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Application Note 58

Comparing Harmonic Load Pull Techniques With Regards to Power-Added Efficiency (PAE)

Abstract- **Three harmonic load pull techniques are compared for optimizing power-added efficiency. A Fujitsu FLL351ME device is used at 1.9 GHz along with Focus iCCMT, iPHT and iMPT electro-mechanical tuners. As long as the tuning range limitations of the triplexer solution are disregarded, the three methods of harmonic tuning: Triplexer method, Harmonic Rejection Tuner (PHT) method, Multi-Purpose Multi-Frequency method, give nearly-identical results.**

INTRODUCTION

As more demanding requirements emerge in wireless amplifier design, engineers have been forced to increase device output power while maintaining low current consumption. In achieving this goal, harmonic tuning has helped overcome efficiency requirements by reducing current consumption. Additionally, tuning harmonic impedances has proven to have a large effect on PAE, Pout, Gain and linearity when testing high power devices at compression. In this note we will compare the three most commonly used harmonic load pull methods: The triplexer method, Harmonic Rejection Tuner method and the Multi-Purpose tuner method. While different in many ways, these techniques should result in the maximum attainable PAE at the same phase of the impedances seen at the harmonic frequencies 2fo and 3fo, as long as they lay inside the tuning range of the corresponding technique.

When dealing with linear components, the power at the output of the device is proportional to the input power. Nonlinear devices deviate from this rule such that the gain response will tend to be reduced with increasing input power. This drop in gain is referred to as compression. *Figure 1* depicts the typical nonlinear region of an amplifier. It is standard practice for manufacturers to specify amplifier performance at P1dB, the gain or output power when operating at 1dB compression. Additionally, it is not uncommon to operate amplifiers well into compression making it important to have additional information at the 2dB or 3dB compression points. Once the amplifier has passed its 1dB compression point, Power-Added Efficiency increases drastically and harmonic tuning begins to have a large effect.

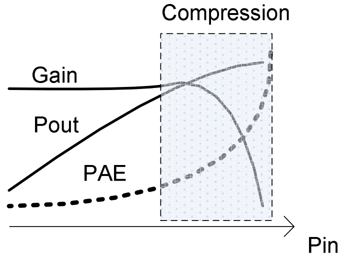


Figure 1: Compression region

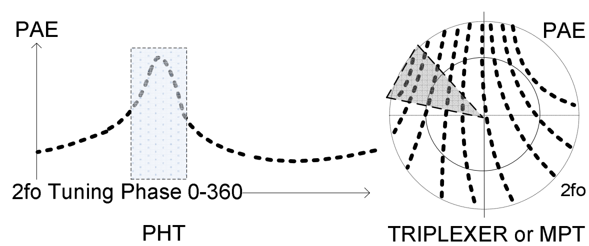


Figure 2: PAE VS 2Fo Phase, and PAE VS 2Fo Load

EFFECTS OF HARMONIC TUNING

Theoretically, optimum efficiency is obtained when the harmonic power generated from the amplifier is fully reflected back to the device at a given phase. Ideally all the harmonic power generated could be reused by being reflected; unfortunately this is not possible due to the non ideal (lossy) transition between the device and the tuner. In some cases even if the reflection created by the harmonic solution is very high, the designer needs to be able to not only vary phase but magnitude as well. The goal is to vary the harmonic impedances seen by the device while keeping the fundamental impedance constant. *Figure 2* demonstrates typical contours of PAE versus second harmonic phase and load conditions.

SIMPLIFIED HARMONIC LOAD PULL SETUP BLOCK DIAGRAMS

The following figures show block diagrams of the three harmonic tuning methods and their associated components.

