SMART LOAD© PST

Smart Load® Power Sensing Termination

Data Sheet & Application Note

General Description:

The Smart Load® Power Sensing Termination (PST) is a power sensing high quality 50 Ohm termination producing a differential output voltage that is a direct function of the RMS RF input power. It is a passive device constructed entirely of thick-film materials on an aluminum oxide substrate. It is internally temperature compensated so as to produce accurate results over the –55C to +125C operating temperature range. Being entirely passive, it minimizes distortion which might result in the creation of intermodulation products to the system.

The Smart Load® PST detects RF power by measuring the actual heating value of the RF energy. Therefore, the output voltage responds linearly to the RMS value of the applied power over the 25 dB dynamic range over the device. This is the most accurate way of measuring multiple signals on different frequencies or complex modulated waveforms with continually changing crest factors. (Crest Factor is defined to be the ratio of the peak value to the RMS value.) Diode detectors inaccurately measure multiple RF signals or signals with high crest factors because they respond to the peak value. When the crest factor is continuously variable, there is no easy way to calibrate a diode detector for accurate power measurement.

The Smart Load® PST footprint is small, measuring only 0.150 inches square, and is designed to be attached to your circuit board using conventional surface mounting techniques. It requires a single + 5 Volt supply at about 12.5 mA. The broad frequency range makes it adaptable to a wide variety of applications such as amplifiers, transmitters, built-in test equipment (BITE), radar systems, course power meters, and VSWR sensors. It is also “Space Qualified” because it is immune to radiation and electro-static discharge.

Theory of Operation:

The operation of the Smart Load® PST is very simple in concept. It consists of four thermistors arranged in a bridge circuit such that that two of the thermistors receive the RF energy and the other two thermistors act as temperature compensation. The Smart Load® PST is offered in two families, a DC coupled version and an internally AC coupled version. The AC coupled offerings comprise of the PST-01, PST-02 and PST-04 which reduce component count through the use of integrated capacitors. Also offered is a DC coupled version of the Smart Load, the PST-06, which does not include integrated capacitors. This allows the RF designer more flexibility in adapting the device to his circuit though broadened frequency response with the use of larger value external capacitors.

Referring to the schematic (Figure 1), thermistors R2 and R4 are the RF sense thermistors while R3 and R5 are the temperature compensation thermistors. R1 is provided as a current limiting resistor so that the circuit can be directly attached to a standard + 5 Volt supply. R6 and R7 are the DC output isolation resistors which provide the differential DC measurement of the applied RF signal while isolating the RF energy from the external measurement circuit. The resistance value of R6 and R7 are 80K Ohm +/- 20%.

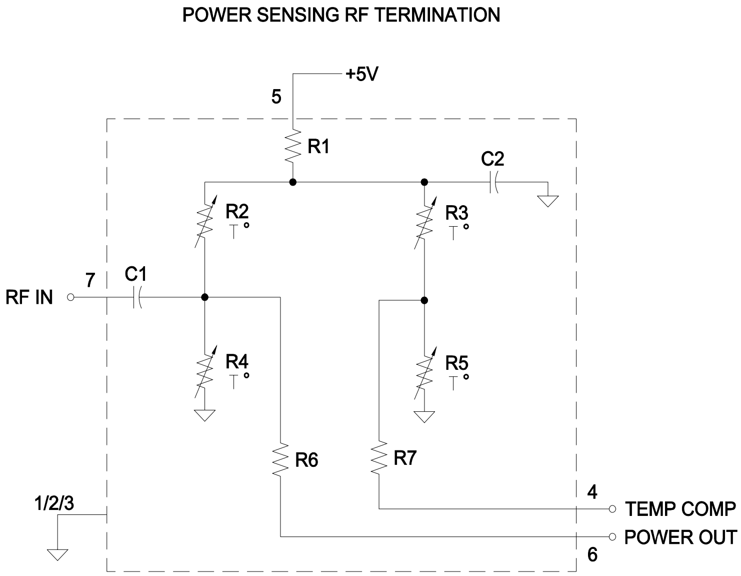


FIGURE 1. Smart Load® PST Schematic

Component Designator	Description
R1	*Fixed Resistor*
R2	Thermistor, PTC
R3	Thermistor, PTC
R4	Thermistor, NTC
R5	Thermistor, NTC
R6	Fixed Resistor
R7	Fixed Resistor
C1**	Capacitor
C2**	Capacitor

Table 1. Smart Load® PST Components. ** The PST-06 Does not contain internal capacitors, external capacitors are required for optimum performance.

The combination of R3 and R5 are identical in thermal and electrical characteristics to R2 and R4, however, they do not receive any RF energy. They form the second section of the bridge circuit so that the DC voltage at the intersection of R3 and R5 is largely identical to the DC voltage at the intersection of R2 and R4 over the –55C to +125C temperature range when no RF signal is present. This assures that the differential output voltage will be constant and close to zero over the operating temperature range when no RF signal is present.

In order to evaluate the operation of the Smart Load® PST, it must first be biased with + 5 Volts DC. It is important that the supply be well regulated. Variation in the +5 Volt supply will contribute to measurement error in the differential output voltage. The current from the supply travels through current limiting resistor R1 to the junction of R2 and R3 where it is equally divided between both sides of the bridge. The current flowing through the four sense thermistors cause them to self heat slightly, but because the bias power is relatively small (on the order of about 4 mW), the thermistors change very little from their nominal values.

When RF energy is applied to the input of the Smart Load® PST (pin 7), it travels to the junction of R2 and R4 through capacitor C1. The parallel combination of these thermistors is very close to 50 Ohms resistive providing a low VSWR match to your circuit over the frequency range of interest. The RF energy is absorbed by these two thermistors causing them to heat up. One of the thermistors is a positive temperature coefficient of resistivity (PTC) while the other has a negative temperature coefficient of resistivity (NTC). As the two thermistors heat up due to the RF energy, one will increase in resistance while the other will decrease. The thermal and electrical characteristics of these two thermistors are matched so that the parallel combination will remain very close to 50 Ohms resistive over the entire input RF power and temperature range of the device. This assures that the Smart Load® PST will continue to provide a low VSWR match to your circuit under all conditions.

As the two sense thermistors change in value due to applied RF power, the DC voltage at the intersection will also change. Measurement of this voltage is made through isolation resistor R6. However, at constant ambient temperatures, the DC voltage at the other side of the bridge (the intersection of R3 and R5) does not change. Therefore, the differential voltage between the two elements of the bridge provide an accurate and linear measurement of true RF power which is based on the RMS (heating) value of the energy.

