My View on the Evolution of Harmonic Load Pull

Christos Tsironis, Dr. Ing.
President, Focus Microwaves Inc.
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Let us commence with a simple, true, and still, for a long time ignored fact:

***"*Load Pull using wideband (also misrepresented as 'fundamental') tuners is nonsense*"*.**

It is nonsense because high power transistor operation creates harmonic signals and wideband tuners, while on one hand create the desired impedance at Fo, they also create uncontrollable impedances at the harmonic frequencies 2Fo, 3Fo etc. So, we have a systematic issue of non-controlled test environment, a situation which a conscious experimental scientist should discard. And, still, most laboratories, including ours, have used this technique for at least 15 years (1985-2000).

Early attempts to use **frequency discriminators (Di- or Tri-plexers)** inserted between the transistor and the wideband tuners were the only means to bypass the problem. The solution, though, is cumbersome, narrow-band, power limited and critical in terms of spurious, and has therefore been poorly accepted: FIGURE 1 shows a typical setup using wideband tuners and Triplexer. FIGURE 6a) shows the tuning range at harmonic frequencies of this setup; more information can be found in reference 1.

It was not before 1998 that I proposed a simple solution to the harmonic tuning problem (US patent 6,297,649) and Focus introduced, in 2000, the **Programmable Harmonic Rejection Tuner (PHT).** FIGURE 2 shows a load pull setup using an output harmonic rejection tuner. These tuners are inserted between a wideband tuner and the transistor; they use a set of remotely controlled open-stub **λ/4** resonators at the first and second harmonic frequencies (2Fo and 3Fo), which slide on top of the center conductor of the airline and can be tuned and back-tuned to have very small effect on Γ(Fo). 360° phase control at high Γ of the order of 0.98 can be reached, which is what is needed for optimizing PAE; PHT have two important characteristics: a) their resonators reflect all harmonic power back to the transistor and thus the wideband tuner now acts as a pure fundamental tuner and b) they are matched at low frequencies and do not cause spurious oscillations: FIGURE 3 shows a PHT and the internal mechanism for changing the resonators. FIGURE 4 shows load pull contours taken using a wideband tuner (the deformation due to uncontrolled harmonic impedance is obvious) and FIGURE 5 shows load pull contours measured after a PHT tuner has been inserted to keep the harmonic impedances constant. The tuning pattern generated by a PHT is shown in FIGURE 6b).

I dare to say that it is only since then that commonly measured and published high Γ load pull contours are true, i.e. contain data generated under controlled impedance test environment (see reference 3). Around 200 of such PHT tuners have been sold and more than 6,000 resonator kits for various frequency bands.

However, band limitations and the fact that the amplitude of Γ could not be controlled, led many customers to want more: <u>wideband tuning and full Γ control at the harmonic frequencies</u>.

Then, in 2004, came **the MPT (Multi Harmonic Tuner)** idea (US patent 7,135,941) and, in 2006 the first units on the market: The Multi-Purpose- Multi-Harmonic Tuner is, basically, a cascade of three wideband, single probe, tuners all covering the same bandwidth and integrated in a single housing; FIGURE 7 shows schematically the concept of wideband, two probe and three probe tuning. In the case of two probes a few millions of tuner settings are possible, allowing high Gamma tuning and two-harmonic frequency tuning, whereas in the case of three probes the billions of possible probe combination settings allow the fundamental (Γ(Fo)) and up to two harmonic reflection factors Γ(2Fo), Γ(3Fo) to be synthesized simultaneously and independently. To my knowledge there is only experimental evidence that the concept works for all frequencies and all impedances within the tuning range and the common frequency bandwidth of all probes, because we never observed the opposite. It is remarkable that a two-probe tuner, while it can cover the whole Smith chart at two frequencies, it can also tune three frequencies independently, but not over the entire Smith chart. In the two-probe tuner case there are areas, inside the |Γ| tuning range of the probes, which the harmonic tuning Γ(3Fo) cannot reach. Integrating the three independent probes inside a single housing (using the same airline) makes sense (FIGURE 9 shows a three probe (MPT) tuner covering 8 to 50GHz), because it eliminates adapter loss and residual reflections associated with an assembly of three cascaded separate wideband tuners, which is also known as a “cascaded tuner” solution. However the integrated (MPT) unit (a): must be calibrated in reasonable time, and (b): efficient tuning algorithms using the calibration data must be available. Calibrating each one of the billions of possible probe setting permutations would take years. Part of US patent 7,135,941 is a calibration method, which uses de-embedding of the initialized tuner, a concept which is not immediately obvious, and enables MPT calibrations in a matter of minutes. The second challenge, efficient tuning and high harmonic isolation, took several years of development and many iterations to overcome, as is often the case for original designs (US patents 8,629,742; 13/915,160 and 12,929,643 (pending)). Suffice to say that the first harmonic tuning operations, in 2004, lasted more than 30 minutes, whereas today they last less than 2 seconds.