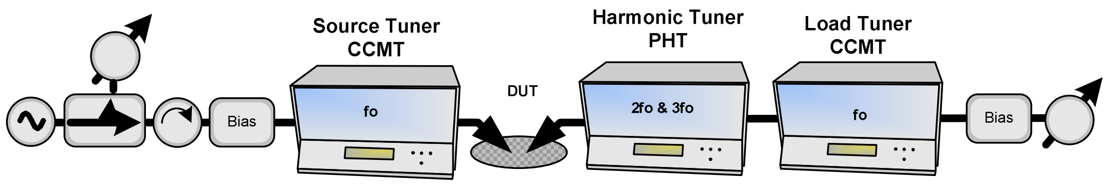


Figure 3: Harmonic Load Pull using PHT harmonic tuners

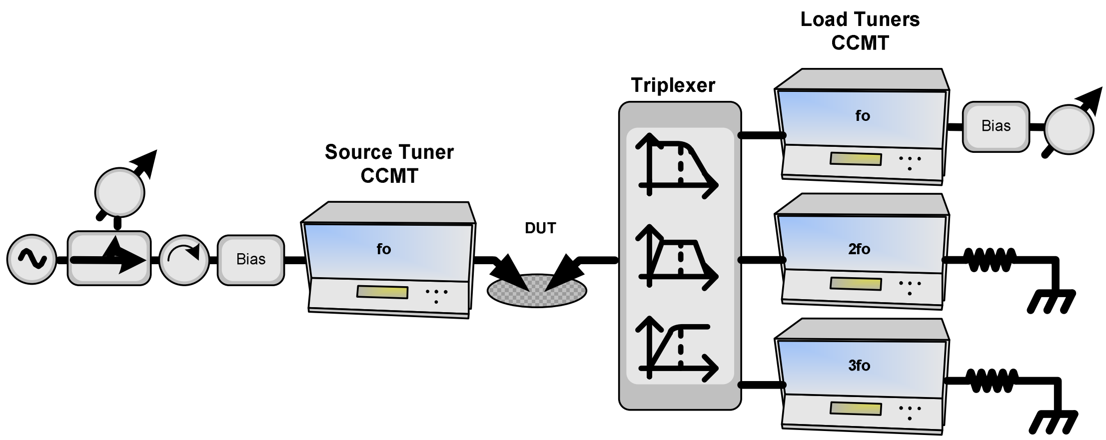


Figure 4: Harmonic Load Pull using CCMT fundamental tuners in conjunction with a Triplexer

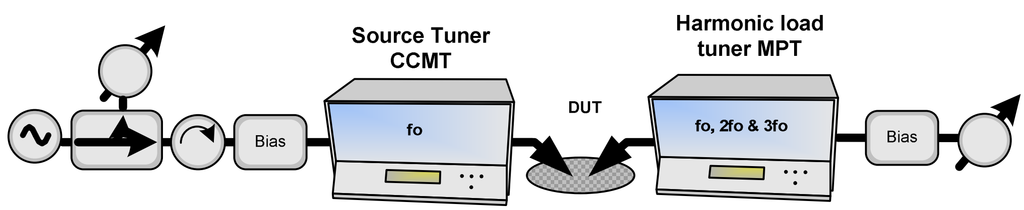


Figure 5: Harmonic Load Pull using a MPT multi-purpose multi-harmonic tuner

Tuning Method	*Description*
Harmonic Rejection Tuners Focus Microwaves PHT, Fig. 3	PHT's use replaceable harmonic resonator capsules which offer full 360 degree phase sweeping at harmonic frequencies 2fo and 3fo while maintaining maximum magnitude |Γ(2fo,3fo)|.
Triplexer and Focus Microwaves CCMT, Fig. 4	Based on filters (LPF, BPF, and HPF) which separate the fundamental and harmonic signals, the setup is composed of three fundamental tuners of different frequency coverage. The triplexer method allows control of both magnitude and phase seen by fo, 2fo and 3fo.
Multi-Purpose Tuner Focus Microwaves MPT, Fig. 5	MPT's use three independent wideband probes and allow control of the magnitude and phase of the reflection factor at all three harmonic frequencies (fo, 2fo and 3fo). It is the proper positioning of the three probes that allow independent tuning at the three harmonic frequencies.

Table 1: General description of harmonic tuning methods.

Tuning Method	*Main Advantages*	*Main Disadvantages*
Harmonic Rejection Tuners Focus Microwaves PHT*, Fig. 3	- Compatible with existing fundamental tuners - Very High tuning range at 2fo and 3fo - Very low insertion loss at fo - High power-handling capabilities (10X fundamental tuner)	- Allows only phase control of harmonic impedances 2fo and 3fo - Individual resonators are narrowband (8-10%) - Limited inherent tuning isolation (requires software "back-tuning" to reach 45dB)
Triplexer and Focus Microwaves CCMT*, Fig. 4	- Amplitude and Phase Control of the harmonic impedances 2fo and 3fo - Simple extension of existing setups - High tuning isolation >45dB between all frequencies	- Setup is cumbersome, unusable for on-wafer testing - Out-of-band reflections of low-loss triplexers cause spurious oscillations - Reduced tuning range at all frequencies due to insertion loss of the triplexer - Triplexers are narrowband and difficult to obtain
Multi-Purpose Tuner Focus Microwaves MPT*, Fig. 5	- Amplitude and Phase Control of the harmonic impedances 2fo and 3fo - Simple extension of existing setups (replaces fundamental tuner) - Ideal for on-wafer measurements - Wideband harmonic tuning (multi-octave) - Vibration-free on-wafer operation	- Requires powerful computer (minimum CPU 2GHz, 1GB RAM, 100GB HD)

Table 2: Advantages and disadvantages of harmonic tuning methods

***PHT:** Programmable Harmonic Tuner
***CCMT:** Computer Controller Microwave Tuner
***MPT:** Multi-Purpose Multi-Frequency Harmonic Tuner

EFFECTIVE TUNING RANGE

The three methods for harmonic tuning described in this application note result in varying Smith Chart coverage at fo, 2fo and 3fo.

