

Theory and Proposed Method for Determining Large Signal Return Loss or “Hot S22” for Power Amplifiers Using Phase Information

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Introduction:

Power amplifiers (PAs) are a critical functional block in today’s wireless communications. They are found in every cell phone, cordless phone, RF remote controller, etc. Any application requiring the wireless transmission of analog or digital signals will require a PA. The PAs are usually placed as close as possible to the antenna in wireless equipment to minimize RF losses, maximize power efficiency and maximize battery life.

RF systems engineers need to determine the PA return loss under actual output power drive levels. This so-called “Hot S22” is needed to calculate mismatch loss at the antennae interface, and to determine the actual wireless system transmit power (a key requirement for regulatory bodies, e.g. FCC).

The verification of PA output return loss has proven to be a problematic and challenging endeavor when the PA is delivering high output power.

High power PAs will inadvertently heat up as the output power levels are increased. Under high output power conditions, the power transistors parameters may significantly change as temperature and bias conditions change [1]. Therefore, the PA output return loss may be substantially different when operated under low output power vs. high output power. Most PA suppliers will only publish return loss values for small signal conditions. These values should be checked against actual high power conditions when conducting systems transmit power budgets. A number of test equipment suppliers have “off-the-shelf” test hardware for measuring the return loss of high power units [2-3], but these solutions are usually very expensive, and may not justify investment for engineers conducting only occasional high power tests.

This paper outlines a simple and cost-effective solution for determining the return loss of a high power PA. A test procedure is outlined based on a mathematical approach to determine the PA large (or small) signal return loss by measuring the insertion phase variation of the PA at specific VSWRs using an inexpensive and simple test arrangement.

1. PA Reflection Coefficient:

Any RF test configuration can be expressed by a source impedance (Z_L), and characteristic impedance (Z_0) as shown in Figure 1.

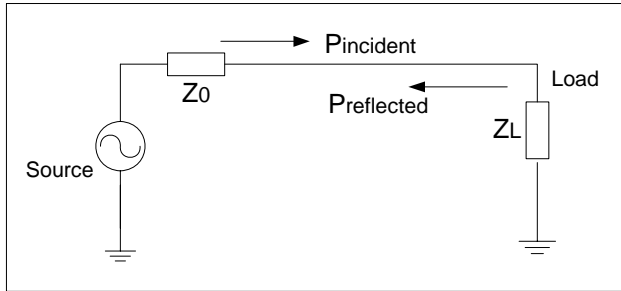


Figure 1: Power transmission from source to load

If the load impedance is equal to the source characteristic impedance then the reflected traveling wave does not exist (i.e. as is the case for matched load).

However, when Z_L is not equal to the PA output impedance, Z_0 , then the traveling wave V between the PA to the load contains two components: one is traveling in $+z$ direction and the other traveling in the $-z$ direction.

$$V = V_+ e^{-\gamma z} + V_- e^{+\gamma z}$$

The traveling wave in $+z$ direction is the incident power, and the traveling wave on the $-z$ direction is the reflected power.

$$V_{inc} = V_+ e^{-\gamma \bullet z}$$

$$V_{ref} = V_- e^{+\gamma \bullet z}$$

Where γ is the propagation constant.

Now let us replace the source with an actual PA and the load with a phase tuner, which rotates the phase 2π radians, and causes in theory full reflection back to the PA as illustrated in Figure 2.

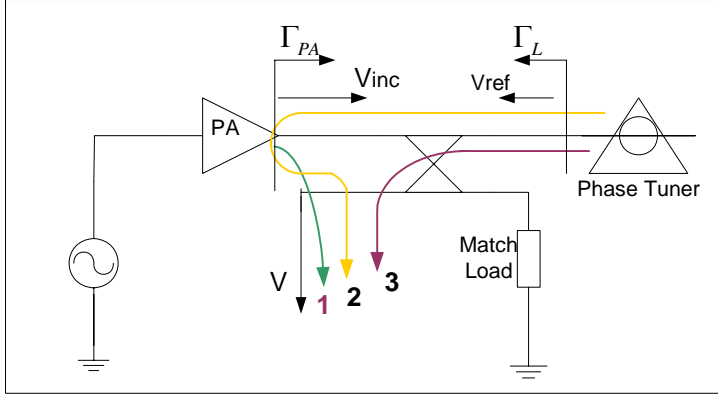


Figure 2: PA in a mismatch system

The reflection coefficient is determined to be the ratio between the reflected to the incident vector as follows:

$$\Gamma_L = |\Gamma_L| \cdot e^{j\theta} \quad \Gamma_L = \frac{V_- e^{j\omega_0 t + (\theta + \phi)}}{V_+ e^{j\omega_0 t + \phi}}$$

$$\Gamma_{PA} = |\Gamma_{PA}| \cdot e^{j\psi} \quad \Gamma_{PA} = \frac{V'_+ e^{j\omega_0 t + (\theta + \phi + \psi)}}{V_- e^{j\omega_0 t + (\theta + \phi)}}$$

