# COMPARISON OF SINGLE DIODE VS. DUAL DIODE DETECTORS FOR MICROWAVE POWER DETECTION

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## ABSTRACT

In this article we review basic diode detection as it pertains to microwave power measurements. The detected voltage as a function of input voltage is derived for the single diode detector, and several of the limitations and drawbacks are explored. The concept of a balanced detector is then explored and its advantages examined. A family of curves is given showing the worst case errors due to harmonics for both the single diode and the balanced detector.

## INTRODUCTION

The use of zero-based Schottky diodes for measuring and detecting RF/Microwave power has grown rapidly over the last decade. The Schottky diode is much more reliable than the point contact types, and exhibits excellent uniformity in its transfer characteristic. This allows the design of standardized instrumentation to compensate for the non-square law portion of its transfer characteristic, giving a dynamic measurement range on the order of 60 dB.

Useful expansion of the dynamic range has, however, highlighted the problems and objections associated with the single diode detector.

The prime problems are:

1. Sensitivity to dc (primarily from thermal EMF's)
2. The inaccuracies of measurement due to harmonics when operating above the diode's square law region.

This paper will discuss an alternative to the single diode detector ---- a balanced, dual diode detector. Some of the advantages of the balanced detector versus the single diode detector to be discussed are: a reduced sensitivity to dc on the center conductor, a reduced sensitivity to second harmonics, and an improved signal-to-noise ratio.

## BASIC DETECTOR THEORY

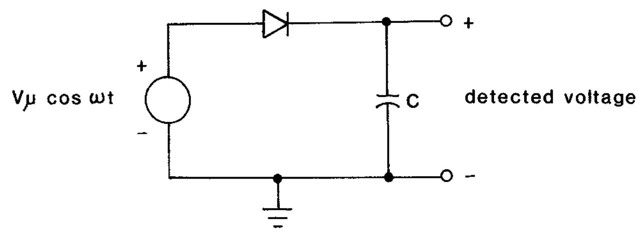


*Figure 1. Basic Detector Circuit*

Modeling the basic detector circuit as in Figure 1, the basic diode equation can be written as:

$$i_d = I_S \left\{ \exp\left(\frac{q v_d}{K T}\right) - 1 \right\} \tag{1}$$

Where $I_S$ is the leakage current, q is the charge of an electron, K is Boltzman's constant, T is the temperature in degrees Kelvin, and $v_d$ is the voltage across the diode.

If we now assume that the capacitor, C, is a good RF bypass and, therefore, there is no ac component on the capacitor, we can solve for the average current through the diode by integrating over one RF cycle:

$$\langle i_d \rangle = I_S \left\{ \frac{1}{\tau} \int_0^\tau [\exp\left(\frac{q v_d}{KT}\right) - 1]\, dt \right\} \tag{2}$$

Where $v_d = V_{dc} + V\mu \cos \omega t$ and $\omega\tau = 2\pi$ and $V_{dc}$ = the voltage on the capacitor.

This can be reduced to:

$$\langle i_d \rangle = I_S \left\{ \exp\left[\frac{q v_{dc}}{KT}\right] \mathcal{J}_o \left(\frac{qV\mu}{KT}\right) - 1 \right\} \tag{3}$$

Where $\mathcal{J}_o$ is the modified Bessel function of the first kind. Note that if the average current is not zero, it will vary directly with the saturation current, $I_S$, which is a strong function of temperature in its own right. Therefore, it is much more common to see the detector's output fed to a very high impedance amplifier so that $\langle i_d \rangle = 0$ and Equation (3) can be simplified and solved for the detected voltage, $V_{dc}$ as:

$$V_{dc} = \frac{KT}{q} \ln\left\{ \mathcal{J}_o\left(\frac{qV\mu}{KT}\right) \right\} \tag{4}$$

If we are interested in low level signals, we can expand $\mathcal{J}_o(z)$ to:

$$\mathcal{J}_o(z) = 1 + \frac{1}{4} z^2 + \frac{1}{64} z^4 + \dots$$

Taking only the first two terms and letting $z = \frac{qV\mu}{KT}$ we see that:

$$V_{dc} \cong \frac{KT}{q} \ln\left(1 + \frac{q^2 V\mu^2}{4K^2T^2}\right) \cong \frac{qV\mu^2}{4KT} \tag{5}$$

and the detector is operating in its square law region, effectively measuring power by measuring a quantity proportional to $V^2\mu$.