The Harmonic Rejection Tuner (PHT) method offers phase control at harmonic frequencies 2fo and 3fo while setting the magnitude at the highest attainable level. An in-series fundamental tuner gives full magnitude and phase control at the fundamental frequency fo. Because the PHT is low-loss, high fundamental tuning is achievable. *Figure 6* demonstrates the coverage using this method.

The triplexer method gives full magnitude and phase control of all three harmonic frequencies fo, 2fo and 3fo. This results in complete Smith Chart coverage, limited by the losses inherent to the triplexer. *Figure 7* demonstrates the coverage using this method, and that the optimal impedance may fall outside the covered area due to the restricted coverage.

The MPT method gives full magnitude and phase control of all three harmonic frequencies fo, 2fo and 3fo. Nearly the entire Smith Chart is covered due to the millions of tuneable probe combinations, resulting in matching at all three frequencies. *Figure 8* demonstrates the coverage using this method.

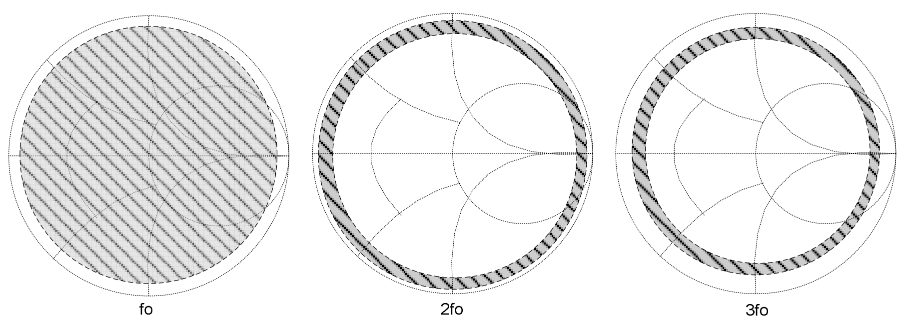


Figure 6: Tuning coverage at fo, 2fo and 3fo using a PHT and fundamental tuner

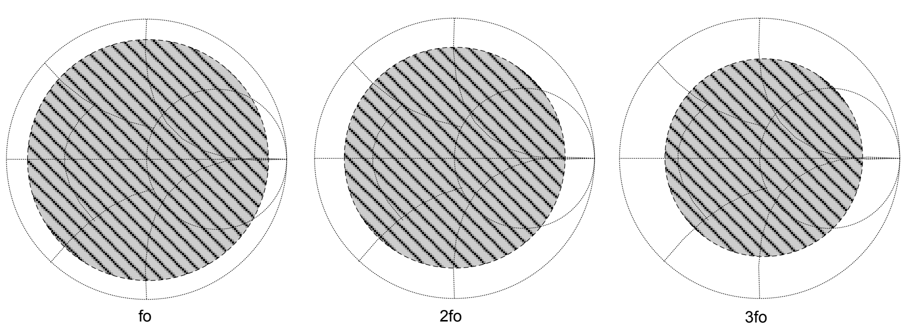


Figure 7: Tuning coverage at fo, 2fo and 3fo using the triplexer method

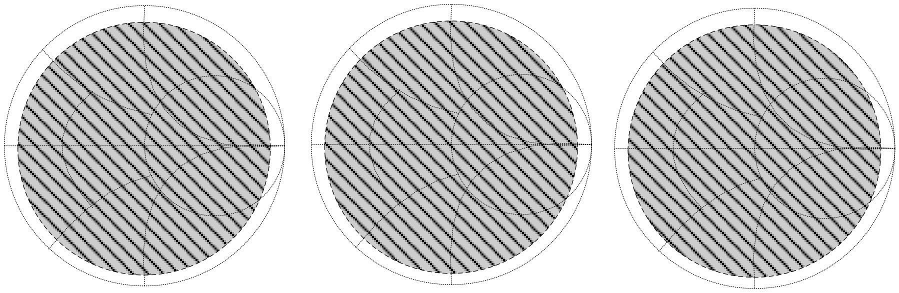


Figure 8: Tuning coverage at fo, 2fo and 3fo using the Multi Purpose Tuner

COMPARING MEASUREMENT DATA OF HARMONIC LOAD PULL METHODS

It is well known and accepted that optimal PAE and Pout conditions occur at |Γ(2fo,3fo)|=1 [1]. In order to determine the highest PAE attainable by each harmonic load pull method, we will concentrate on discovering the optimal phase at maximum |Γ| for 2fo. Presented below are the results of harmonic load optimization of a Fujitsu FLL351ME FET at fo=1.9GHz, keeping the fundamental load and source impedances constant, using the three harmonic load pull methods described in this application note. A comparison of the results can be found in *Table 3.*

