Benchmarking Comparison of Thermal and Diode Sensors for Pulsed Power Measurement

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***Abstract* – A pulsed power system has been constructed to explore conditions under which accurate pulsed power measurements can be made with both a thermal sensor and a diode sensor. For the thermal sensor, pulsed power is estimated from a simple calculation based on the average power of the pulsed RF signal. For the diode sensor, gating is used to enable direct measurement of the pulsed power. As expected, the results of measurements taken with varying pulse lengths and a constant period show that the dynamic range of the thermal sensor is approximately proportional to the pulse length. The results also indicate that, while a thermal sensor can provide accurate results for many situations, the diode sensor can be used to measure with higher precision than the thermal sensor for lower duty cycles. The paper demonstrates a benchmarking procedure that can be used to explore limitations and capabilities of power sensors as well as elements such as the input RF switch used for pulsed power measurements.**

I. INTRODUCTION

Pulsed RF signals are used in a wide variety of applications in modern communication systems. The applications vary from radar systems [1] to the mass production of silver (Ag) nano-sized powder for various industrial applications [2]. Pulsed RF also has become extensively used in characterization of active devices and it is more suitable for many applications than continuous-wave (CW) RF signals [3]. Using pulsed RF for load-pull provides various advantages. First, devices that are operated in pulsed condition in an application, such as radar, can be tested under the same conditions as in the final application. Second, the device temperature during measurement can be lower under pulsed conditions than for CW testing, reducing the chance of device failure during high-power device testing. Devices are often operated in pulsed mode because they can, in many cases, remain linear for higher RF power levels due to the reduction of thermally induced nonlinearities [1]. When both pulsed RF and pulsed DC measurements are combined they can provide insight into the influence of low frequency discrepancy effects (self heating or trapping effects) on the performance of transistors for modeling purposes [4]. Even before examining specific devices under test (DUTs), however, it is shown herein that the duty cycle of the pulsed signal can have a strong impact on the test system capability (e.g. dynamic range); therefore, an understanding of test system accuracy for varied duty cycles is critical to obtaining reliable pulsed power data. While many publications can be found on the construction of pulsed load-pull systems (e.g. [5]). In the present paper, an experiment in which diode and thermal RF power sensors are compared for pulsed measurements at varying RF power levels and duty cycles to establish a solid baseline for pulsed testing with each of these sensor types.

II. TERMS AND DEFINITIONS

The duty cycle is given in terms of the pulse width τ and the period T as

$$\text{Duty Cycle} = \frac{\tau}{T} \qquad (1)$$

Thus the duty cycle of the RF pulse can be increased by either increasing the pulse width or decreasing the time period of the RF signal. The Pulse Repetition Rate (f_p) is the frequency at which the pulses occur and is given by

$$f_p = \frac{1}{T} \qquad (2)$$

A thermal sensor was used first in this set-up. A thermal sensor calculates the pulsed power P_p in terms of average power P_a as follows [6]:

$$P_p = \frac{P_a}{\tau f_p} \qquad (3)$$

where f_p can be calculated by (2), τ is the pulse length and P_a is the average power. It is important to keep in mind that the above relationship holds good only if the pulses are approximately rectangular in shape. When the pulse shape is irregular it may lead to erroneous power measurements and so a shape factor correction must be applied. Often the shape factor correction must be estimated and hence may be subject to a relatively large uncertainty [6].

In the second set of measurements, a diode sensor was used. Diode sensors are capable of measuring pulsed power due to their fast raise time. Diode sensors can be used to predict the peak voltage of the RF signal. The relation between the peak RF voltage and the rms power P_{rms} is given by [7] as

$$P_{rms} = \frac{(V_p \times 0.707)^2}{R} = \frac{V_p^2}{2R} \qquad (4)$$

where R is the resistance of the load across which the diode is connected.