For very large signals, Equation (4) simplifies again. This time to:

$$V_{dc} = V\mu - \frac{KT}{2q} \ln\left(\frac{2\pi q V\mu}{KT}\right) \tag{6}$$

Here $V_{dc}$ varies almost directly as $V\mu$, the peak RF voltage, and the detector is said to be in its peak detecting region.

Figure 2 shows the theoretical performance of the single diode detector with a sinusoidal input. Notice that the voltage out is linear with respect to power at low levels, and approaches being linear with respect to the peak of the RF voltage at high levels.

The detector of Figure 1 suffers from two main faults. One is its sensitivity to dc voltages on the center conductor, and the other is its sensitivity to harmonics when operating above its square law region. Any dc voltage superimposed on the microwave signal (caused most often by thermal EMF's) will be passed through the detector by the leakage current term and thereby limit the low end of its useful range. For example, a 10 μV offset could cause a -50 dBm signal to look like either -47 dBm (if the offset added) or -∞ dBm (if the offset opposes the detected signal).

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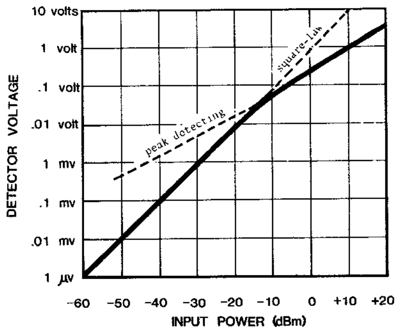


*Figure 2. Theoretical Detector Response*

The sensitivity to harmonics can easily be visualized if one thinks of the detector as a positive peak detector. The detector has no idea of the shape of the RF signal coming into it when it is peak detecting. It can be a square, triangle, or sine wave and still give the same detected voltage as long as the peak voltage is the same in each case. Therefore, if the fundamental and the harmonic voltages add on the positive peaks of the fundamental, the detector detects their sum rather than the square root of the sum of their squares, as would a true power detector.

## THE BALANCED DETECTOR

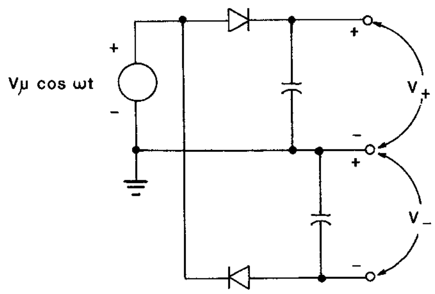


*Figure 3. Balanced Detector Circuit*

One way to combat both of these problems is to balance the detector as in Figure 3. If one now measures the voltage differentially ($V_+ - V_-$), any dc voltage on the 50Ω load will appear only as a common mode voltage, and will not affect the differential voltage. Since there is no load on the capacitor, any dc signal superimposed on the Vµ cos ωt signal will be passed directly through to the capacitors via the leakage currents in the diodes. If we call this signal $V_\varepsilon$ then:

$$V_+ = \frac{KT}{q} \ln\left\{ \mathcal{I}_o\left(\frac{qV\mu}{KT}\right)\right\} + V_\varepsilon \quad (7)$$

and

$$V_- = -\frac{KT}{q} \ln\left\{ \mathcal{I}_o\left(\frac{qV\mu}{KT}\right)\right\} + V_\varepsilon \quad (8)$$

and the differential voltage will be:

$$V_+ - V_- = \frac{2KT}{q} \ln\left\{ \mathcal{I}_o\left(\frac{qV\mu}{KT}\right)\right\} \quad (9)$$

Which is independent of $V_\varepsilon$.

Notice also that since one diode detects positively and the other negatively, the detector tends to be a peak-to-peak detector rather than just a peak detector. This gives the balanced detector a decided advantage in reducing the sensitivity to second (and all even) harmonics. This is shown more graphically in Figure 4a, where a second harmonic level of -15 dBc is superimposed on a fundamental signal.