ϕ is the shifted phase caused by the PA

θ is the phase angle of the reflection coefficient Γ_L

ψ is the phase angle of the reflection coefficient Γ_{PA}

The summing vector, V , in the coupling port contains three vectors which are directed from three different paths. i.e.

$$V_1 = V_{inc} \cdot CF$$

$$V_2 = V_{inc} \cdot \Gamma_{PA} \cdot \Gamma_L \cdot CF$$

$$V_3 = V_{inc} \cdot \Gamma_L \cdot CF \cdot DR$$

Where CF is the bidirectional coupling factor and DR is the directivity for the bidirectional coupler.

$$V = V_1 + V_2 + V_3$$

$$V = CF \cdot V_+ e^{j\omega_0 t + \phi} + CF \cdot \Gamma_{PA} \cdot \Gamma_L \cdot V_+ e^{j\omega_0 t + \phi} + CF \cdot DR \cdot \Gamma_L \cdot V_+ e^{j\omega_0 t + \phi}$$

Using directional couplers with $DR > 20\text{dB}$, ensures V_3 is much smaller than V_2 , i.e.

$$V_2 \gg V_3$$

$$V_{inc} \cdot \Gamma_{PA} \cdot \Gamma_L \cdot CF \gg V_{inc} \cdot \Gamma_L \cdot CF \cdot DR$$

$$\Gamma_{PA} \gg DR$$

It is recommended that the directivity for the bidirectional coupler should be higher than the PA return loss by 15dB. This will ensure vector V_3 will remain negligible.

$$\text{Directivity} \geq \text{PA R.L} + 15\text{dB}$$

If V_3 is negligible, then vector V can be reduced to:

$$V = V_1 + V_2$$

$$V = CF \cdot V_+ e^{j\omega_0 t + \phi} (1 + |\Gamma_{PA}| \cdot |\Gamma_L| \cdot e^{j(\theta + \psi)})$$

$$\Gamma_{Total} = \Gamma_{PA} \cdot \Gamma_L = \frac{V'_+ e^{j\omega_0 t + (\theta + \phi + \psi)}}{V_+ e^{j\omega_0 t + \phi}}$$

$$V = CF (V_+ e^{j\omega_0 t + \phi} + V'_+ e^{j\omega_0 t + (\theta + \phi + \psi)})$$

The summing vector V as illustrated in Figure 3, contains vector V_1 which represent the incident wave and vector V_2 which represents the reflected wave.

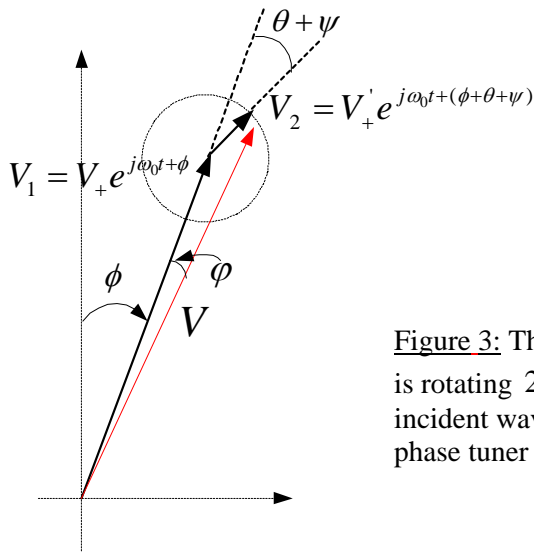


Figure 3: The reflected wave vector V_2 is rotating 2π radians across the incident wave vector according to the phase tuner position.

The angle φ is the angle between the incident vector V_1 to the summing vector V and it also determined as the variation in PA insertion phase between PA insertion phase at VSWR=1:1 to the PA insertion phase when the phase tuner is shifted within 2π radians with VSWR>1:1.