To validate or qualify a pulsed power system all the factors that influence it have to be taken into account. In an attempt to isolate the effects of duty cycle on the pulsed measurement results, multiple measurements of pulsed power were taken in which the time period was kept constant and the duty cycle was changed by varying the pulse width. When the pulsed power is derived from an average power measurement (as in the case of the thermal sensor), the dynamic range is reduced as the duty cycle is lowered. The reduction in dynamic range from a CW measurement for a pulsed power measurement with period T and pulse length τ is given by

$$\text{Reduction in Dynamic Range} = 10 \log \frac{T}{\tau} \qquad (5)$$

III. EXPERIMENTAL SETUP

A symbolic representation of signals at different ports of the RF switch is depicted in Fig.1. Port A is the input port, port B is the signal applied to the control port of the switch, and port C is the output of the switch that is input to the device under test. In this work, both thermal and diode sensors were used to measure pulsed power. Fig. 2 shows the measurement setup, which includes a sensor (Anritsu MA2422B thermal sensor or Anritsu MA2411B diode sensor), UMCC - model # SR-T800-2S RF switch, power meter (Anritsu ML2496A pulsed power meter or Anritsu ML2438A power meter), HP 8648C signal generator, and a Highland P400 digital delay generator. The Automated Tuner System (ATS) software from Maury Microwave [8] was used to automate the measurements and make system loss corrections as applicable. The delay generator was used to provide the necessary logic control for the RF switch. An active-low switch was used for the measurement: when the digital control pulse is low, the switch passes the RF input through the switch.

IV. RESULTS

For measurements performed with the thermal sensor, the average power is inherently measured by the sensor. The result is then converted to pulsed power by the software. Before taking any measurements, the duty cycle and the pulse repetition rate f_p must be input to the ATS software to allow the pulsed power to be accurately calculated.

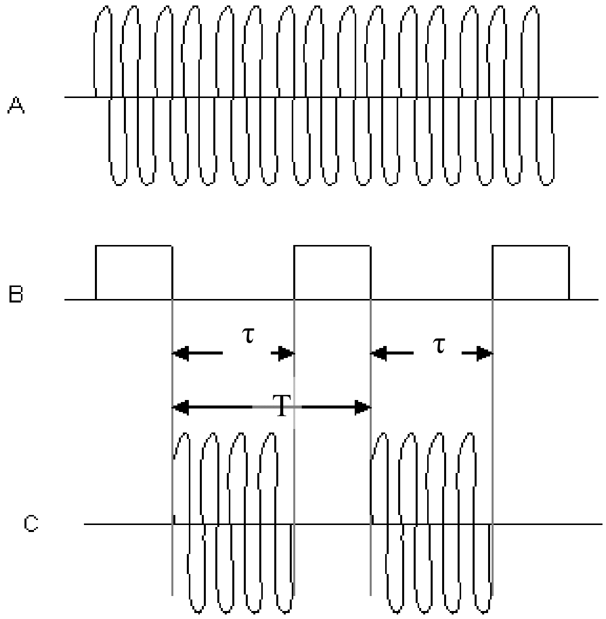


Fig.1: RF signal representation at ports A, B, and C of the RF switch as shown in Fig. 2

The pulsed power calibration is performed by changing the pulse width τ of the control logic of the delay generator so that the pulse B shown in Fig. 2 changes. The RF switch allows the RF signal at TTL low to pass through it. The calibration of the system showed that the system had an input insertion loss, before the DUT, of -2.451 dB. The ATS software corrects for such losses as a result of the calibration procedure.

The reduction in dynamic range as pulse length is decreased for a thermal sensor can be seen when a calibration is performed. Fig. 3(a) shows the measured pulsed available power (at the sensor) versus the programmed power for various pulse lengths and a constant period of 100 µs and RF signal frequency 2GHz.

In Fig.3 (a) the Y axis ($P_{available}$) is the pulsed power calculated by Maury automatically when f_p and τ are known. It is important to note while observing this data that the thermal sensor measures average power. For reduced pulse length (and hence reduced duty cycle) a reduction in the dynamic range of the sensor was observed due to the fact that the power is applied for a shorter amount of time, thus decreasing the average power delivered to the sensor. The thermal sensor used has a manufacturer specified dynamic range of -30dBm to 20dBm. Fig.3 (a) shows that as expected the sensor actually has an absolute low end that is lower than its specification. For a 50 % duty cycle (in the Fig. 3 case a 50 µs pulse length), the average power detected by the sensor at each pulsed power setting is 3 dBm lower than in the continuous-power case. For the 50 % case, it would be expected that a pulsed power of -30+3 = -27 dBm would be the lowest pulsed power measurable by the sensor, based on the specified range.

