Application Note

Hot S_{22} and Hot K-factor Measurements

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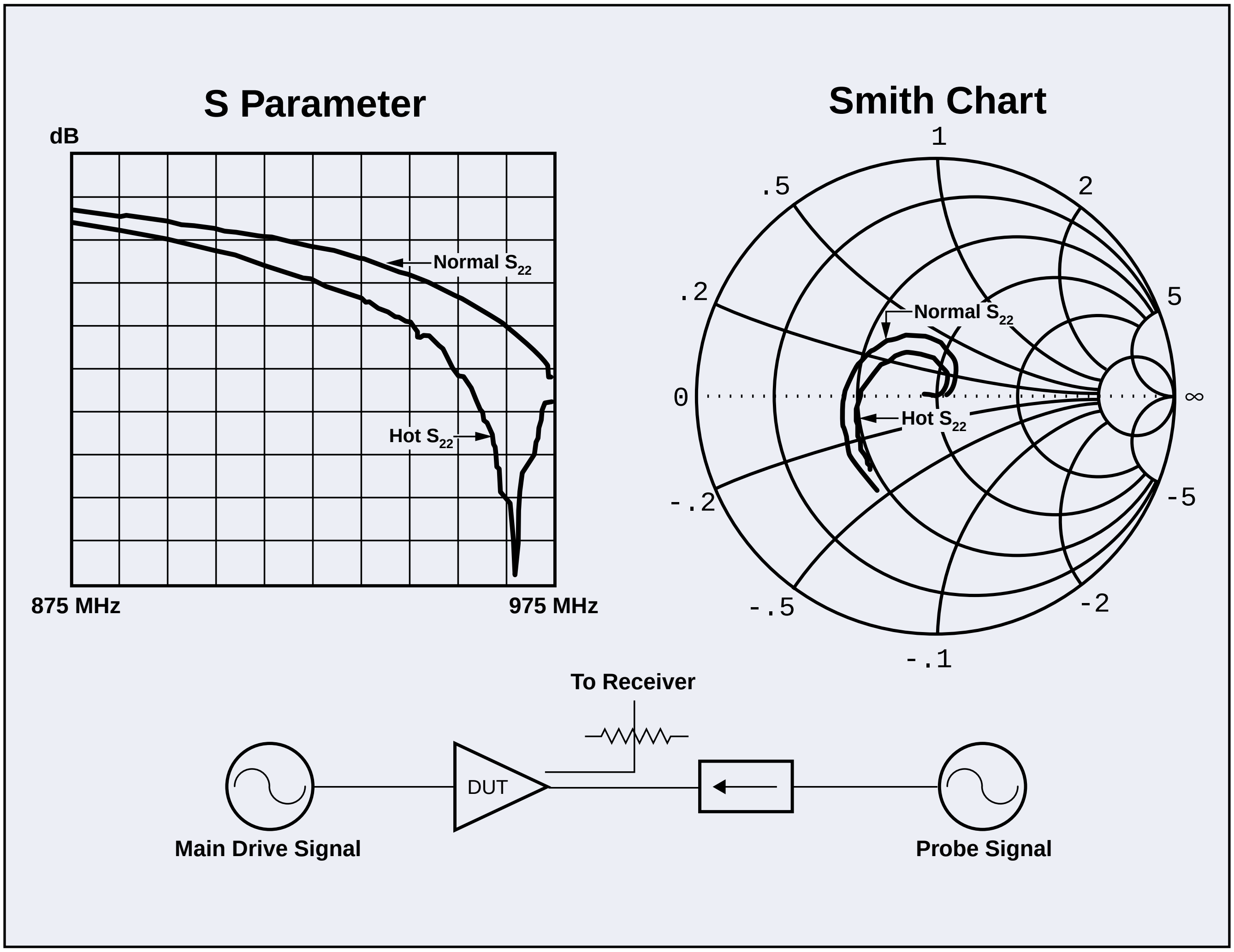

