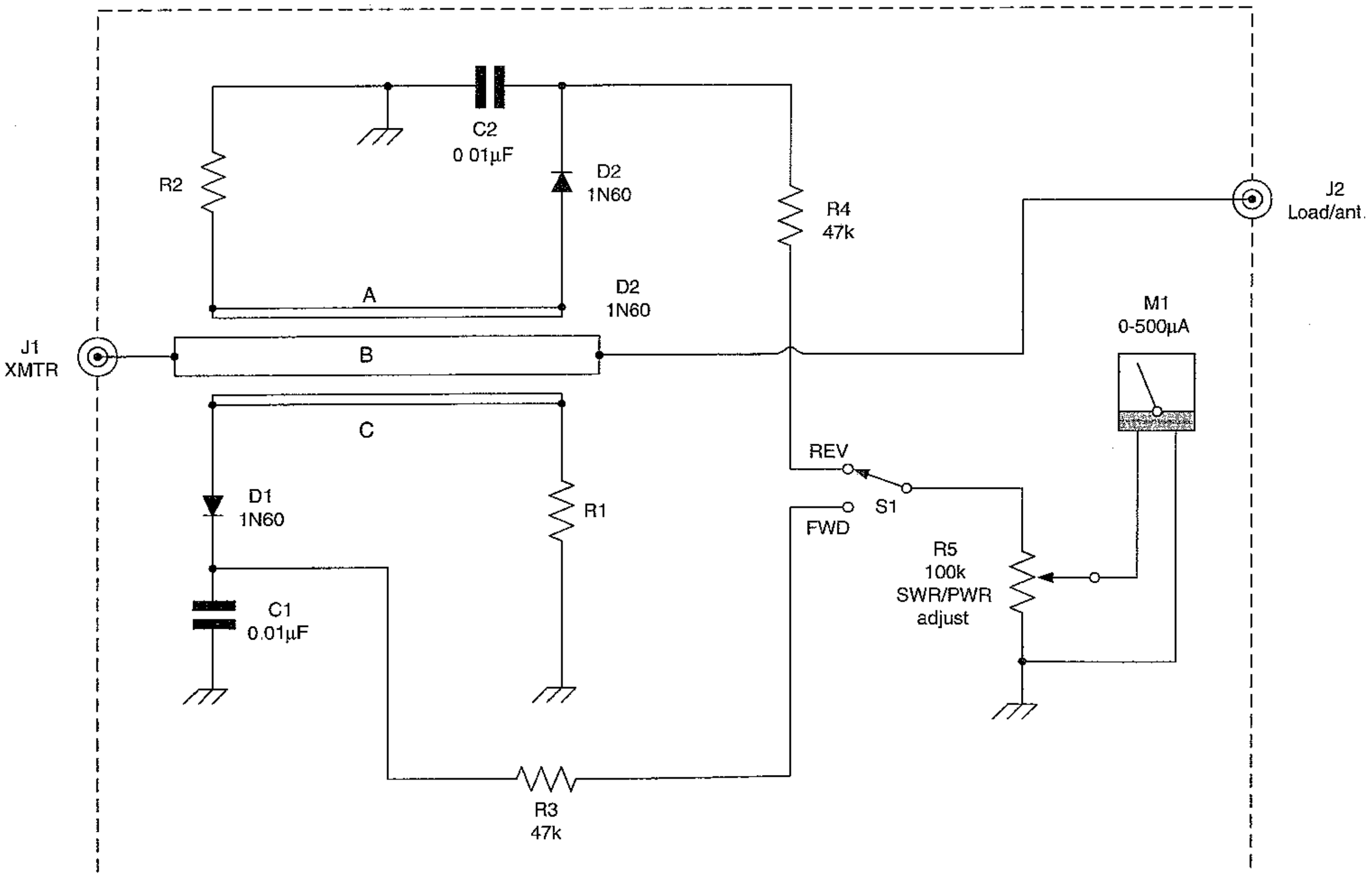


Fig. 14. Printed circuit mono-match RF wattmeter useful from HF to VHF.

needed. A number of people prefer to make a compromise by assuming a 68Ω load, so the capacitance needed in C_2 for a 1/68 ratio is about 12pF.

Series resistor R_1 is a one-ohm unit. In commercial micromatch RF wattmeters, this resistor is made using ten 2W, 10Ω resistors connected in parallel.

The RF power level is calibrated by adjusting the sensitivity control, R_2. In at least one commercial micromatch, there are actually three switch selectable sensitivity controls. These are calibrated for 10W, 100W and 1000W ranges.

Monomatch. The classical transmission line monomatch RF wattmeter is shown in **Fig. 14**. It can be used in the HF through VHF ranges. It consists of three printed transmission line segments – A, B and C – connected as a directional coupler.