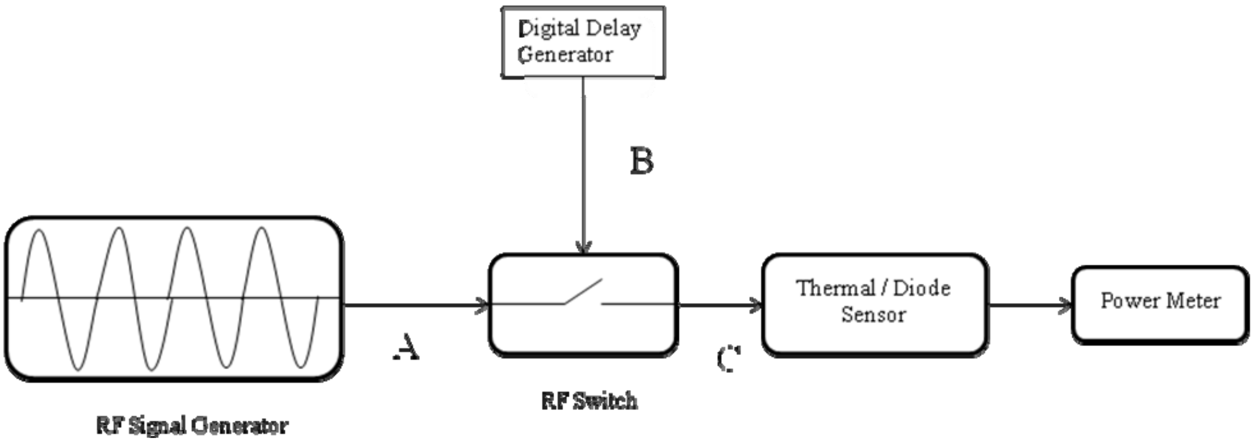


Fig.2: Pulse Power Measurement Set-Up

The duty cycle of 5 percent (5 µs pulse length) means that the average power that can be measured in each setting is reduced by approximately 13 dBm, this effect can be clearly observed from Fig.3 (a). In Fig.3 (b) we can see the same plot with Y axis as average Pout (available) in which we can clearly see the lower limit of the sensor is actually around -34 dBm where it hits the noise floor. Because the specification for the low-power measurement limit of the sensor is -30 dBm (the actual observed lower limit during the experiments was -34 dBm), for the case of a 5 percent duty cycle, the lower limit for pulse power is (-30 + 13) = -17 dBm.

This is consistent with the results in Fig. 3a. The results in Fig.3(b) indicate that this setting allows measurements to about -20 or -21 dBm (the sensor seems to show a trend of possessing a "noise floor" about 3 or 4 dB lower than would be calculated from the specification).