Practical S-parameter Measurements for Power Amplifier Applications

Introduction

The S-parameters of a power amplifier under excited conditions represent critical information having a bearing on efficiency, output power, stability, and often the economic viability of the design. The output reflection coefficient, in particular, is of considerable interest. One way of indirectly getting this information is through load-pull measurements in which output power is measured as a function of load impedance. While this load-pull measurement does access the practical impact of output reflection coefficient (among other things), it is expensive and time-consuming to perform. In some cases, primarily in power devices operating well away from compression or in somewhat matched amplifiers, a more direct, quasi-linear measurement of S-parameters while the amplifier is operating under normal drive may be useful. Such measurements, termed hot S-parameters, can provide some information on the degree of mismatch in-system, potential operational stability, and the effects of this amplifier's performance on subsequent stages or antennae. The purpose of this note is to explore what hot measurements can do and what are the practical measurement constraints.

Load-pull: a different but related measurement

A typical load-pull system consists of the device or amplifier structure under test, electronic or mechanical tuners (whose impedances have been measured previously in many different states), one or more power meters, and associated hardware. As is always the case, output power will be a function of load match. Unlike the small signal case, the relationship will be non-trivial in the large signal limit due to load line limitations along with other issues (even while still quasi-linear). Once the device is operating non-linearly, the relationships become even more complicated.

A simplified setup diagram is shown in Figure 1 (see, for example, [1]-[2]). Usually the input tuner is set for something near conjugate match although in highly bilateral devices, the interaction between input and output match can be substantial. The output tuner is usually moved through its various states and the output power mapped as a function of load impedance. A set of constant output power contours on a Smith chart plane of load impedance can then be plotted. This level of characterization is critical for power devices and is usually used to help generate the required matching circuits.

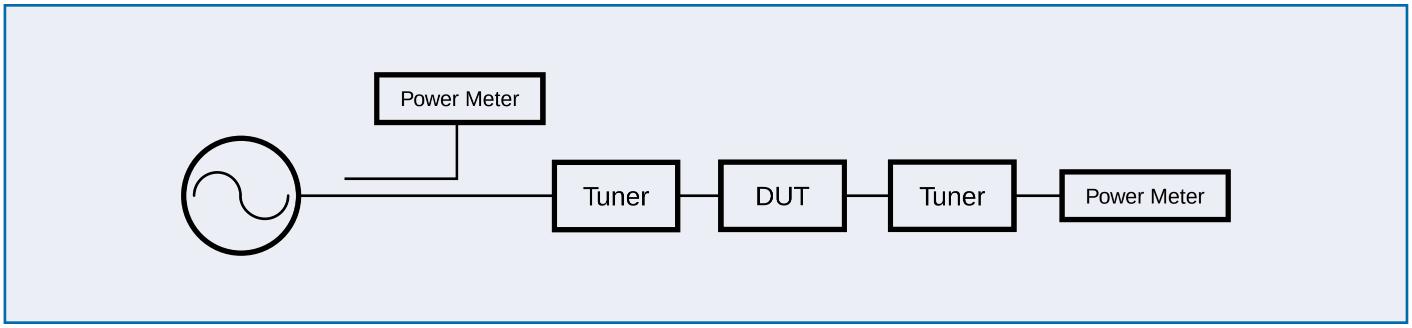

Figure 1. *A simplified load-pull setup is shown here. The impedance presented to the DUT output is pre-measured for a variety of tuner states. The output power can then be plotted as a function of load impedance.*

The simplistic analysis usually requires that the device is operating quasi-linearly. If not, the impedances of the tuners at harmonic frequencies must usually also be considered [1].

Hot S_{22} and when it can be useful.

Hot S_{22} is a considerably different measurement and is illustrated in Figure 2. Since the setup is simpler and uses only one fixed load impedance (that of the measuring instrument, typically better than a –15 dB match in a 50 ohm environment), the interpretation of the data is quite different. In this measurement, the amplifier is excited at some given power level in the normal way. In addition, a small pilot tone is used to directly measure the reflection coefficient of the output port of the DUT. This way the DUT is in the appropriate operating state for the measurement. The analysis here will assume that the main drive signal is sinusoidal and offset slightly in frequency from the probe tone to allow for receiver selectivity. A more thorough analysis including the case of modulated drive is covered elsewhere [3].