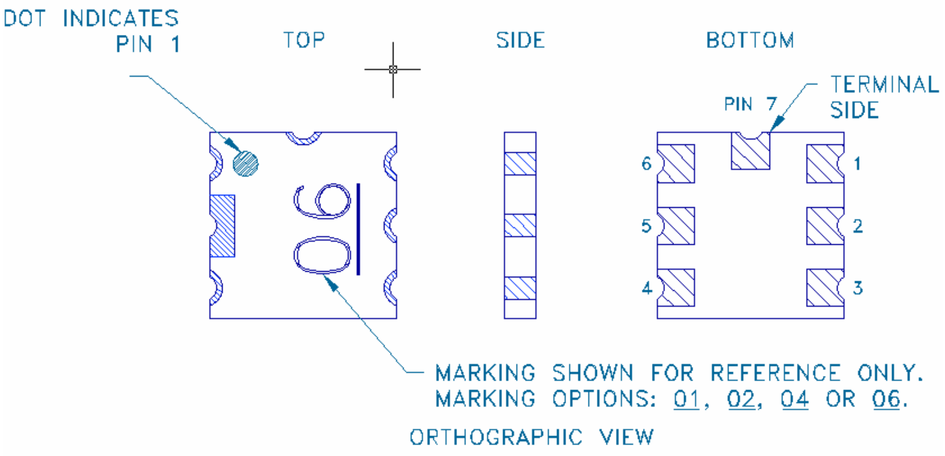
In the event the ambient temperature does change, the four thermistors in the bridge circuit will all change by the same amount. Since the voltage at both sides of the bridge circuit change by the same amount, the differential output voltage will remain constant over temperature for any constant RF input power.

Mounting Instructions:

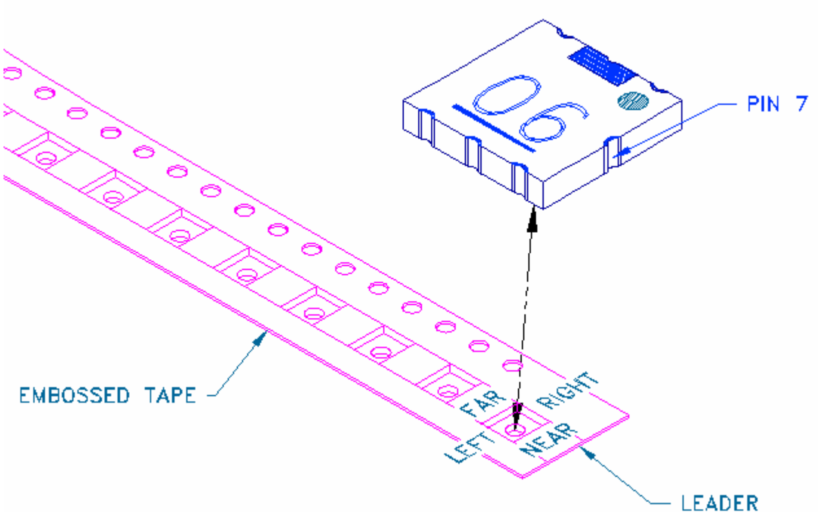
The Smart Load® PST is a surface mount device with an alumina substrate measuring 0.150 inches square and containing seven mounting pads each of which is 0.030 inches square. The mounting pads are constructed of a thick film material such as platinum gold or platinum silver which is over-plated with a nickel barrier and pre-tinned with solder to assure a reliable electrical contact to the circuit board.

The parts should be attached to the circuit board using industry-standard SMT techniques. It is important that both the SMT device and the circuit board be cleaned with isopropyl alcohol prior to soldering to assure they are free of any surface contamination such as finger oils, organic compounds, or surface oxides. Surface oxides can easily be removed by using a solvent-resistant eraser. Gently burnish the contact area with the eraser until the surface is shiny. Frequently clean the eraser on a piece of white paper to remove the oxide buildup. After burnishing, the device should be cleaned with isopropyl alcohol to remove any hydrocarbon contamination from the mounting pads. When soldering the part in place, it is permissible to subject the device to a peak temperature of 300° C for 10 seconds or less to assure the solder melts completely and evenly.

Package:



Tape and Reel Notes:



Note: Tape and Reel options and dimensions are available upon request.

Commonly Used Attachment Materials:

Material	**Composition**	**Thermal Conductivity (Watts/cm/°C)**	**Melting Temperature (°C)**
Gold-Tin Solder	80% Gold / 20% Tin	0.58	280
Lead-Free Solder	99.3% Tin – 0.7% Copper	Note (1)	227
Lead-Free Solder	96.5% Tin / 3.5% Silver	0.33	221
Lead-Free Solder	96.5% Tin / 3% Silver / 0.5% Copper	Note (1)	217 - 220
Sn63 Solder	63% Tin / 37% Lead	0.49	183
Conductive Epoxy	Silver Filled	0.01 to 0.02	N/A

Note: (1) Data not available at this writing.

Table 2: Typical Solder Compositions.

Circuit Board Design

As with all RF devices, proper grounding is extremely important to avoid variations or resonances in the response curve. Although pins 1, 2, & 3 are internally connected together and specified as grounds on the Smart Load drawing, it is necessary to ground all three to ensure a good low impedance path to ground. Functionally, the part will operate with any one of the three pads connected to ground, but will not provide the optimum response over frequency unless all three are grounded.

The + 5 Volt bias is applied to pin 5. It can be either positive or negative in polarity and should generally be within 5% to 10% of the nominal voltage. As stated previously, the + 5 Volt supply must be well regulated and as noise-free as possible. Variations in the supply voltage will show up as errors in the output voltage. A change in the polarity of the bias supply will also change the polarity of the output voltage. This can be corrected by reversing the connections to pins 4 and 6. It is always advisable to connect a 0.1 uF chip bypass capacitor between pin 5 and ground. This connection should be as short and direct as possible to assure stable and noise-free operation of the Smart Load.

The RF power to be measured is applied to pin 7 of the Smart Load® PST. The PST-01, PST-02, and PST-04 all contain an internal input coupling capacitor to isolate the DC component of the measurement circuit from the external circuit. These devices can be connected directly to your circuit as long as any external DC voltage appearing at pin 7 is less than 25 volts.