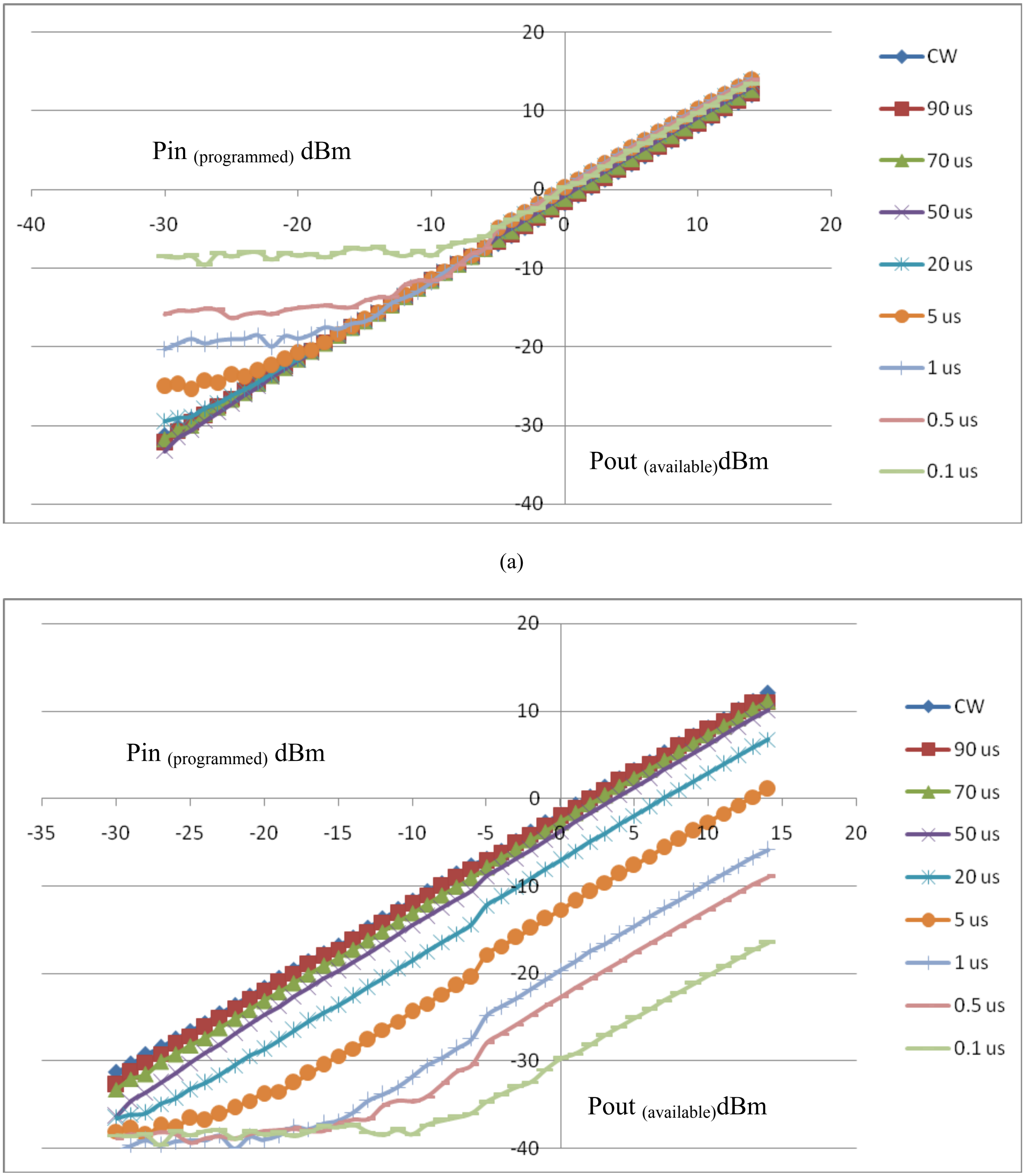
Due to the noise and reduction in dynamic range as the duty cycle is reduced, deterioration in the precision of the measurements can be observed. From Fig.3(a) it can be seen that the low pulsed-power measurement limit of the sensor creeps significantly high for very low pulse lengths and in Fig.3(b) it can be seen that for 0.5 µs the sensor is in the noise floor for up until a Pin of -11 dBm. At 0.1 µs the lowest power ($P_{available}$) that could be accurately measured is -4 dBm. This low duty cycle deterioration is present for both calibration as well as DUT testing. Further experimentation was performed using calibration under both pulsed and CW conditions, and these tests showed that the best approach is to calibrate under CW conditions prior to performing DUT testing under the desired duty cycle. The reasoning for this is sound: the sensor measures average power, so calibrating with larger average power values will enhance the precision of both the calibration and the ensuing measurements.

Fig.4 shows the calibration results using a diode sensor (for comparison with Fig. 3(a)). It can be observed that the diode sensor exhibits no low-power dynamic range issue for pulses tested between 90 and 0.5 µs. For pulse lengths below 0.5 µs, some problems are observed with the diode sensor measurements.