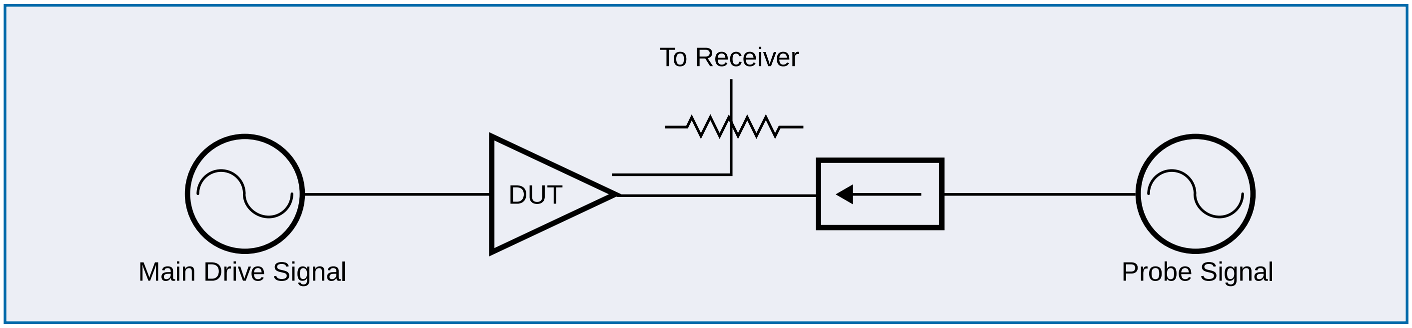

Figure 2. *Simplified setup of a hot S_{22} measurement is shown here. Normally one or both signal sources and the coupler/receiver unit are part of a VNA. This isolator shown, optional if the drive levels are low enough, prevents ALC pulling of the probe source by the DUT output signal.*

Because of the complex relationship between the output impedance state and output power, it will be difficult to extract enough information from the hot S_{22} measurement to perform a matching analysis unless the device is being operated very close to the small signal regime. This procedure is then most useful when the measurement impedance realm is relatively close to that the DUT would experience in practice; i.e., if the DUT is an amplifier assembly that will be embedded in a system with other amplifiers, filters, or antennae. This is a very important point. Once an amplifier assembly is ready for system insertion, how it performs in a nominal impedance environment is then a key measure that will determine power budgets, stability issues, and overall efficiency. Even if the amplifier is still in the quasi-linear regime, its hot S_{22} will probably not be equal to the small signal value (due to load line effects, etc.) and the value under normal operating conditions is critical to evaluating system impact.

Even more so than load-pull, hot S_{22} intrinsically makes some quasi-linearity assumptions. This has more to do with the definition of S_{22} itself than the measurement proper. If the DUT is very non-linear, the output currents and voltages are quite non-sinusoidal and a definition of impedance becomes, at best, highly generalized. The measurement will proceed largely unaffected in this case, but the interpretation of the data will be somewhat complicated.

An example measurement is shown in Figure 3. A reflection-only calibration on port 2 was performed as is normal for this measurement. Two traces show the behavior while the amplifier is in the small signal regime and at light compression. The probe power in both cases was –5 dBm and since this was only a moderate power amplifier, only 10 dB of additional attenuation was needed and an ordinary MS4623B could be used. Compression of the receiver was avoided and ALC pulling of the probe source was not an issue due to the similar and benign power levels involved.