The first harmonic load pull method explored is the Harmonic Rejection Tuner (PHT) method. A PHT is placed in-series between the fundamental tuner and the DUT as shown in *Figure 3.* As described, the PHT is able to sweep the phase of the second harmonic frequency while maintaining a maximum |Γ| at 2fo. A phase sweep at |Γ|= 0.95 resulted in an optimum phase of 157 degrees and PAE of 67.05%. The phase sweep results are shown in *Figure 9.*

The second harmonic load pull method explored is the triplexer method, as shown in *Figure 4*. Because of the typical insertion losses of the triplexer, the maximum tuning range achieved varied between |Γ(2fo)|=0.75 and |Γ(2fo)|=0.77 at the DUT reference plane. While hindered by limited |Γ|, we still observed a significant variation of PAE when tuning the harmonic impedances at 2fo. As shown in *Figure 10*, the maximum PAE of 64.41% was measured at a phase of 160 degrees. *Note: since the contours shown in Figure 10 do not close because of the limited tuning range, one may assume that an increased tuning range would result in higher values of PAE.*

The third harmonic load pull method explored is the Multi-Purpose Multi-Frequency MPT method, as shown in *Figure 5.* The MPT method has lower losses at harmonic frequencies 2fo and 3fo when compared to the triplexer method; the resulting tuning range is increased to |Γ(2fo)|=0.94. As anticipated, the contours are quite similar with an optimum phase at 159 degrees resulting in a PAE of 67.10%, as shown in *Figure 11*. In fact, the increased tuning range has allowed us to measure a higher PAE thereby proving the assumption that the optimal PAE condition occurs as |Γ(2fo)| approaches 1.

Tuning Method	*|Γ(2fo)|*	*Optimum Φ at 2f0 and PAE%*
Harmonic Rejection Tuners	- |Γ|=0.95	- Φ = 157 degrees - PAE=**67.05**
Triplexer	- |Γ|=0.77	- Φ = 160 degrees - PAE=**64.41**
Multi-Purpose Tuner	- |Γ|=0.94	- Φ = 159 degrees - PAE=**67.10**

Table 3: Results of harmonic optimization using three harmonic load pull methods.

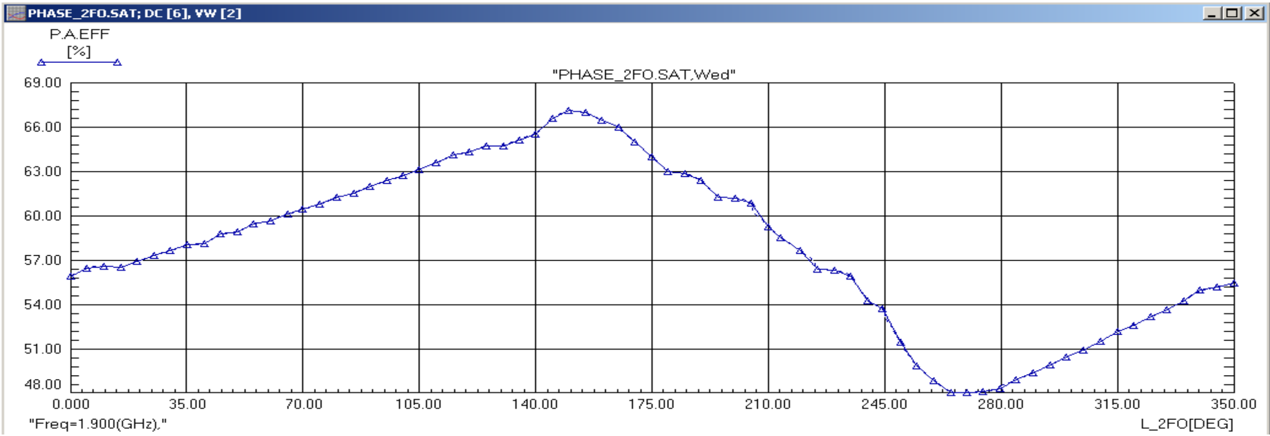
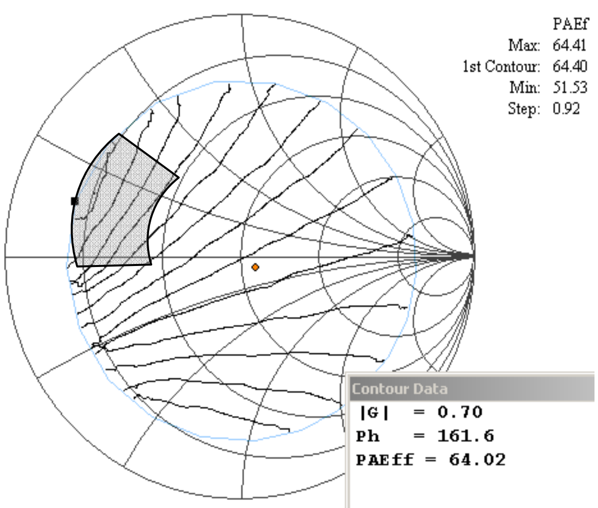