Fig.5 shows power versus time as viewed by the power meter for several different pulse lengths at an input power of 0 dBm. The power meter has been configured to report the average power measured between the two vertical cursors shown on the screen view. Fig. 6 shows the power-versus-time view for a significantly lower input power value (-20 dBm). In this case, it appears that, while a satisfactorily flat region can still be used to obtain a reasonable measurement at the 0.5 µs pulse length, the power trace in the 0.2 and 0.1 µs cases appears very uneven, and it is difficult to place the cursors to get an accurate measurement. This seems to be a reasonable explanation for the difficulty in obtaining accurate low-power calibrations for the 0.1 and 0.2 µs pulse lengths in Fig. 4. It was concluded that caution should be exercised when attempting to use the diode sensor is to measure pulsed power at 0.1 µs and 0.2 µs pulse lengths for low power values. The use of a different RF switch may produce more favorable results for these lower duty cycles.

Fig. 7 shows a comparison between the measured Gt of the thru for both of the sensors at a pulse length $\tau = 0.5$ µs pulse length during a power sweep. Ideally Gt should be zero for all power levels, but it can be observed that the thermal sensor loses precision at lower input power values. Also note that the diode sensor used in this setup had a stated dynamic range of -20 to +20 dBm, compared to -30 dBm to +20 dBm for the thermal sensor. However, in our application the thermal sensor is being used to measure average power over a large time span including both on and off pulse conditions, whereas the diode sensor is used to measure the signal during a gated interval during the on time of the pulse. Accordingly, the diode sensor has a clear advantage for lower pulse ranges because the signal can be gated and it can be decided under which time period the power should be measured.

From Fig. 7, it can be clearly observed that precision begins to deteriorate significantly for the thermal sensor as the pulsed power goes below about -5 dBm.



(a)

(b)

Fig.3: (a). Calibration Data: $\mathrm{Pin}_{\mathrm{programmed}}$ Versus pulsed $\mathrm{Pout}_{\mathrm{available}}$ for Thermal Sensor for Various RF Pulse Width and Constant Period of 100 µs (b). Calibration Data: $\mathrm{Pin}_{\mathrm{programmed}}$ Versus average $\mathrm{Pout}_{\mathrm{available}}$ for Thermal Sensor for Various RF Pulse Width and Constant Period of 100 µs