There are two locations on the phase tuner where the maximum and minimum PA insertion phase is achieved. At these two locations, the reflected vector is perpendicular to the incident vector ($\theta + \psi = \frac{\pi}{2}$ or $\theta + \psi = -\frac{\pi}{2}$), and the angle φ reaches the highest value, φ_{\max} .

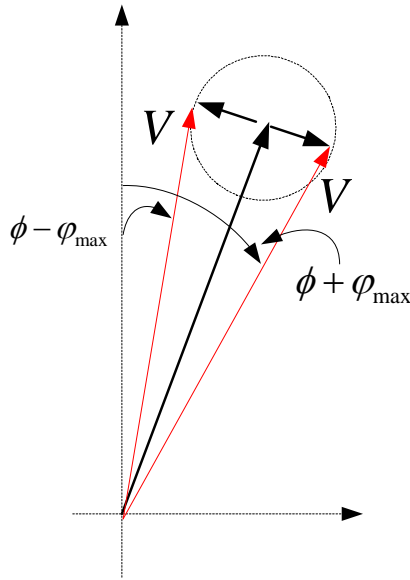


Figure 4: Vector diagram for maximum and minimum insertion phase. Maximum or minimum phase variation occurs where the forward incident vector is perpendicular to the reflected vector and the insertion phase variation is the angle φ between the forward vector and the summing vector.

At these two locations of 90 degrees insertion phase, the product of the load and PA reflection coefficients can be written as:

$$\Gamma_{Total} = \Gamma_L \cdot \Gamma_{PA} = \frac{V_+ e^{j\omega_0 t + (\phi + \frac{\pi}{2})}}{V_+ e^{j\omega_0 t + \phi}} = \frac{V_+ e^{j\omega_0 t + (\phi - \frac{\pi}{2})}}{V_+ e^{j\omega_0 t + \phi}} = \tan \varphi_{\max}$$

$$-20 \log |\Gamma_{Total}| = -20 \log \tan \varphi_{\max}$$

$$-20 \log |\Gamma_{PA}| - 20 \log |\Gamma_L| = -20 \log \tan \varphi_{\max}$$

$$-20\log|\Gamma_{PA}| = -20\log \tan \varphi_{\max} + 20\log|\Gamma_L|$$

Since the phase tuner has a full reflection then $\Gamma_L = 1$ and the PA return loss (in dB) can be expressed as:

$$PA_R.L = -20\log \tan \varphi_{\max}$$

φ_{\max} can be found by rotating the phase tuner within 2π radians and maximum insertion phase can be searched using a phase detector with a test setup shown in the Figure 5.

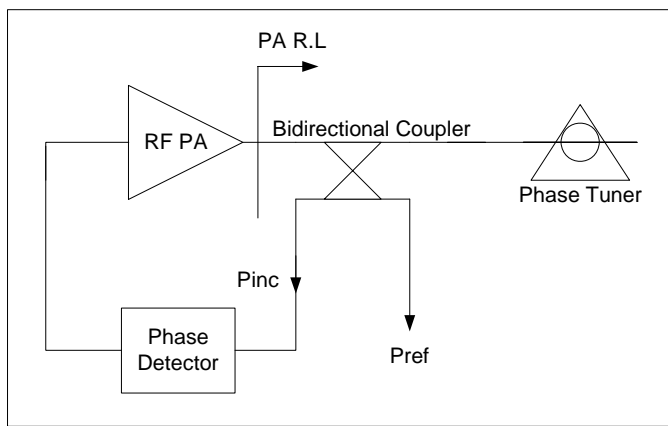


Figure 5: Test set up for measuring maximum insertion phase

2. PA reflection coefficient with determined mismatch load:

In practice, PAs are specified over a limited VSWR range. The PA can be damaged or unstable with a load VSWR above what has been specified by the vendor. Therefore, the same analysis will be given when the load phase tuner is connected to the PA through an attenuator in order to limit the VSWR which will reflect on the PA.