The PST-06, however, is a DC coupled device which was specially designed to extend the RF response to lower frequencies. Therefore an external input coupling capacitor is required in the path between the source of RF power and pin 7 of the Smart Load® PST. The value of the capacitor is dependent on the lowest frequency of interest, but good results can be generally obtained with chip capacitors in the range of 100 pF to 0.1 uF.

The RF line coupling power to the Smart Load® PST should be constructed using industry standard microstrip techniques to maintain a low VSWR right up to the input of the device. The width of this line will vary depending on the dielectric constant and thickness of the circuit board material. The optimum width of this line can be determined from widely published formulas and tables.

The Smart Load® PST is generally considered to be a low power device and it is important to avoid over-stressing the sensitive internal measurement circuit by applying too much RF power. Generally, for the PST-02, PST-04, and PST-06, the maximum continuous RF power should not exceed 0.250 watts. For the PST-01, the recommended maximum continuous RF power is 0.50 watts. In cases where the maximum RF power exceeds these guidelines, a passive attenuator can be placed at the input of the device to reduce the RF power to recommended levels.

A frequently asked question is whether it is better to use the PST-01 or PST-04 with the appropriate attenuator. The PST-01 is constructed with larger internal sense resistors to enable it to absorb more power. However, this also has the effect of slowing down the response time from 12 milliseconds to 20 milliseconds. We recommend using the PST-01 for all applications that will allow a response time of 20 milliseconds.

The output voltage connections (pins 4 & 6) from the Smart Load are relatively high impedance, on the order of about 100K Ohms. Therefore, they are susceptible to noise pickup if the connecting traces on the circuit board are too long or run too close to digital lines. It is best to keep these lines as short as possible and connect them directly to a differential operational amplifier to increase the signal level. Once the output signal is amplified to a level of several volts, the susceptibility for noise pickup is vastly reduced.

Typical Operation:

After the Smart Load® PST is soldered into the board, be sure that pins 1, 2, & 3 are grounded, the RF source is attached to pin 7 and the 5 volt bias is attached to pin 5. Turn on the 5 volt bias supply. With no RF signal applied, the current flowing into pin 5 should measure between 11 mA and 14 mA. The voltage from pin 4 to ground and pin 6 to ground should be nominally about 0.625 volts when measured with a voltmeter having an input resistance of 10M Ohms. The differential voltage measured from pin 4 to pin 6 should be 10 mV or less.

Some method should be devised for nulling out the differential offset voltage to zero. This will depend on the type of op-amp that is being used. Some op-amps provide for an external control to null the offset voltage. For op-amps that do not have this built-in feature, the circuit shown for the evaluation board can be used to null out the offset voltage. Conversely, if the output voltage is being sampled by an A to D converter, the output offset voltage can be mathematically subtracted.

If all DC voltages are normal and the output offset voltage has been nulled out, apply exactly 0.250 watts to the device at a frequency between 600 MHz and 3.0 GHz. Measure the output voltage between pins 4 and 6. The sensitivity can be determined by taking the algebraic difference between the quiescent (non-RF) voltage and the output voltage with the RF applied and multiplying this number by 4. The sensitivity is expressed as mV per Watt. Typical sensitivity values range between 300 mV/Watt and 800 mV/Watt depending on the model and device screening of the Smart Load® PST.

The output voltage vs. RF input power can be graphed by varying the RF power from zero to the maximum allowed and plotting the resultant output voltage. The graph will show that the response curve is a linear function of the RF input power. Repeating the test with multiple signals or modulated carriers will demonstrate that the device responds to the RMS (heating) value of the input energy, not the peak value as with diode detectors. Since the device is completely passive, it can be demonstrated that it produces only low level passive intermodulation products when multiple signals are present.

Typical Application:

In a typical application where the RF power to be measured is higher than several watts, the Smart Load® PST is generally connected to the sample ports of a directional coupler. For lower power applications, for example a local oscillator, it is permissible to connect the Smart Load directly to the RF source through a power splitter. The level of the RF input signal applied to pin 7 of the Smart Load® PST can be optimized by using small chip attenuators such as the EMC TS05 family. The value of these attenuators should be selected to limit the RF input power to 0.250 watts for the PST-02, PST-04, and PST-06 and 0.50 watts for the PST-01.

In most applications, the output pins (pins 4 & 6) should be connected directly to an operational or instrumentation amplifier such as the AD622 or any other operational amplifier with a high input impedance. Two 1K resistors can be added in series with the two output voltage lines as close to the op-amp as possible to prevent unwanted resonances. A capacitor connected between the inverting and non-inverting input of the op-amp will serve as a low pass filter to eliminate differential noise on the input lines. The value of this capacitor depends on the required response time of the detection circuit, but 0.1 uF is a good choice for many applications. Refer to *Application Circuits* section for further information.

For most applications, the gain of the op-amp should be set to between 10 and 40. This will give an output voltage of several volts with 0.250 watts of RF input power applied to the Smart Load. Avoid excessively high gains above 50 as these will increase the possibility of random noise pick-up by the op-amp from the surrounding traces and may even lead to circuit instability.

Accuracy:

The accuracy of the Smart Load® PST is limited by the sum of the of the fixed internal error sources of the device. The primary error sources are the initial accuracy of the differential offset voltage and the accuracy of the temperature compensation. The initial accuracy of the differential offset voltage or simply "Offset Voltage" is specified at +/- 10 mV. This error is due to the tolerance of the laser trimming process of the four thermistors in the bridge circuit. Since this error is fixed it can be easily compensated for by using a circuit with a calibration or nulling capability. This type of nulling circuit is shown in Figure 9.

The second source of error is due to nonlinearity in the response of the device to input RF Power over temperature. As an example, the chart below shows the typical differential output voltage of the PST over temperature for a constant applied RMS input power of 20dBm at 1 GHz. This drift vs. temperature is not compensated by the bridge configuration of the Smart Load® PST circuit and therefore limits measurement accuracy by an amount of +/- 10 mV. This is primarily a fixed level of error and not directly proportional to the power if the applied RF energy. The typical measurement error due to temperature variation is shown below in figure 2. The shape is characteristic of the device and can be compensated for using a lookup table approach in a digital compensation circuit.