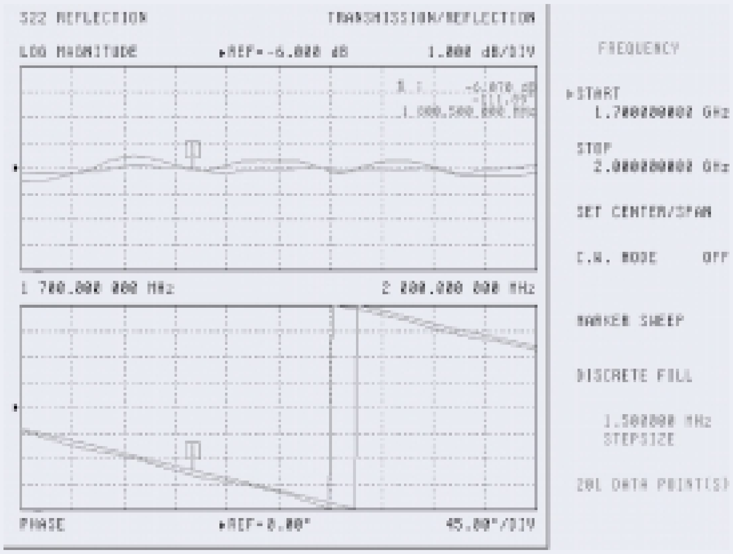

Figure 3. *An example hot S_{22} measurement with the amplifier in both a small signal and a modest compression state (< 0.5 dB compressed) is shown here. Small changes in the match state are clear.*

Another example with a 1W amplifier is shown in Figure 4. Again two traces are present with first at a very low input power and the second with an output power of about 25 dBm. This measurement was done with a PATS test set and receiver compression was easily avoided.

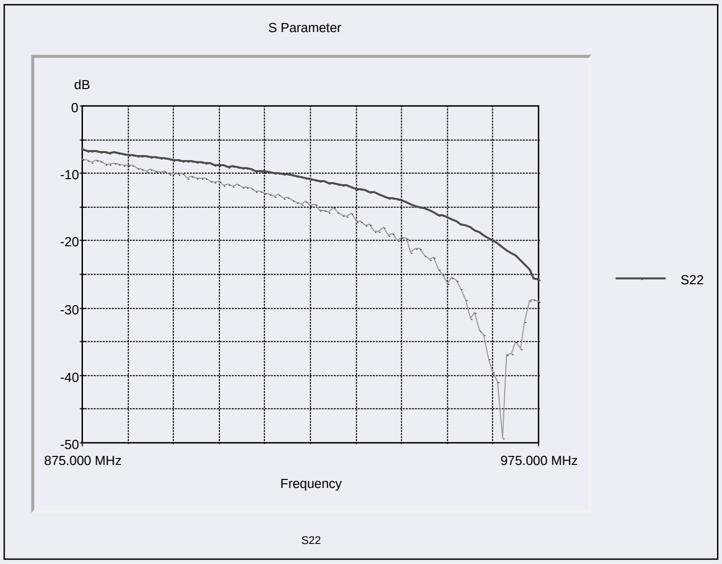

Figure 4. *Hot S_{22} measurements of a 1W amplifier at low input power and at a level to get ~ 25 dBm output power (upper curve) are shown here. In this example there is a more substantial reflection change.*

The other hot S-parameters and K-factor

To get a more complete picture of the device performance, the other S-parameters must also be measured. One obvious requirement is that both of the reverse measurements must be done under hot conditions. S_{12}, like S_{22}, must be measured with a main power tone applied to port 1 and a smaller probe tone applied to port 2. At the very least, two 1 path-2 port calibrations will be required to get the necessary measurements.

The forward measurements offer at least a pair of choices:

a) Measure S_{11} and S_{21} with the main power tone (only) applied to port 1. This is the obvious measurement and can be made with the help of a forward 1 path-2 port cal (at the appropriate main tone power level).

b) Measure S_{11} and S_{21} of a small pilot tone applied to port 1 in conjunction with a power tone (using a combiner prior to the test coupler). This would allow the use of a 12 term cal for all measurements but it has a few complications:

- The quasi-linearity assumptions will be more strongly tested since the probe signal is in the gain path. A variety of mix products may be generated that could distort the measurement so some care in selecting the probe signal amplitude is required.
- Since the probe tone is small and the signals are coming from the same port, ALC pulling issues are more of a concern. The combining structure may need to have increased isolation.