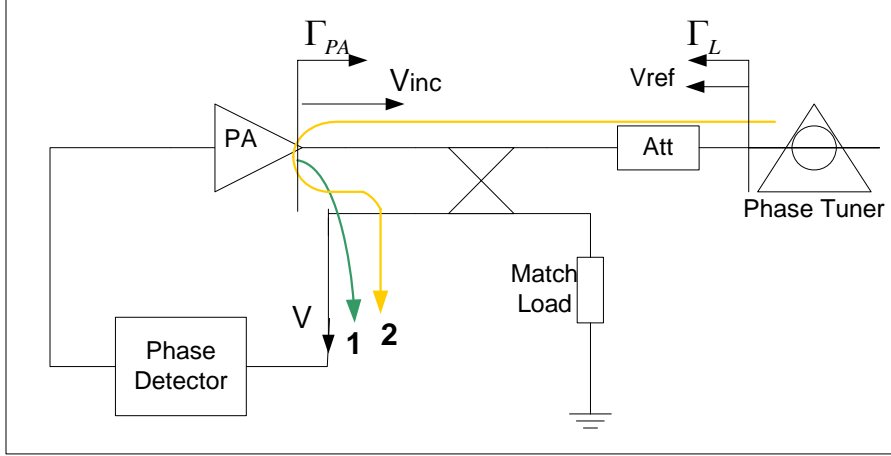


Figure 6: Test set up for measuring maximum insertion phase with limited VSWR

$$V = V_1 + V_2$$

$$V = CF \cdot \left(V_+ e^{j\omega_0 t + \phi} + (Att)^2 \cdot V_+' e^{j\omega_0 t + (\theta + \phi + \psi)} \right)$$

$$\tan \varphi_{\max} = (Att)^2 \cdot \frac{V_+' e^{j\omega_0 t + (\theta + \phi + \psi)}}{V_+ e^{j\omega_0 t + \phi}} = (Att)^2 \cdot \Gamma_L \cdot \Gamma_{PA}$$

$$\Gamma_{PA} = \frac{\tan \varphi_{\max}}{(Att)^2 \cdot \Gamma_L}$$

$$PA _ R.L = -20 \log \Gamma_{PA} = -20 \log \left(\frac{\tan \varphi_{\max}}{(Att)^2 \cdot \Gamma_L} \right)$$

Since the phase tuner has a full reflection, $\Gamma_L = 1$ and the PA return loss can be expressed as:

$$PA_R.L = -20\log\Gamma_{PA} = -20\log\left(\frac{\tan\varphi_{\max}}{(Att)^2}\right)$$

or:

$$-20\log(\tan\varphi_{\max}) = PA_R.L(dB) + 2 \cdot Att(dB)$$

If the PA return loss is high and the attenuator used between the PA to the phase tuner is high, then the phase angle φ_{maz} may be small and difficult to measure in order to have accurate results. Therefore, it is suggested to use a small attenuator (e.g. 1 dB to 3 dB) between the PA and the phase tuner.

3. Test Method:

Step 1:

Connect the PA as illustrated in Figure 7 using a 50 Ohms load at the output of a bidirectional coupler (additional attenuation can be connected in front of the phase detector whenever it is desired to measure return loss for very high power PA).

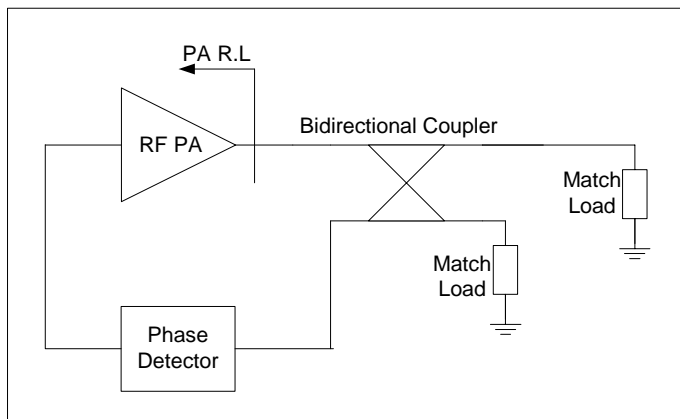


Figure 7: Test Setup for matched load.

Measure the insertion phase at the various frequencies of interest using small signal or large signal input power.

The insertion phase with 50 ohms load will be the reference insertion phase before loading the PA with different VSWRs.

In Table 1 below, we show the measured value for a high power (2 Watts) 350 MHz to 470 MHz Skyworks' PA – the SKY65141. A photo of the PA mounted in its test fixture is shown in Figure 12.

Frequency (MHz)	Insertion Phase at VSWR 1:1 and $P_{in} = -4\text{dBm}$ $\theta_{50\Omega}$
350	171.4
410	71.2
470	-30.5

Table 1: Insertion phase with VSWR 1:1 for Skyworks' high power PA – the SKY65141.