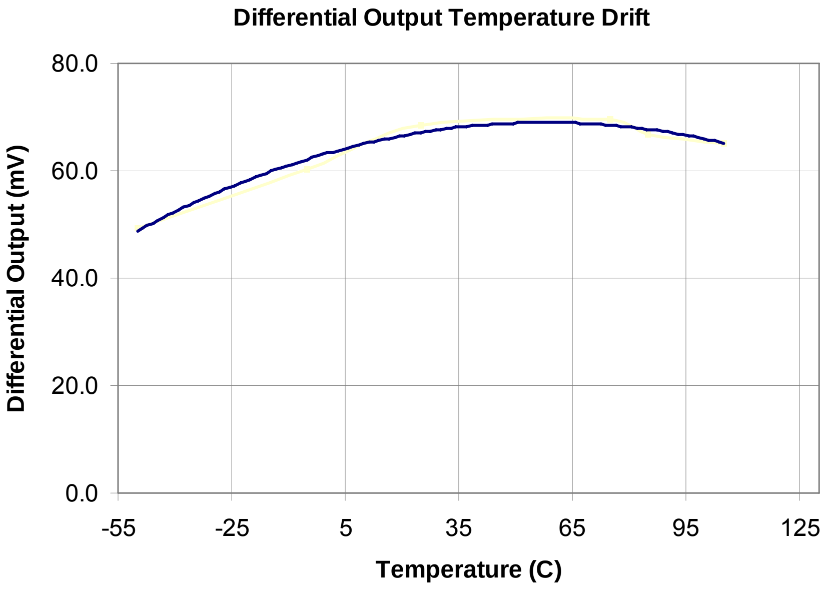


Figure 2: Error contribution due to temperature for a fixed RF input power of 20 dB.

The Table below shows the effect of the combined measurement errors versus input power from 0.0 dBm to +24.0 dBm. The standard deviation reflects the combined measurement error due the initial accuracy of the Offset Voltage and the nonlinear measurement error contribution due to temperature variation.

Temp Range	RF Power (dBm)	Mean (mV)	SD (mV)
-55 to +105C	0.000	0.594	5.727
-55 to +105C	10.000	5.689	6.022
-55 to +105C	20.000	60.044	8.923
-55 to +75C	24.000	159.167	12.517

Table 3: Mean and Standard Deviation Values of the Differential Output Signal with Respect to Applied RF Power.

Because the error sources are relatively fixed in magnitude and not directly proportional to the applied input RF power, the accuracy of the device will degrade at lower level input powers. This effect is shown in the figure 3 below. Therefore for applications not requiring use of the full dynamic range of the device it is recommended that the RF power input to the device be biased towards the high end of the allowable input power range.

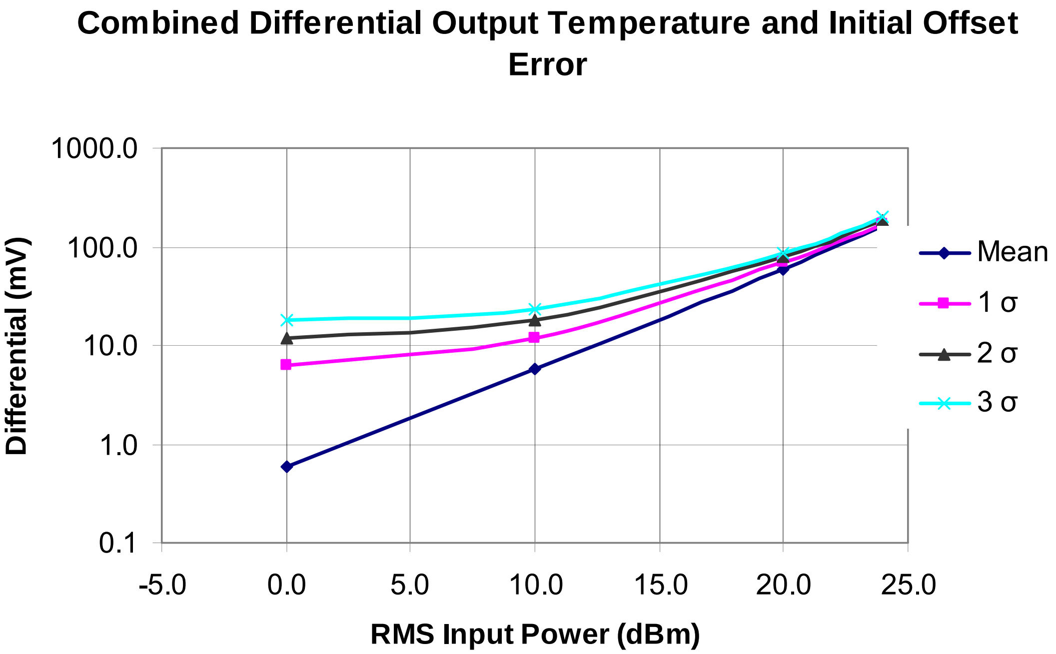


Figure 3: Mean Value of the Differential Output vs. RF Input Power and the Standard Deviation Associated with the Device's Measurement Accuracy.

Application Examples:

VSWR FAULT DETECTION:

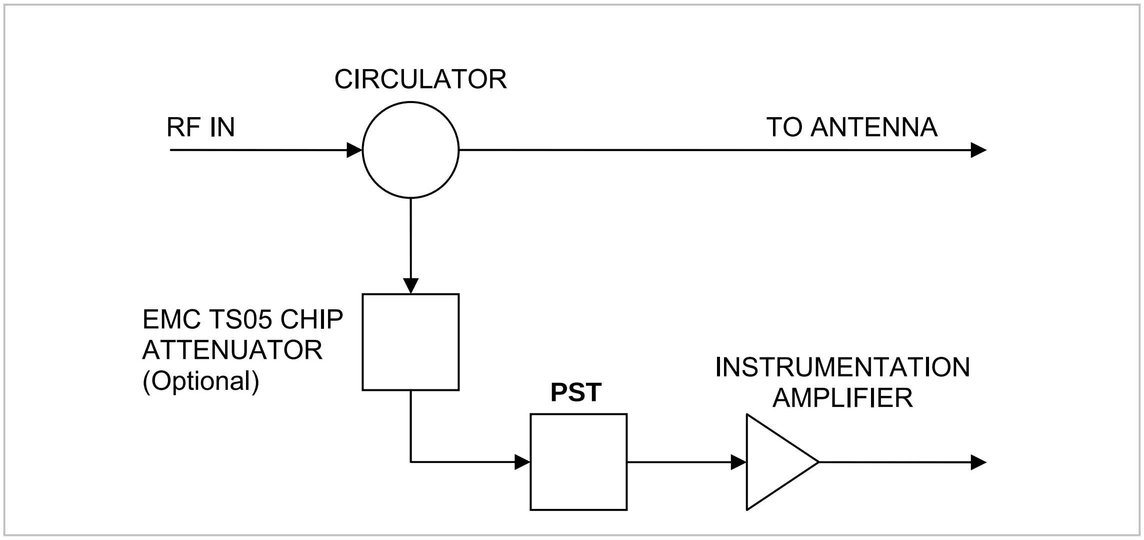


FIGURE 4. PST / CIRCULATOR VSWR FAULT DETECTOR.