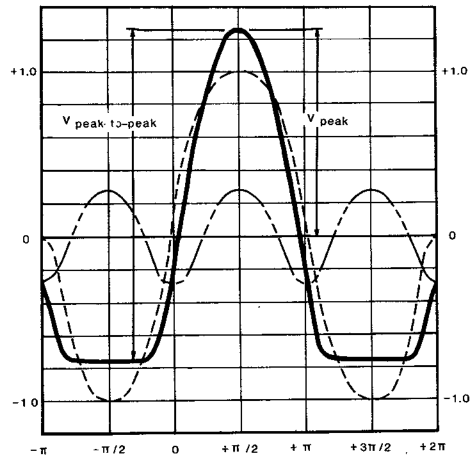


*Figure 4a. Peak-to-Peak Voltage for Harmonics "In Phase"*

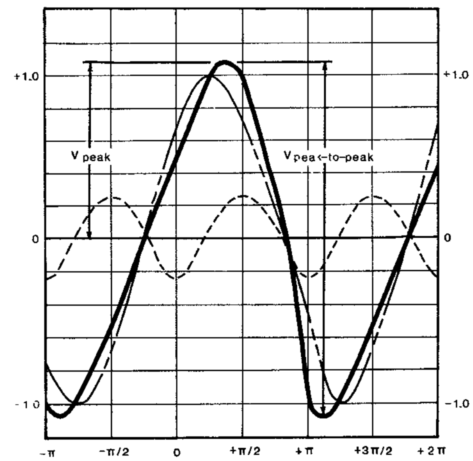


*Figure 4b. Peak-to-Peak Voltage for Worst Case Harmonic Phase*

Lapsing back to the single diode detector for a moment, one can use a little imagination and see how shifting the phase of the fundamental signal with respect to the harmonic signal would produce a peak voltage that would vary between the sum of the fundamental and harmonic peaks to the difference between the fundamental and harmonic peaks. If the single diode detector were peak detecting, the error could be positive, negative, or zero with respect to the actual power. The balanced detector, on the other hand, looks at the peak-to-peak voltage and is far less sensitive, as we shall see.

Plots of the theoretical worst case errors as a function of the input power (considering the relative phase between the fundamental and the second harmonic) are shown in Figures 5, 6, 7, and 8. These represent the performance for -20, -25, -30, and -40 dBc harmonics respectively, and compare the single diode detector to the dual diode (balanced) detector.

There are several points of interest concerning Figures 5, 6, 7, and 8. As one would expect, the errors for both the single diode and balanced detectors approach zero at low levels. Here, the diodes are well into their square law region and are producing a voltage proportional to the square of the input voltage, which is directly proportional to the total input power. As the input signal level increases, the diodes make the transition to peak detecting, and the error rises and begins to flatten out as full peak detection is approached.

It is interesting to note that, while the single diode detector's error is nearly symmetrical around zero, the balanced detector's error is not. The reason for this is the fact the worst case error condition for the single diode detector occurs when the relative phase of the fundamental and harmonic signals are as shown in Figure 4a (and $180^\circ$ from that for the negative error), while the worst case error for the balanced detector occurs when the relative phases are shifted by $45^\circ$ or $\pi/4$ as shown in Figure 4b. Under this condition, the harmonic signal tends to increase the positive peak and the negative peak equally so that both go in the direction of larger peak-to-peak volts. The result is that the error band for the balanced detector is not symmetrical and favors the positive errors. Stated differently, the detector will indicate that there is more power than there actually is. It is curious to note that between -25 dBm and 0 dBm input power there are areas where harmonics will give only a positive error. This region is where the detectors are making the transition from square law detection to peak detection.

One of the less obvious benefits of the balanced detector is a 3 dB improvement in the signal-to-noise ratio when compared to the single diode detector. At first glance, it may appear that the signal-to-noise ratio would remain constant since one is using what amounts to two individual detectors (one positive and the other negative) that individually have the same signal-to-noise ratio as the single diode detector. Fortunately, however, this is not the case.

The noise model of the balanced detector looks like two resistors in series -- each resistor representing the video impedance of one of the detector diodes. Since the resistors are in series, the noise voltages add incoherently (the noise sources are independent). Thus, the balanced detector noise voltage that is generated is $\sqrt{KTBR_V x2}$ which is greater than the noise voltage generated by the single diode detector, $\sqrt{KTBR_V}$, by $\sqrt{2}$. In the balanced detector, the detected signals add coherently and generate twice the detected voltage of the single diode detector. Thus, the signal-to-noise ratio of the balanced detector is improved over that of the single diode by a factor of $2/\sqrt{2} = \sqrt{2}$ or 3 dB.