Step 2:

Disconnect the 50 ohms load at the output of the bidirectional coupler and connect a 1.5dB pad in order to present the PA a VSWR of 6:1. Place a phase tuner after the fixed attenuator pad. The phase tuner must be capable of continuously varying the insertion phase from 0 to 360 degrees. The test setup is illustrated in Figure 8A.

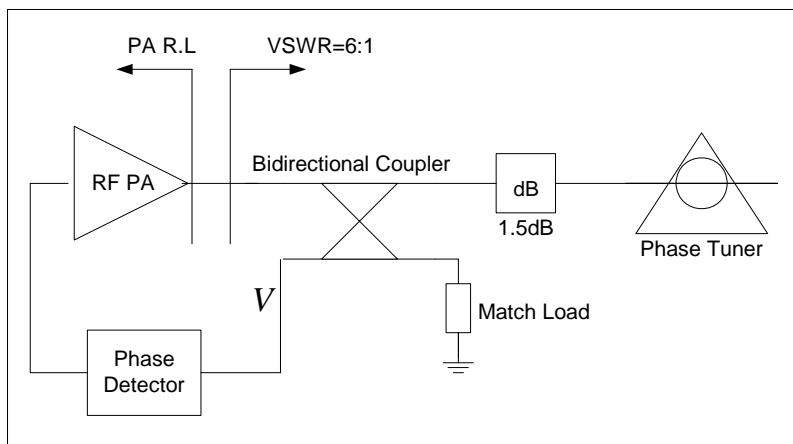


Figure 8A: Test Setup for mismatched load.

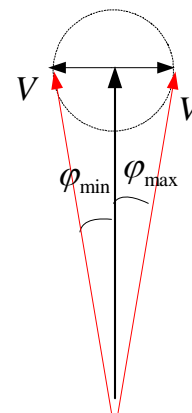


Figure 8B: Vector Diagram at the coupling port when $\phi = 0$.

Adjust the phase tuner in order to find the highest and lowest insertion phase and calculate at each frequency what the maximum phase variation is compared to the insertion phase at 50 Ohms as indicated in Table 2.

Note, the attenuator value is selected to be within the specified PA load VSWR range. The total output insertion loss should be measured at each maximum insertion phase location on the phase tuner in order for the return loss to be calculated accurately.

Frequency (MHz)	Minimum Insertion Phase ($\phi - \varphi_{\max}$)	Maximum Insertion Phase ($\phi + \varphi_{\max}$)	Maximum Insertion Phase Variation φ_{\max}
350	157.1	179.9	12.2
410	62.3	75	6.7
470	-42	-26.2	8.6

Table 2: Measured maximum and minimum insertion phase with VSWR 6:1 at various pass band frequencies.

In theory $\varphi_{\max} = \varphi_{\min}$, therefore the following equation is valid:

$$\frac{\varphi_{\max} - \varphi_{\min}}{2} = \varphi_{\max} - \varphi_{50\Omega} = \varphi_{50\Omega} - \varphi_{\min}$$

However, in practice φ_{\max} and φ_{\min} may not be equal since the phase tuner may not be ideal and symmetric. Therefore, the insertion phase at VSWR 1:1 ($\varphi_{50\Omega}$) is subtracted from the absolute value for the maximum phase variation ($\phi - \varphi_{\max}$ or $\phi + \varphi_{\max}$).

The return loss of the PA is calculated according to the following formula:

$$PA_R.L = -20 \log \left[\frac{\tan \varphi_{\max}}{(Att)^2} \right]$$

Where θ_{\max} is in degrees and Att is the measured attenuation from the PA output to the phase tuner input.

4. Test Results:

The theoretical analysis shown in the above sections was verified using a high power 2 Watts SMT PA from Skyworks -- the SKY65141. The PA was tested over its entire operating frequency range -- 350 to 470 MHz.