VSWR DETECTION:

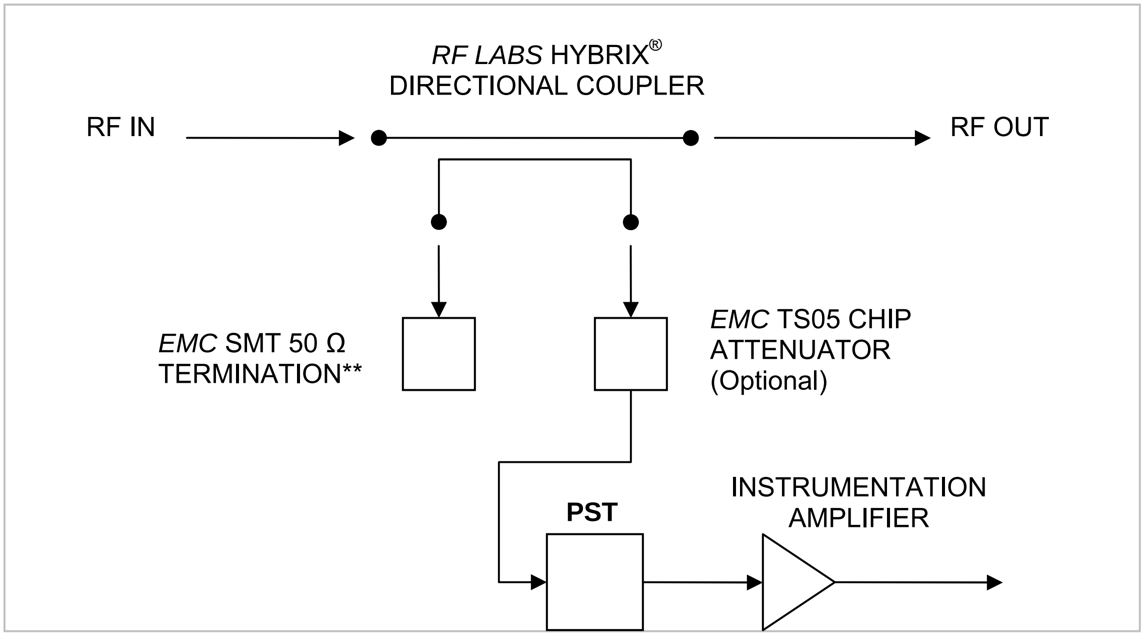


FIGURE 5. PST / COUPLER VSWR DETECTOR. **RF LABS *DS SERIES Hybrix* Directional coupler with an internal termination reduces part count.

POWER MONITRING:

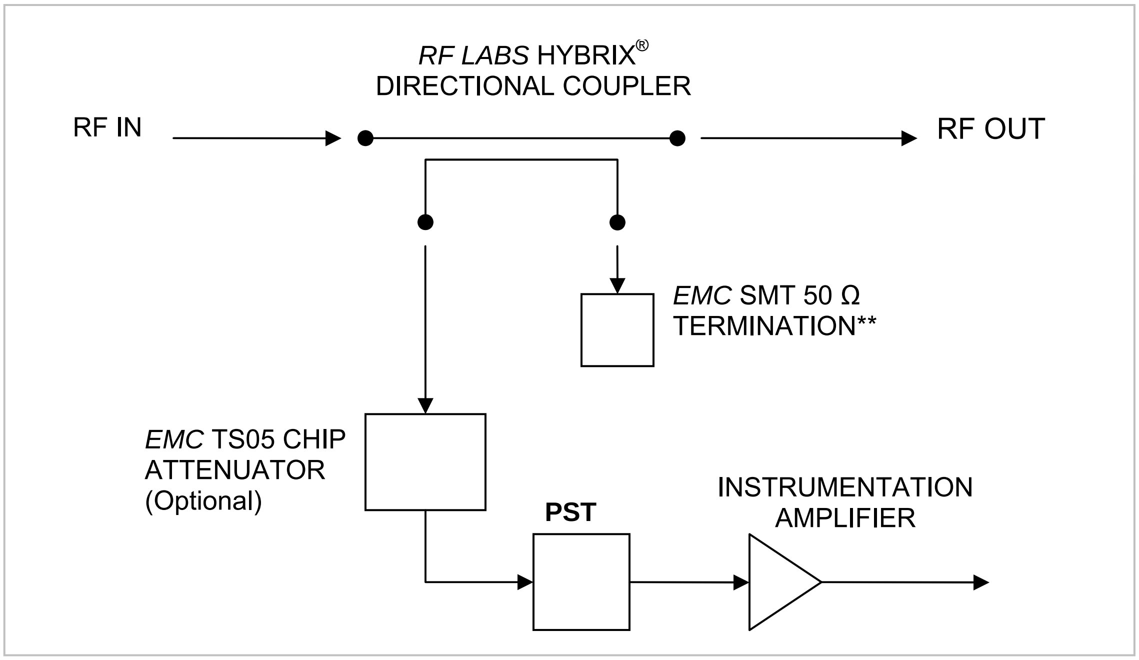


FIGURE 6. PST RMS RF POWER DETECTOR. **RF LABS *DS SERIES Hybrix* Directional coupler with an internal termination reduces part count.