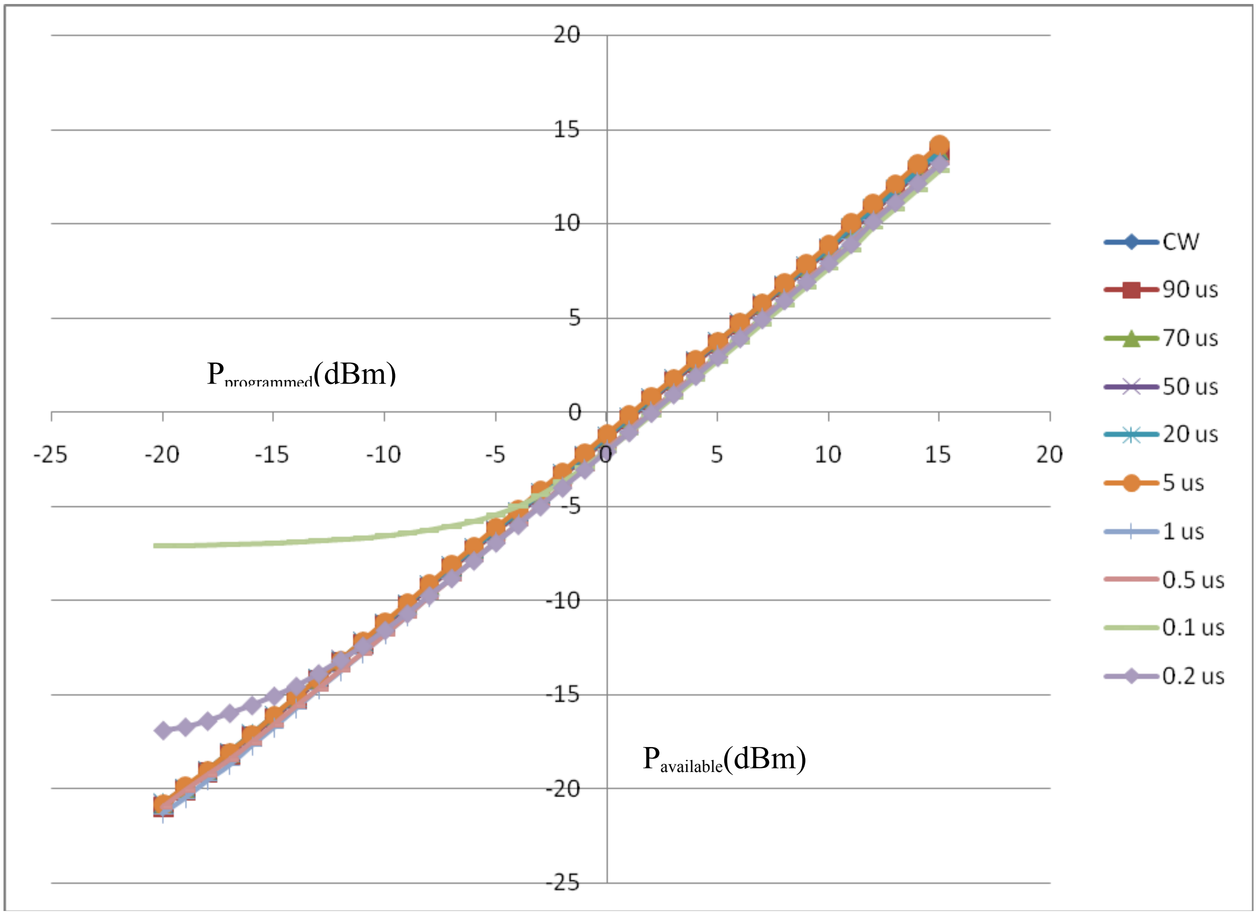


Fig.4: Calibration Data: $P_{available}$ Versus $P_{programmed}$ for Diode Sensor for Various RF Pulse Width and Constant Period of 100 µs

For the thermal sensor, the lower power rating is -30 dBm. Based on equation (5), the dynamic range reduction for τ = 0.5 µs, T = 100 µs is

$$\text{Reduction in Dynamic Range} = 10\log\frac{T}{\tau} =$$

$$10\log\frac{100}{0.5}$$

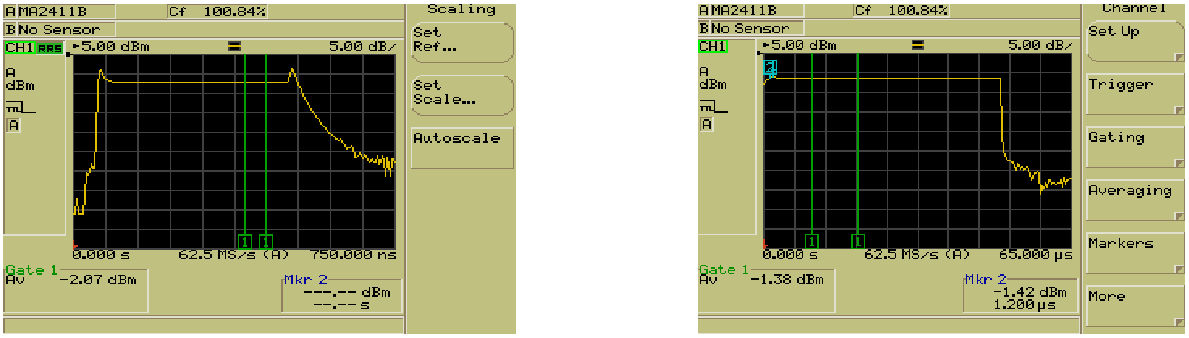
$$= 23\text{ dB}$$

This means that the lower end of the accurately measurable input power range should be -30 dBm + 23 dB +2.5 dB (insertion loss of the switch) = -4.5 dBm. This coincides exactly with the deterioration of the thermal sensor precision observed in Fig.7.