Actual return loss measurement was made with a small input signal and the results are given in the following graph:

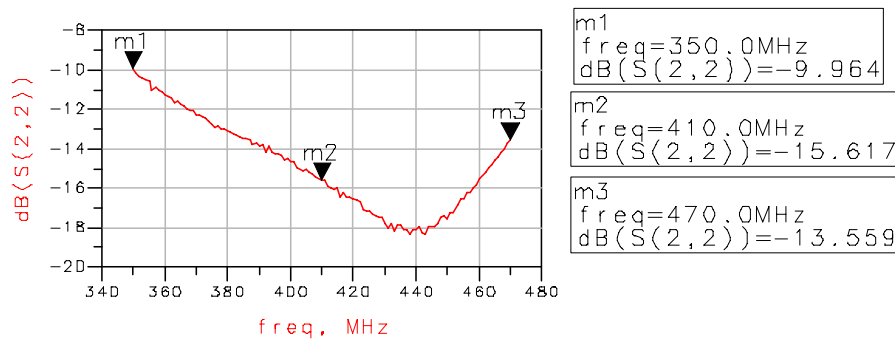


Figure 9: Return Loss measurements at low power using network analyzer

The measurement results are compared to the calculated return loss using the proposed phase measurement procedures outlined in the above sections.

The new test procedure was done using different load VSWRs to demonstrate the return loss measurement is repeatable at different VSWR. The return loss obtained using the new proposed phase technique is shown in Figures 10 and 11.

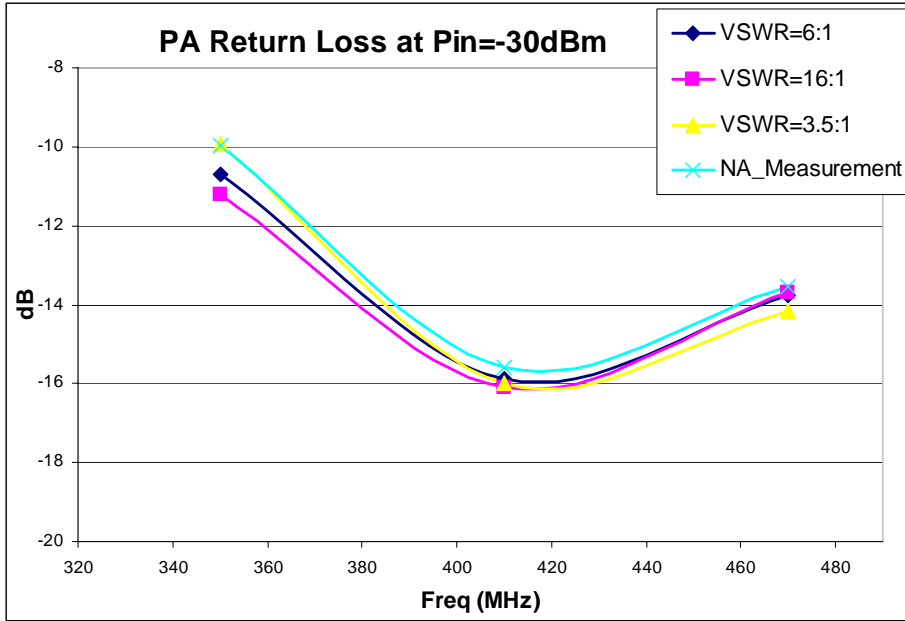


Figure 10: Return Loss Calculation with different VSWRs versus network analyzer measurement.

The same method was used to calculate the PA return loss using higher input signal with VSWR 3.5:1.