Figure 9: Variation of PAE vs 2fo phase sweep, using the harmonic rejection tuner.



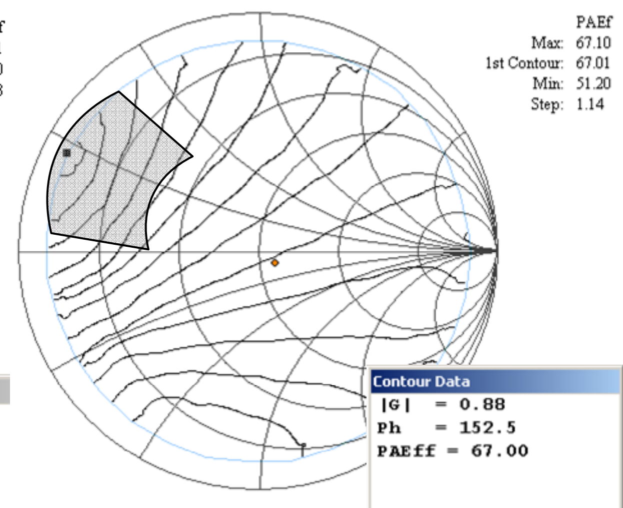


Figure 10: Variation of PAE vs 2fo load pull, using the triplexer method

Figure 11: Variation of PAE vs 2fo load pull, using the MPT

HARMONIC TUNING ISOLATION

An important factor of any load pull device characterization system is the accuracy at which we can control the impedance seen by the DUT at the fundamental frequency. If the impedance changes without our knowledge, or if we cannot keep it constant when varying harmonic impedances, the results obtained through our procedure will be invalid. Therefore, when regarding harmonic load pull systems, it is important to determine the isolation across frequencies.

The triplexer method of harmonic tuning relies on the isolation inherent within the isolator to remove the effects of one tuner on another. A triplexer typically has 45dB-60dB of isolation; therefore parasitic oscillations may be caused by high out-of-band reflections especially at low frequencies. The frequency response of a triplexer is shown in *Figure 12.*

The harmonic resonators within a Harmonic Rejection Tuner (PHT) offer inherent frequency isolation between 25dB-40dB. This frequency isolation limitation is the result of the sum of vectors generated by the reflection at fo, 2fo and 3fo and the residual reflection of the slabline. The fundamental frequency isolation can be software-corrected by repositioning the fundamental tuning probe, improving isolation to 40dB-60dB. The frequency response of a PHT is shown in *Figure 13.*

The Multi-Purpose Multi-Frequency Tuner (MPT) requires a redefinition of frequency isolation. In both other methods, the movement of one tuner affects all frequencies to some varying degree. The MPT repositions all three RF probes for every requested combination of fo, 2fo and 3fo, resulting in a perfect combination of all frequencies. There is no single movement within the MPT which will have adverse effects on frequency isolation, since it is the tuning software which will determine how to position the RF probes for each set of frequencies. *Figure 14* shows the repeatability at which the MPT probes are positioned for the requested impedances at fo, 2fo and 3fo.