A MA2411B Cf 100.84%
B No Sensor
CH1 RRS ▸5.00 dBm 5.00 dB/
A dBm A Av100
0.000 s 62.5 MS/s (A) 500.000 ns
Gate 1 Av −1.91 dBm
Mkr 2 ---.-- dBm --.-- s

A MA2411B Cf 100.84%
B No Sensor
CH1 RRS ▸5.00 dBm 5.00 dB/
A dBm A
0.000 s 62.5 MS/s (A) 500.000 ns
Gate 1 Av −2.12 dBm
Mkr 2 ---.-- dBm --.-- s

(a) Pulse Width = 0.1 µs (b) Pulse Width = 0.2 µs

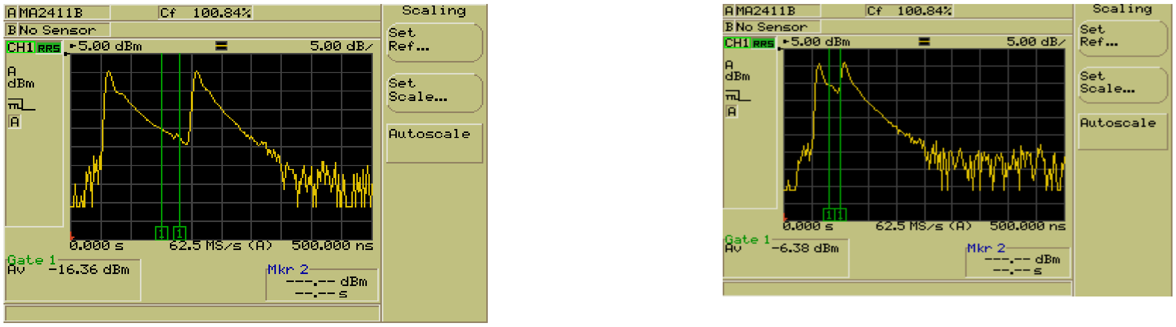


A MA2411B Cf 100.84%
B No Sensor
CH1 RRS ▸5.00 dBm 5.00 dB/
A dBm A
0.000 s 62.5 MS/s (A) 750.000 ns
Gate 1 Av −2.07 dBm
Mkr 2 ---.-- dBm --.-- s

A MA2411B Cf 100.84%
B No Sensor
CH1 ▸5.00 dBm 5.00 dB/
A dBm A
0.000 s 62.5 MS/s (A) 65.000 µs
Gate 1 Av −1.38 dBm
Mkr 2 −1.42 dBm 1.200 µs

(c) Pulse Width = 0.5 µs (d) Pulse Width = 50 µs

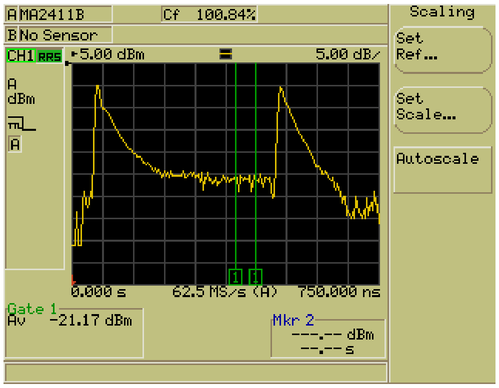
Fig.5: Power Meter Screenshots of Power Versus Time for Different Pulse Widths for T = 100 µs and $P_{Programmed}$ = 0 dBm



A MA2411B Cf 100.84%
B No Sensor
CH1 RRS ▸5.00 dBm 5.00 dB/
A dBm A
0.000 s 62.5 MS/s (A) 500.000 ns
Gate 1 Av −16.36 dBm
Mkr 2 ---.-- dBm --.-- s

A MA2411B Cf 100.84%
B No Sensor
CH1 RRS ▸5.00 dBm 5.00 dB/
A dBm A
0.000 s 62.5 MS/s (A) 500.000 ns
Gate 1 Av −6.38 dBm
Mkr 2 ---.-- dBm --.-- s

(a) Pulse Width = 0.1 µs (b) Pulse Width = 0.2 µs



A MA2411B Cf 100.84%
B No Sensor
CH1 RRS ▸5.00 dBm 5.00 dB/
A dBm A
0.000 s 62.5 MS/s (A) 750.000 ns
Gate 1 Av −21.17 dBm
Mkr 2 ---.-- dBm --.-- s