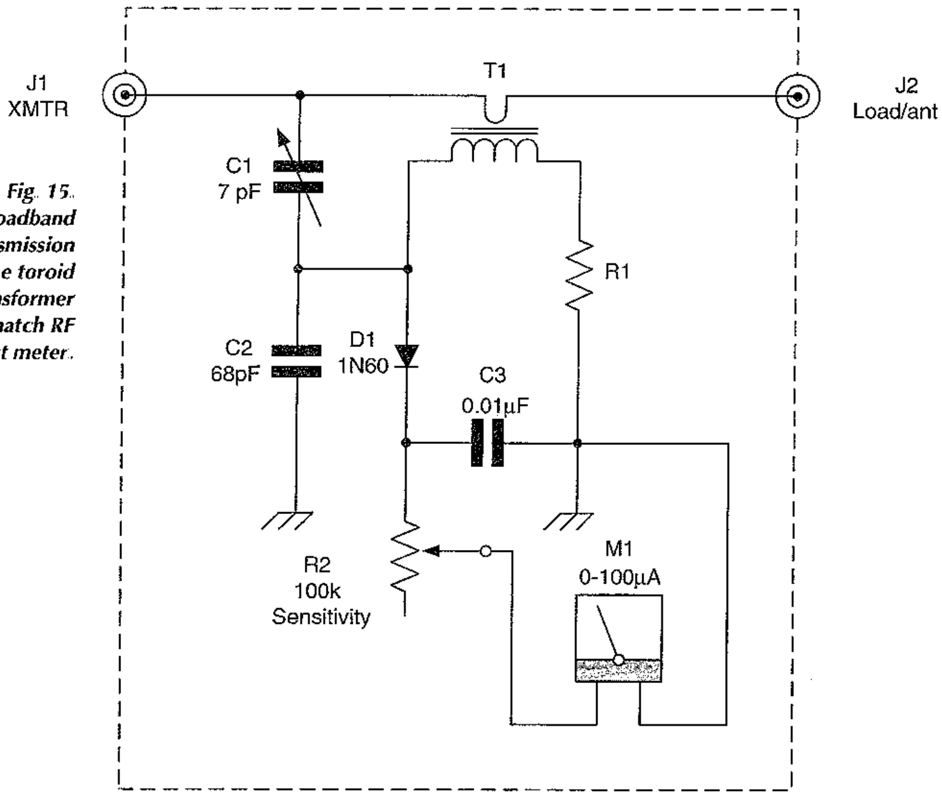


Fig. 15. Broadband transmission line toroid transformer mono-match RF watt meter.

In older instruments, the transmission line directional coupler was made using a length of RG-8/U coaxial cable with a pair of thin enamel insulated wires slipped between the shield and inner insulator. In more recent instruments the three transmission line segments are etched on a printed circuit board.

Sampling lines A and C are terminated in either 50Ω or 75Ω noninductive resistors such as carbon composition or metal film types. Again, a compromise value of 68Ω is often seen, so that either 50Ω or 75Ω antennas can be measured with only a small error.

Figure 15 shows an alternative monomatch system that uses a broadband transmission line transformer, T_1, made using a ferrite or powdered iron toroidal core. This circuit is usable throughout the HF range.

Detail for implementing the transformer is shown in **Fig. 16**. A 12 to 40mm toroid core is wound with 10 to 30 turns of #22 through #30 enamelled wire, leaving a gap of at least 30° between wire ends. A rubber grommet is inserted in the hole to receive the through transmission line.

Small diameter copper or brass tubing can be used, provided that it is a snug fit to the grommet.

In my second article on RF power measurement, I will discuss a commercial in-line RF wattmeter, and a calorimetry method used for high power RF measurements. I also intend to cover the problems of low-power measurement, and several error and uncertainty sources found in RF power measurements. ■

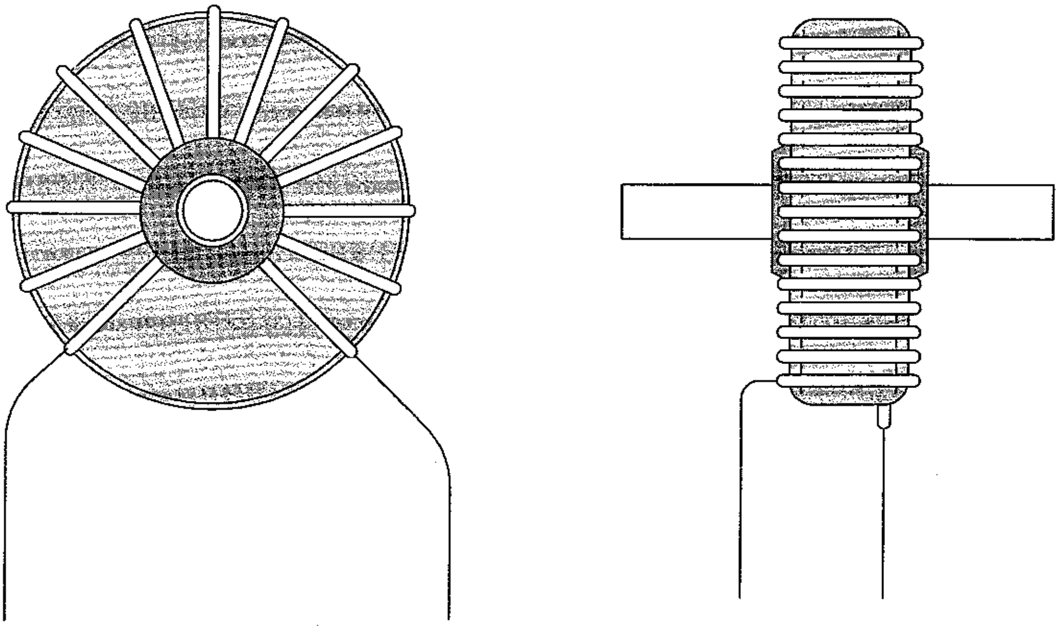


Fig. 16. Detail of transformer assembly for T_1 of Fig. 15.