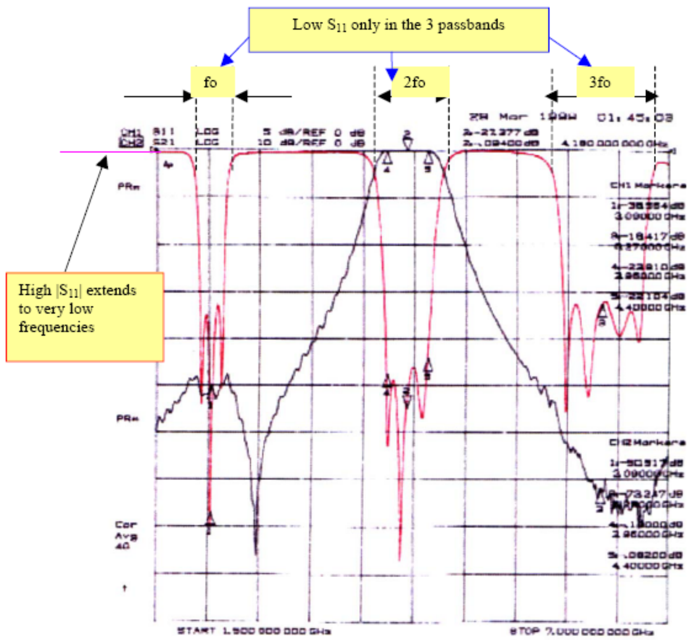


Figure 12: Frequency response of triplexer, $|S_{11}|$

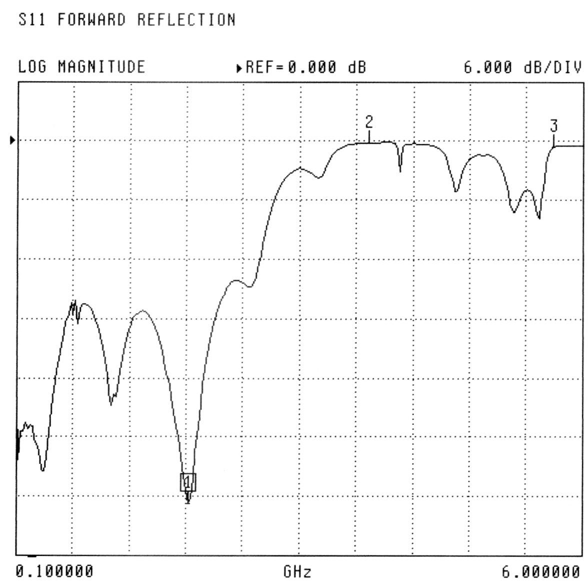


Figure 13: Frequency response of PHT, $|S_{11}|$

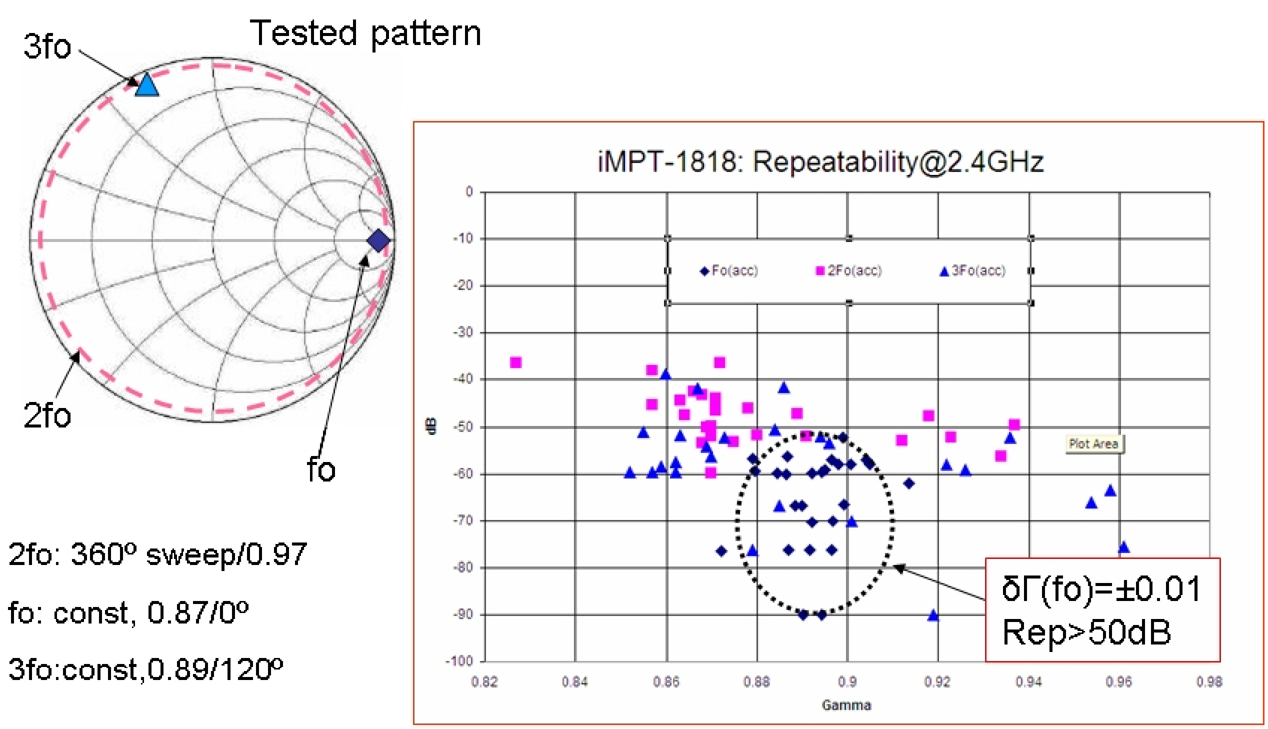


Figure 14: Repeatability of fo, 2fo and 3fo impedance positioning of the MPT

SPECIFYING TUNING RANGE FOR HARMONIC LOAD PULL SYSTEMS

It may be confusing, and misleading, to rely uniquely on the VSWR capabilities of a tuner. Tuner manufacturers provide VSWR specifications at the tuner reference plane only; the engineer should be concerned with the tuning range at his device. Depending on the interface between the tuner and the DUT, the VSWR seen at the device reference is reduced. *Figure 15* demonstrates this principle by showing a hypothetical fundamental tuner with 20:1 VSWR at the tuner reference plane being reduced to 14:1 VSWR at the DUT reference plane because of an interface (fixture) with 0.2dB insertion loss at fo, 0.4dB at 2fo and 0.6dB at 3fo.

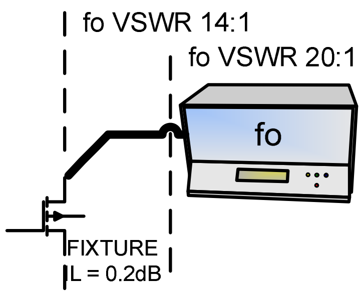


Figure 15: Tuning coverage at given reference planes, basic fundamental tuner.