Both measurements, in principle, should yield equivalent results. A single calibration can be used for (b) and the process is discussed in more detail in [3]. To invoke the measurement involving (a), a pair of 1 path-2 port cals are then required: one in the reverse direction at the probe power level and one in the forward direction at the main drive level. The measurement can be sometimes be speeded up by putting each calibration in a different side of alternate sweep (where two complete calibrations are kept internally and each setup is swept alternately).

Of great interest in quantitatively evaluating the stability of an amplifier are various stability factors. The stability factor K (e.g., [4]) is given by the following equation.

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{12}S_{21}|}$$

where

$$\Delta = S_{11}S_{22} - S_{12}S_{21}$$

The necessary and sufficient condition for unconditional stability is that $K>1$ and $|\Delta|<1$. Generally as an amplifier approaches compression, $|S_{12}|$ increases which tends to decrease K. It is thus important that if stability at high power is of interest, that all the parameters (including S_{12}) be measured while in the appropriate power state.

It is reasonable to ask what such a K factor means since the impedance locus being analyzed is fixed and so many linearity assumptions have been made. Again, the measurements most make sense when the DUT will be used in an environment close to 50 ohms so the value is greatest for amplifiers and modules as opposed to bare devices. Since oscillations are usually more likely to occur in a backed-off state [1], quasi-linear operation (as well as in compression) may be justified.

Measurement constraints

Assuming that the setup under consideration can yield useful information, the next question revolves around the parameters that make it tractable. The main issues are tone frequencies and power levels.

Tone frequencies: To make the measurement possible for the tuned system receiver, the main power tone and the probe tone must be offset in frequency. The measurement becomes simpler (in terms of receiver compression issues) the further apart the tones the better. For the measurement to be meaningful, however, the spacing must at least be small relative to the DUT bandwidth. In general, the spacing must be less than the scale of any relevant frequency dependence of the DUT as well. While the user must be the judge of the latter scale, it has been found the separations of 500 kHz-2 MHz are often acceptable. A separation of at least 500 kHz is recommended for maximum dynamic range although it can be much smaller under some circumstances. The practical lower limit is that the separation should be at least several IF bandwidths so that the receiver can distinguish the signals. As discussed in the IMD application note [5], avoid multiples of 125 kHz for the separation due to internal image response reasons

Power levels: For the receiver to make a valid measurement, there are two concerns: damage levels and compression. This issue is further bifurcated based on if a standard MS462XA/MS462XB is being used or if a MS462XC is being used in conjunction with a Power Amplifier Test Set (PATS). The standard system may be appropriate if the DUT output power is relatively low (~< 20-23 dBm); at higher levels an external test set will generally be required. It is assumed that the pilot tone amplitude coming from port 2 is considerably below the DUT output power (so that total receiver power ~ DUT output power) and is not higher than +10 dBm under any circumstances.

A/B: Damage level is 27-30 dBm, <0.1 dB compression level is 10 dBm. The device output MUST be padded to avoid damage level.

C with PATS: Damage level is 47-50 dBm usually, <0.1 dB compression level is 40 dBm usually. An internal test set step attenuator in the receive path can be used. The compression point is approximately given by 3 dBm + test set loss to the b2 port if a different test set is being used.

Several issues must be considered if trying to reduce levels to avoid compression. Too much padding in front of port 2 will seriously degrade effective directivity and hence the dynamic range of the reflection measurement (generally more than 10-15 dB requires extra care). In the test set, the coupling loss is higher and attenuation after the coupled arm is available which does not have a deleterious effect on directivity. Also, the level to which the signal must be reduced is somewhat dependent on the tone spacing. If the offset is very small, then the compression limits apply equally to the probe tone and the DUT output tone. As the separation increases, the DUT output tone becomes somewhat less relevant and the compression level may be considered to increase by up to 5 dB. An additional approach, particularly helpful for smaller separations, is discussed in the appendix.