(b) Pulse Width = 0.5 µs

Fig.6: Power Meter Screenshots of Power Versus Time for Different Pulse Widths for T = 100 µs and $P_{programmed}$ = -20 dBm

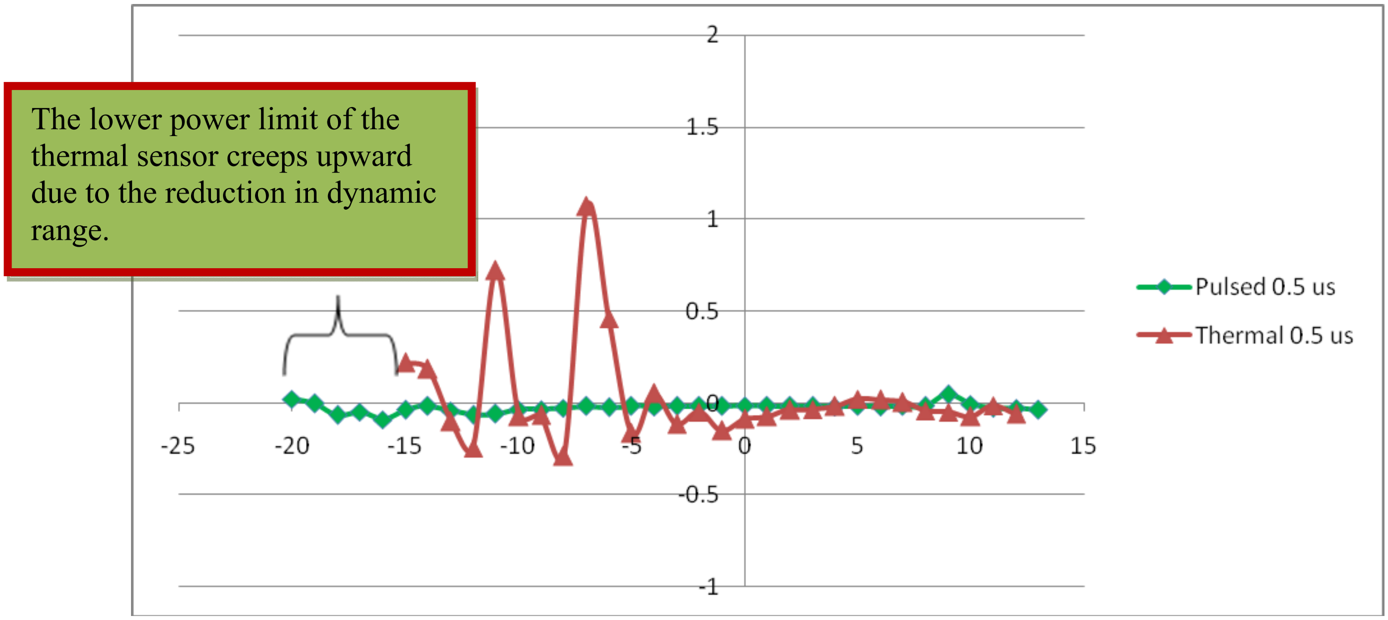

The lower power limit of the thermal sensor creeps upward due to the reduction in dynamic range.

Fig.7: Thru Transducer Gain for the Diode and Thermal Sensors for τ = 0.5 µs, T = 100 µs (Duty Cycle = 0.5 Percent).

V. CONCLUSIONS

This work demonstrates the results of an experiment to compare the accuracy and precision of pulsed power measurements using two different types of power sensors. Pulsed power measurements for various duty cycles have been analyzed. As expected, the dynamic range of the thermal sensor used reduces as the duty cycle reduces, while the diode sensor setup produced more accurate readings for lower duty cycle values. Limitations of the diode sensor to measure for low duty cycles at low power values were traced to limitations of the pulse shape generated by the RF switch used. The type of benchmark testing outlined here has proven helpful in developing a pulsed load-pull system in the laboratories of the authors and provides insight on what duty cycles and power ranges can be used with confidence for testing of active devices.

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