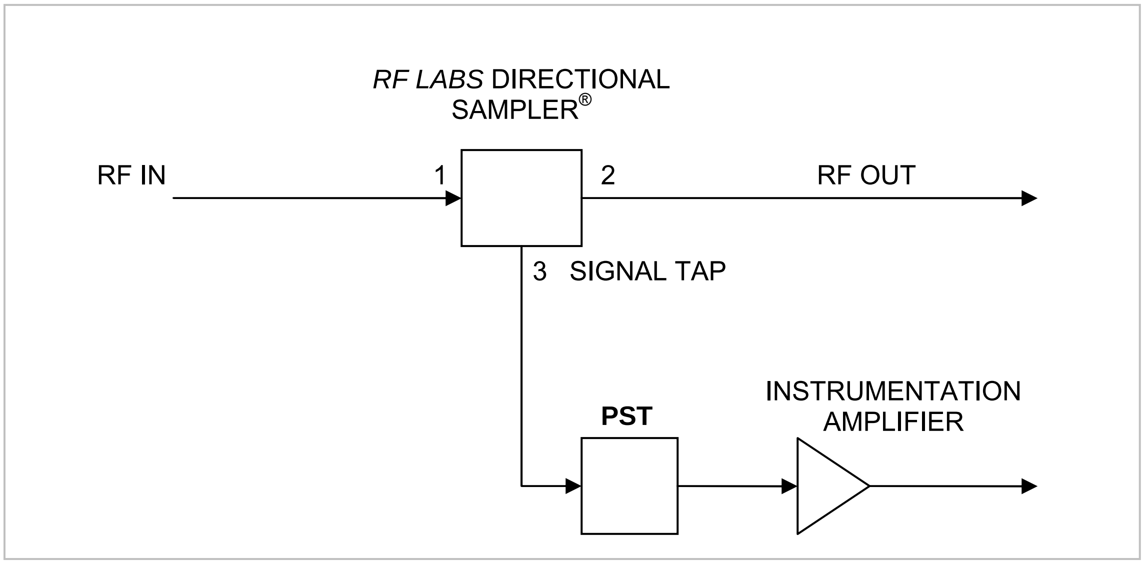


FIGURE 7. PST RMS RF Power Detector. This implementation uses the *RF LABS* DIRECTIONAL SAMPLER®, a three port device for power monitoring. It provides a low insertion loss through line from port 1 to 2 and a broadband signal tap at port 3 at -20 to -40 dB of the input RF signal.

AUTOMATIC GAIN CONTROL:

.

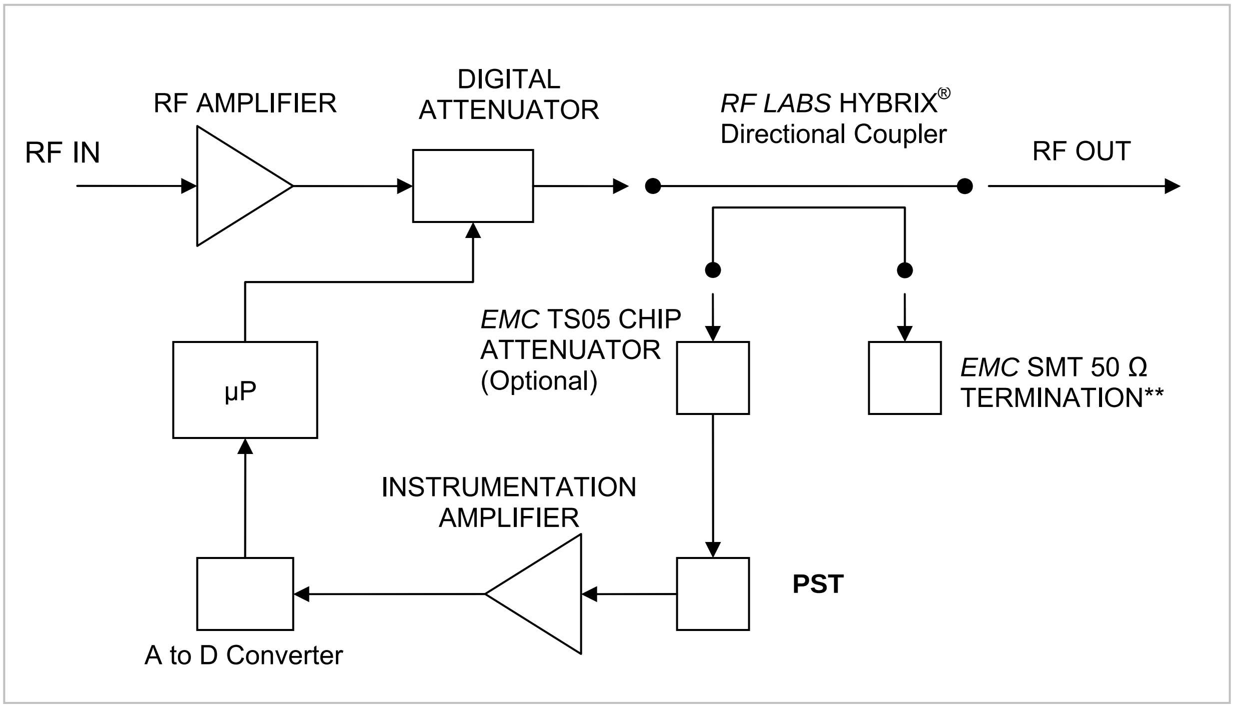


FIGURE 8. PST Automatic Gain Control Application. ** RF LABS *DS SERIES Hybrix* directional coupler with an internal termination reduces part count.

TYPICAL PERFORMANCE CHARACTERISTICS

PST04 ELECTRICAL:

All measurements performed at Vs = +5 VDC, +25C and RF input = 1 GHz unless otherwise noted.

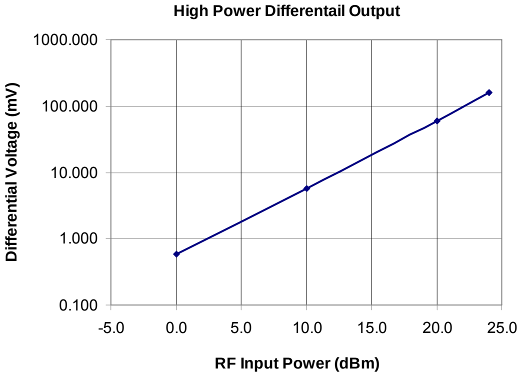


Figure 1.1: Typical differential output vs. RMS input power from 0.0 to +24.0dBm.