Test set considerations: While most of the discussion has assumed the use of the integral MS462xA/B test set or the PATS test set, user test sets are also possible in conjunction with the MS462xC. When considering such a test set, there are a number of issues to consider:

- Port 3 of the MS462xC (or an external synthesizer) must be routed to the DUT input somehow. A second source must provide the DUT drive since internal source 1 will be used as the probe signal. If necessary, the DUT drive may be injected via a coupler. Since IMD measurements [5] are often a part of the test setup, port 3 routing is normally available.
- An isolator/circulator is often needed in the port 2 routing (on the system side of the test coupler) to prevent ALC pulling. This may not be needed if signal levels are low enough.
- Pay attention to the compression levels discussed in the previous subsection. A variable attenuator in the coupled arm of port 2 can help with some setup issues.
- Hot measurements when the amplifier is being driven under modulated conditions are possible [3]. One may have to reduce IFBW/increase averaging to keep an appropriate signal-to-noise ratio. Routing for the modulated input must, of course, be provided as it is in the PATS test set.

Figure 5 illustrates the relevant components of a test set that is connected to the MS462xC. Not all components are shown. There are four receiver ports on the MS462xC (a_1, a_2, b_1, b_2) and all are normally connected (even if only hot S_{22} is of interest). The isolator is shown to prevent ALC pulling or damage but a circulator could be used as well. Note that a combiner is shown in the test set to facilitate IMD measurements and can be helpful for hot S_{11} and S_{21} measurements. Additional amplifiers are sometimes placed in the port 1 path to provide sufficient drive power to the DUT since the maximum available from RF1 or RF3 is on the order of +10 dBm. The PATS test set consists of all of that shown in Figure 5 together with an amplifier loop, an additional switched input path (for injection of other signal types), an additional coupled output path (to feed a power meter for example), and a terminated circulator instead of an isolator for power handling reasons.