## CONCLUSION

The single diode detector has been compared with the dual diode balanced detector. The balanced detector has demonstrated a much improved sensitivity to even harmonics and an ability to reject dc voltages on the detector's center conductor. This, coupled with the 3 dB improvement in the signal-to-noise ratio of the balanced detector, makes the balanced detector the detector of choice for critical microwave power measuring.

## REFERENCE


G. Yasumura, R. Genin, S. Wetenkamp
U.S. Patent No. 4,360,865 1982


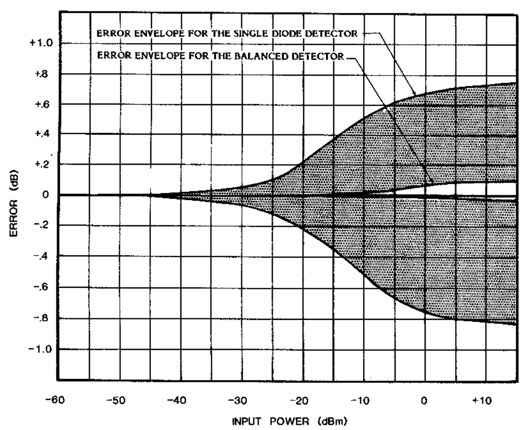


*Figure 5. Worst Case Detector Error for Harmonic Level: -20 dBc*

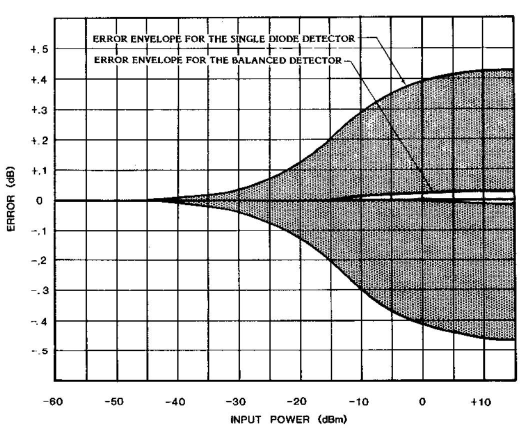


*Figure 6. Worst Case Detector Error for Harmonic Level: -25 dBc*

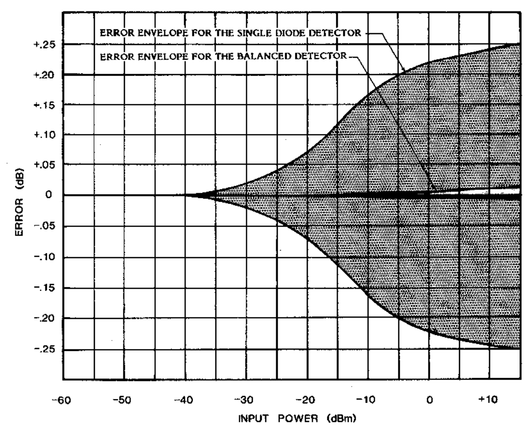


*Figure 7. Worst Case Detector Error for Harmonic Level: -30 dBc*

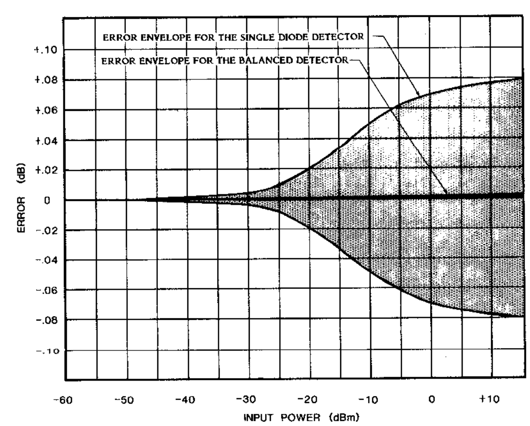


*Figure 8. Worst Case Detector Error for Harmonic Level: -40 dBc*