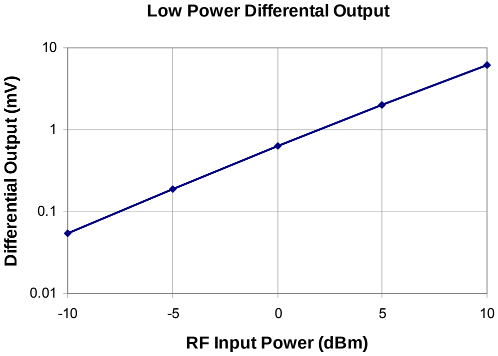


Figure 1.2: Typical differential output vs. RMS input power from -10.0 to 10.0dBm.

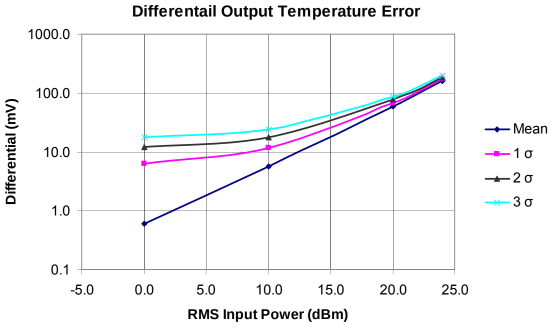


Figure 1.3: Typical differential output vs. input power shown with measurement error due to temperature drift from -55 to +125 C. Temperature error shown for one, two, and three standard deviations.

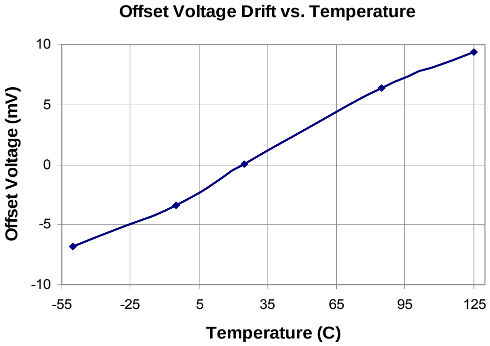


Figure 1.4: Typical offset voltage drift vs. temperature from -50 t0 +125 C. No RF input power applied.

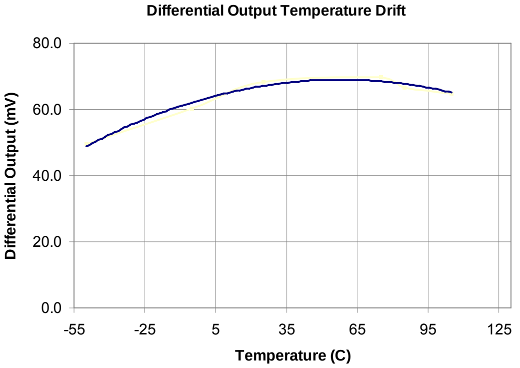


Figure 1.5: Typical differential temperature Drift shown for a constant RF input power of +20 dBm.

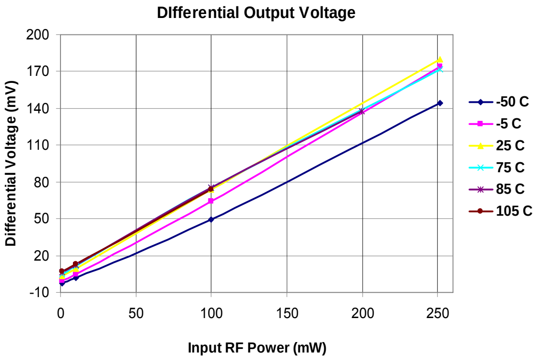


Figure 1.6: Typical sensitivity curves shown for a single sample at six discrete temperatures from -50 C to +105 C.

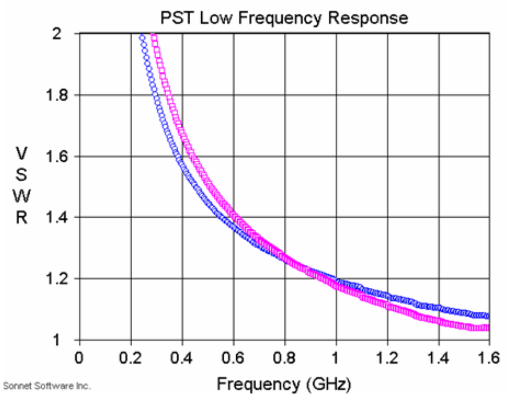


Figure 1.7: Typical frequency response, DC to 6.0 GHz. Two samples shown.

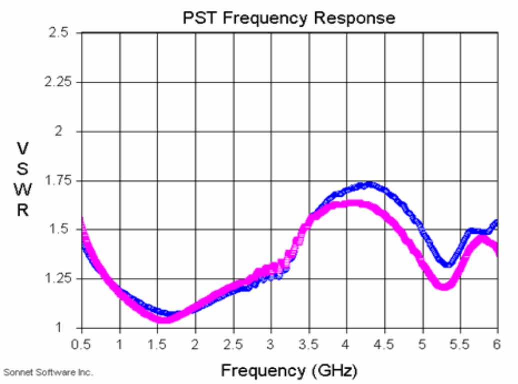


Figure 1.8: Typical frequency response, DC to 6.0 GHz. Two samples shown.

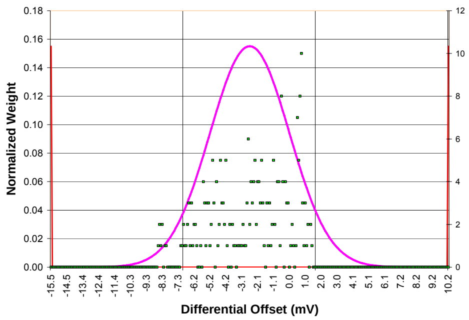


Figure 1.9: Differential offset voltage distribution with no RF input. Mean = -2.6 mV, Standard Deviation = 2.7 mV.

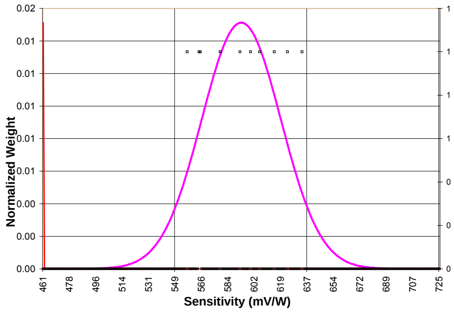


Figure 1.10: Sensitivity distribution. Mean = 559 mV/W, Standard Deviation = 27 mV/W.