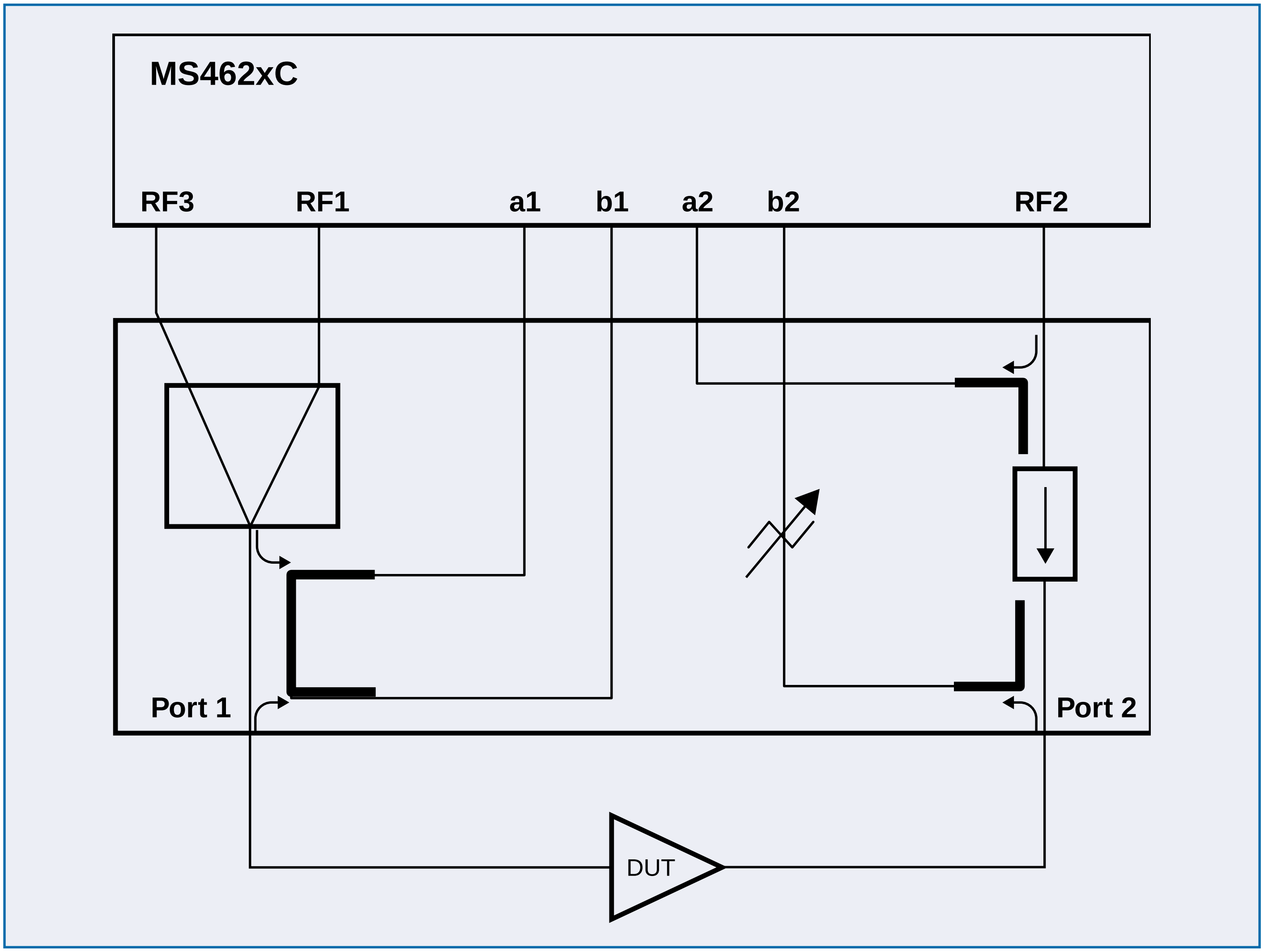

Figure 5. *A possible test set configuration that allows hot S_{22} measurements is shown here. A combiner is used for IMD measurements (combining RF1 and RF3 sources) but RF1 is turned off for the hot S_{22} measurement. RF3 provides the DUT stimulus while RF2 provides the probe signal. Similarly RF1 would provide the probe signal for a hot S_{11} or S_{21} measurement.*

Calibration and Uncertainty issues

If only hot S_{22} is of interest, a reflection-only port 2 calibration is usually done since nothing will generally be gained from a full 12 term cal: the DUTs are usually fairly unilateral, and there are some power budget and/or wiring complications involved in adding the forward measurements. In many circumstances, the measurement uncertainty will simply be that of a base reflection measurement under given port 2 conditions (see uncertainty software or MS462X data sheets). Keep in mind that the use of an external test set may alter these uncertainties slightly depending on corrected port parameters. This statement presumes that the measurement is kept out of compression and uncertainties will rise radically as the total received power exceeds the thresholds discussed previously. The statement also assumes that all signals involved are quasi-sinusoidal. If the DUT is generating significant output harmonics, the S_{22} definition itself is somewhat questionable and uncertainties cannot be readily defined. In the case of heavy DUT non-linearity, there may be additional spurs generated as well that can interfere with the measurement and any uncertainty analysis.

For the other hot S-parameters, generally a 12-term cal will be used and standard uncertainties apply as long as the linearity assumptions detailed previously hold. As with hot S_{22}, compression and spur effects can be large once the receiver is operated non-linearly. Hot K factor is entirely a computational entity so its uncertainties follow directly from the S-parameters. Sometimes out-of-band K factor is of interest (e.g., device tends to oscillate at low frequencies). In these cases, some caution is advised since the DUT matches are often very poor and K becomes computationally sensitive.

Often power amplifiers have very low output impedances so the issue of uncertainty related to a 50 ohm calibration may come up. This topic is implicitly covered in the S-parameter uncertainties directly since they are dependent on the magnitude of reflection coefficient being measured. In general, the relative uncertainties in reflection coefficient are lowest for higher $|S_{ii}|$.

Conclusions

This note has explored hot S-parameter and K-factor measurements, their value, their relationship to load-pull measurements, and many of the important measurement considerations. It is a relatively simple measurement that can characterize the match of an amplifier under real operating power levels and real system-level impedance environments and can help analyze overall system performance and behavior. Since it is a fixed impedance measurement, it will not be as helpful for model development or bare device matching but does require much less effort. The measurement considerations must primarily focus on power levels present in various parts of the setup.

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