Defining the maximum tuning range for a harmonic load pull solution becomes more complex: each frequency might have a different VSWR at the tuner reference plane; and the insertion loss at each frequency might differ for a given interface.

When considering a PHT solution, it is important to note that the losses associated with the harmonic tuner are only at the fundamental frequency, and not at 2Fo or 3Fo. The same fundamental tuner with 20:1 VSWR at the tuner reference is reduced to 14:1 VSWR at the harmonic tuner reference and further reduced to 10:1 VSWR at the DUT reference. 2fo and 3fo have VSWR of 40:1 and 35:1 respectively at the harmonic tuner reference, and are reduced to 15:1 and 9:1 at the DUT reference. A graphical representation of this scenario can be found in *Figure 16.*

A bi-Harmonic Tuner is similar in functionality to the PHT and iCCMT combined, but is contained within a single casing. Because there is no transition between fundamental and harmonic tuning, the losses associated with the harmonic tuner pathway are removed and 20:1 VSWR at fo is maintained. A graphical representation of this scenario can be found in *Figure 17.*

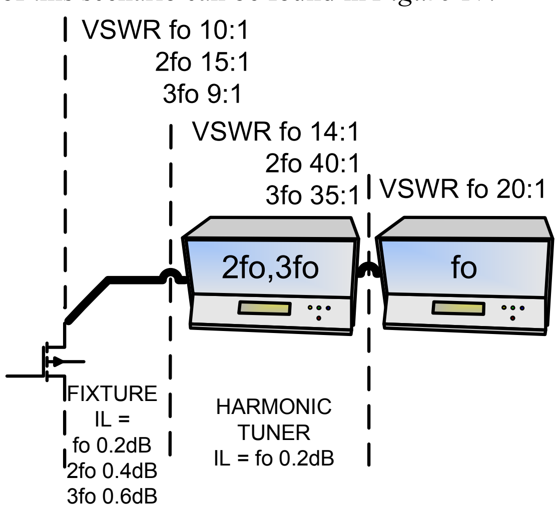


Figure 16: Tuning coverage at given reference planes, harmonic tuner and fundamental tuner