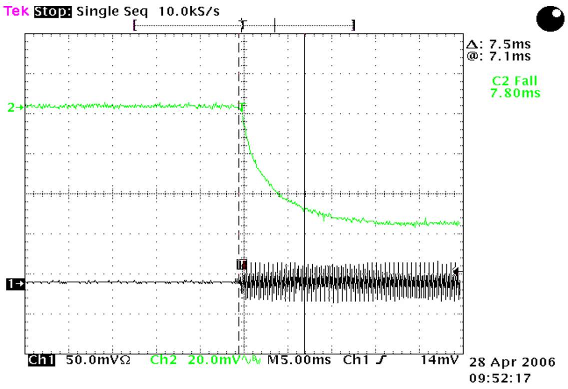


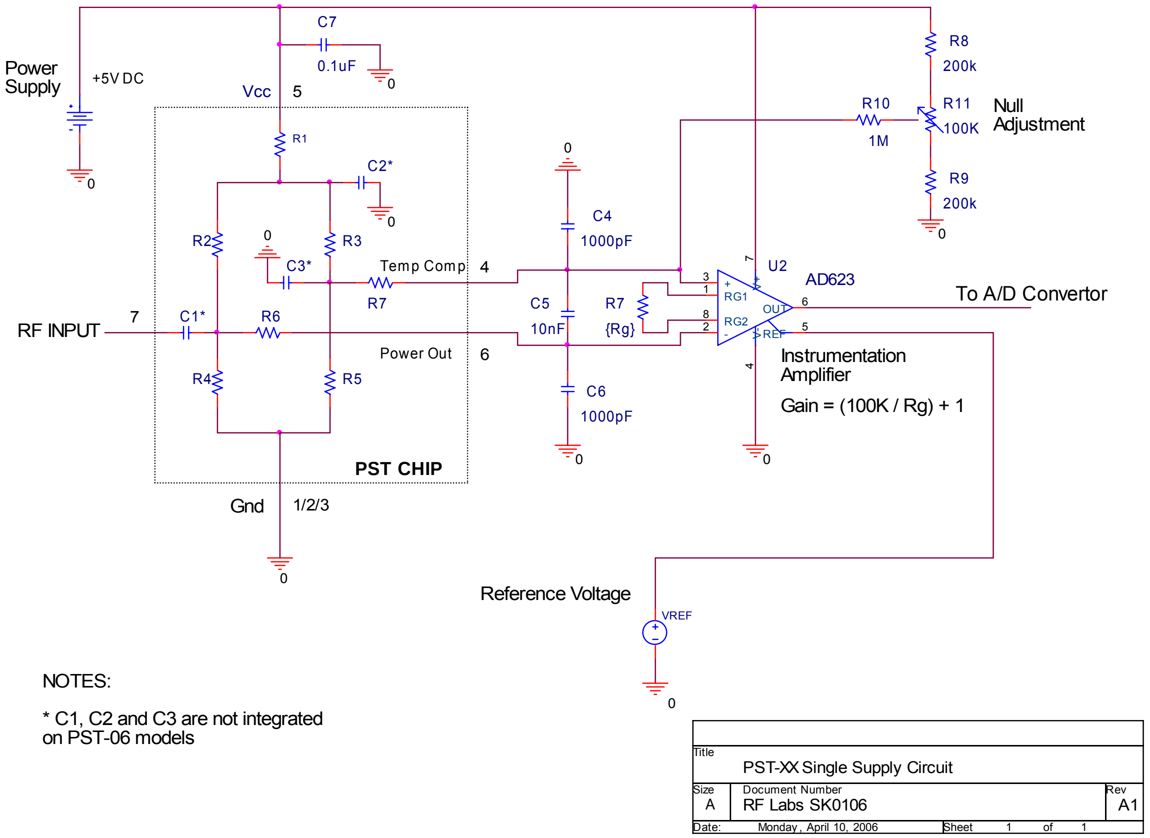
Figure 1.11: Differential output response time to an applied step input. The 10/90 response is >12 ms over full temperature range.

Application Circuits:

Smart Load® PST Single Supply

Description: The reference circuit shown in figure 6 provides an accurate differential measurement for the Smart Load® PST (Power Sensing Termination) series devices used in single supply applications. An overview of the functionality is presented in the following paragraphs.

Measurement Dynamic Range: To maximize the full scale dynamic range of the Smart Load® PST measurement device, whether in an analog or digital system, proper selection of amplifier gain and dc offset are required.



NOTES:

* C1, C2 and C3 are not integrated on PST-06 models

Title
PST-XX Single Supply Circuit
Size A
Document Number RF Labs SK0106
Rev A1
Date: Monday, April 10, 2006
Sheet 1 of 1

Figure 9: Smart Load® PST Single Supply Amplifier Reference Circuit.

The difference in voltage between the Smart Load® PST outputs (Power Out – Temp Comp.) is amplified by Instrumentation Amplifier (IA) AD623. The AD623 is an example of a low cost, single supply, rail to rail I/O instrumentation amplifier. Substitution of an equivalent IA is of course permissible.

The differential gain is set by resistor R_G according to the formula:

$R_G = 100KOhm/(Gain-1)$. Refer to the AD632 Data sheet for further information.

Resistor tolerances in the Smart Load® PST may cause the output voltage to fall below ground if the IA output is referenced to 0V at zero input RF power. Therefore a DC offset is required in single supply applications. The offset voltage of the IA is set by applying a reference voltage at pin 5 of the IA. It is recommended that a low impedance reference such as an Analog Devices REF192 or equivalent be used. If a low impedance reference is not available, pin 5 may be connected directly to a reference source such as a zener diode, DAC or resistor divider. However, because the high impedance associated with a resistor divider network will alter the gain slope of the amplifier it is recommended that resistors **<** 1 K ohm be used if a low impedance reference is unavailable.

Note: The Power and Temp Comp outputs have a series impedance of 100K Ohms +/- 20% internal to the Smart Load® PST represented by R6 and R7 in the EMC catalog.

Calibration: Resistors R8 through R11 form a trim network to null the output of the bridge circuit at zero RF input power. This is an optional circuit and may not be required depending on the calibration requirements of the application. A similar calibration can be accomplished digitally in an ADC circuit or by direct adjustment of the IA reference voltage.

Filtering: All instrumentation amplifiers can rectify out of band RF energy producing a DC measurement error. Capacitors C4, C5 and C6 add common and differential mode filtering. These filters are optional though serve to reduce the DC output error caused by parasitic RF energy paths.