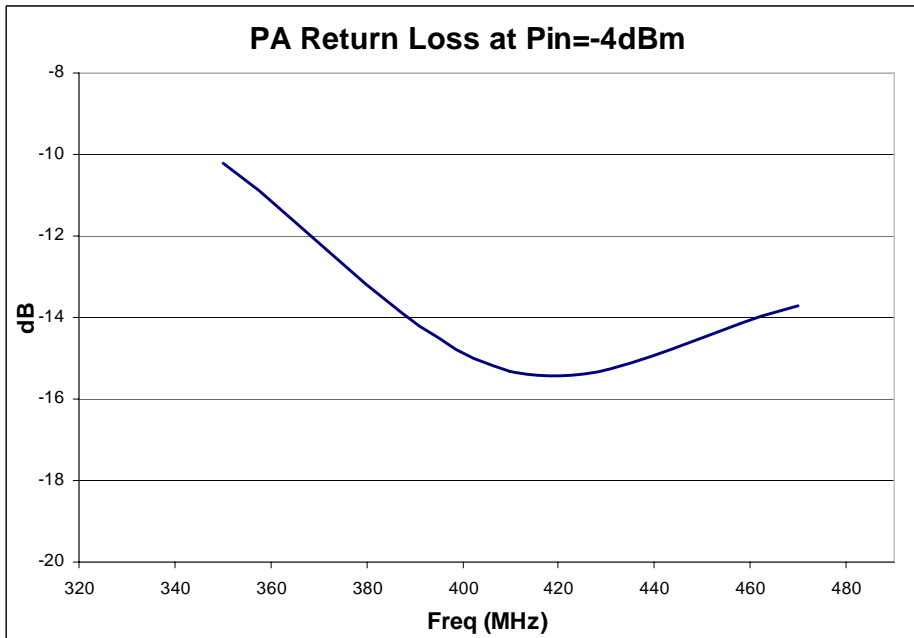


Figure 11: Return Loss Calculation with high input drive level

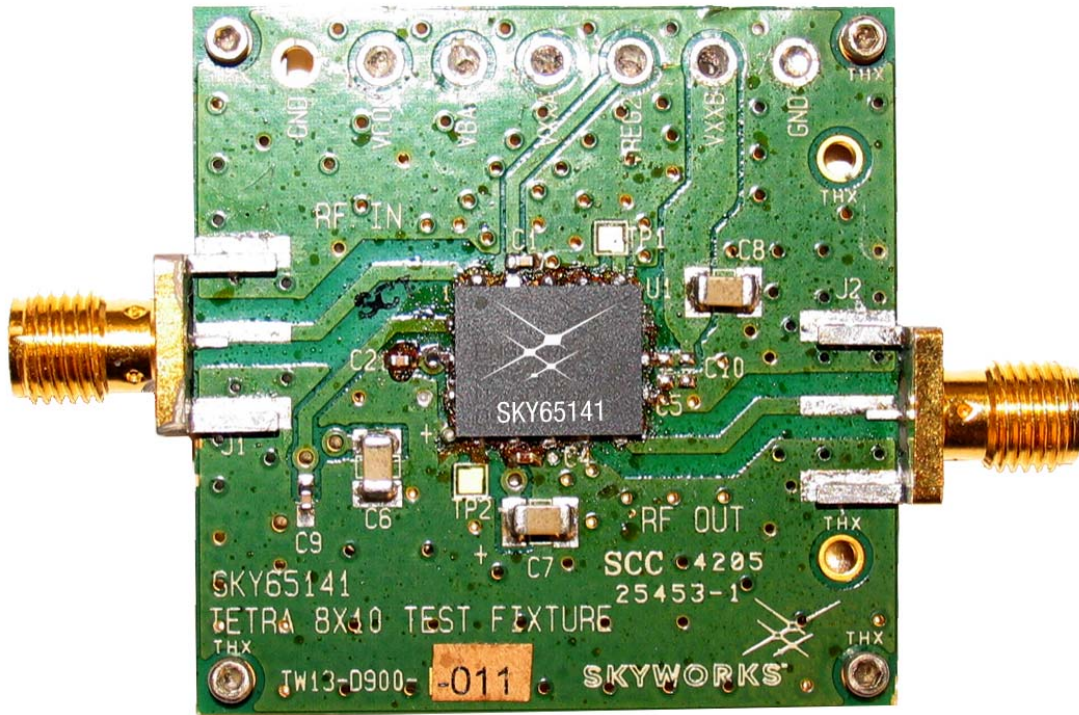


Figure 12: Photo of the High Power PA (SKY65141) mounted in its Test Fixture

Conclusions:

- PA return loss is a parameter which can vary depending on the PA output power, PA bias current, etc. Therefore, the PA return loss under high output power condition should be measured, and not be assumed to be the same as the return loss measured under small signal output power condition.
- The PA return loss can be calculated from the phase between the summing (incident and reflected vectors) to the incident vector which is measured with a matched-load.
- This paper demonstrates that “hot” PA return loss calculation can be accurately calculated by measuring the maximum insertion phase variation at any given VSWR, and at any given input drive level.
- The proposed return loss measurement technique can be implemented using low cost test components, eliminating the need for costly network analyzers.

REFERENCES

- [1] L. Liou, J.Ebel, and C. Huang, “Thermal Effects on the Characteristics of AlGaAs/GaAs heterojunction bipolar transistors using two-dimensional numerical simulation”, IEEE Trans. Electron Devices, vol. 40. pp. 35-40, 1993.
- [2] “Recommendations for Testing High-Power Amplifiers”, Agilent Application Note 1408-10.
- [3] “Hot S22 and Hot K-Factor Measurements”. Anritsu Application Note AN11410-00295.