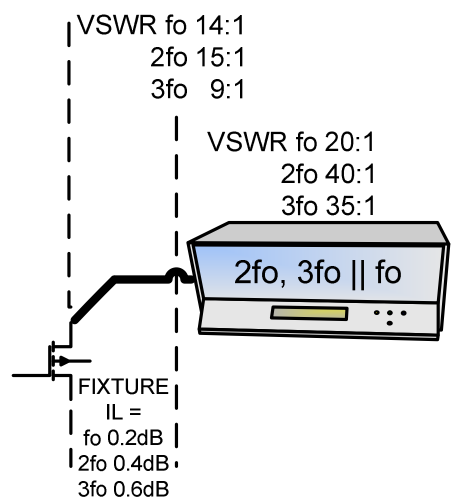


Figure 17: Tuning coverage at given reference planes, combo tuner

It is essential to consider the losses at fo, 2fo and 3fo associated with the triplexer solution. Because the triplexer has high insertion losses, the tuning range at the DUT is severely reduced, as demonstrated in *Figure 18*. The same fundamental tuner with 20:1 VSWR is reduced to 10:1 after passing through a triplexer and fixture. The harmonic frequencies suffer even more, since the losses of the triplexer are greater at higher frequencies; 2fo is reduced from 20:1 VSWR to 7.1:1, and 3fo is reduced from 20:1 to 5.4:1.

Focus' MPT is more difficult to characterize in terms of VSWR at each frequency, since it is the total combination of three RF probes which results in controlled impedances at fo, 2fo and 3fo. For the sake of continuity, it will be assumed that the MPT has a VSWR of 20:1 at all three frequencies at the tuner reference plane. Because there are no additional losses in the form of an additional tuner or triplexer, it is only the fixture which will reduce the VSWR at the DUT, as show in *Figure 19*.

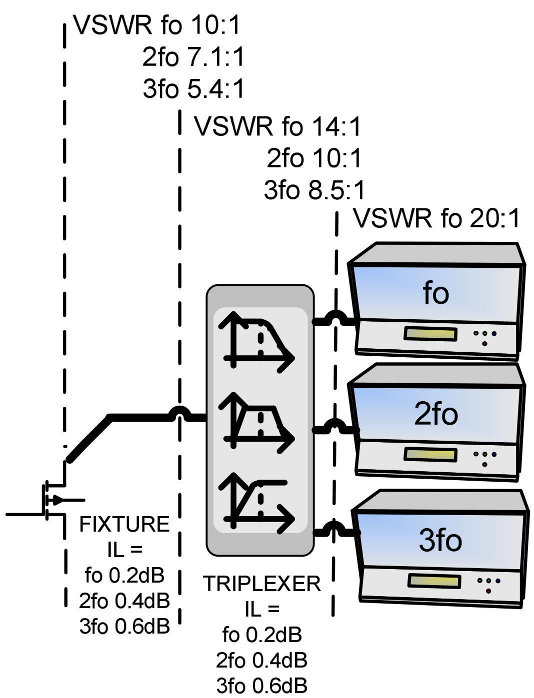


Figure 18: Tuning coverage at given reference planes, three fundamental tuners using a triplexer

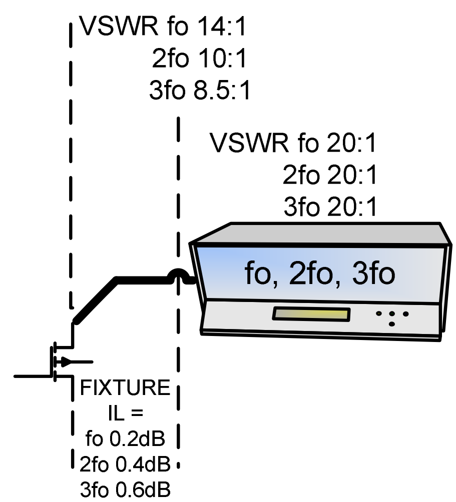


Figure 19: Tuning coverage at given reference planes, Multi Purpose Tuner

CONCLUSION

Each solution described in this application note has associated advantages and disadvantages; therefore it is very difficult to recommend one specific solution for all scenarios. There are engineers who require full Smith Chart coverage of the second and third harmonic frequencies; it is in their best interest to use either the MPT solution or the triplexer solution. There are engineers who might want an inexpensive upgrade to their existing fundamental load pull bench; they would benefit greatly from the PHT solution. Before an engineer can make an informed decision on which solution to choose; it is important to properly define the needs and budget available.

In order to obtain maximum functionality of a harmonic load pull system; full magnitude and phase adjustment, maximum tuning range on fo, 2fo and 3fo, and ease of integration for packaged and on-wafer measurements, Focus Microwaves recommends its MPT harmonic load pull solution.

LITERATURE

[1] J. Staudinger, "Multiharmonic Load Termination Effects on GaAs MESFET Power Amplifiers", Microwave Journal, April 1996, pages 60-77.