High tuning accuracy and harmonic tuning isolation are extremely difficult tasks for a unit, which houses a cascade of three independent highly reflective probes cascaded in the same airline, as anybody versed with transmission lines and multiple reflections knows. Today, after almost 10 years of pioneering work at Focus, MPT provides excellent tuning accuracy of typically 50dB and similar harmonic tuning isolation (see FIGURE 12). The road has been bumpy: early prototypes showed un-acceptable performance and some researchers at Focus recommended abandoning the project as hopeless. But we persisted. Today’s excellent performance is the result of ongoing improvements in software algorithms and mechanical precision, based on more than 200 units developed by a long-standing coherent research team at Focus, manufactured, sold and used in the field. We learned that the software, mechanical and reliability problems increase exponentially when adding probes. Whereas there are maybe 10 issues with a single probe (CCMT) tuner, there can be 10^3 with a three probe MPT. The typical tuning pattern coverage created by a three-probe MPT is shown in FIGURE 6c).
We also tested the validity of the multi-probe harmonic tuning concept at four frequencies. FIGURE 10 shows the Quattro, a four probe tuner, which operates from 1.8 to 10GHz and can tune independently Fo to 4Fo, creating patterns as shown in FIGURE 11, where all points of the load pull pattern at Fo (2GHz) can be tuned (black dots), while Γ(2Fo) to Γ(4Fo) remain fixed (red, blue, green dots).

Then there is **Active Tuning**.

Active tuning means: "**injecting a signal into the output of the transistor, which is coherent (synchronized) with the input signal and can be amplitude and phase controlled, to emulate a virtual (active) load**"; for the transistor this is as if the signal were reflected by a real (passive) tuner.

The attractivity of the matter lies, beyond the fact that $|\Gamma|=1$ can be reached, since the added injected power overcomes the insertion loss of the fixture, also in that it is a stimulating R&D subject, uses standard commercially available RF components and avoids the requirement for high mechanical precision, associated with electro-mechanical (passive) tuners.

There are basically two types of active load pull systems: Open Loop and Closed Loop.

Closed Loop active system configurations (active load), whereby the outgoing signal is sampled, amplified, phase modulated and re-injected into the transistor output, were published since the mid 80ties and were introduced commercially by Focus in 1998 (ALPS, Active Load Pull System, see reference 7); these systems did not penetrate into the market, because of spurious and other side-effects (FIGURE 13 shows a harmonic ALPS operating at Fo from 0.8 to 3GHz using active load and harmonics up to 9GHz, filtering and amplifying the harmonic components generated by the transistor).

Open Loop active system configurations, whereby a second synchronized signal is injected into the transistor output, avoids many problems associated with closed loop systems, such as spurious oscillations. A remaining shortcoming of this solution is the requirement for high RF power of the output injected signal source or power amplifier, to overcome the mismatch between the low impedance of many power transistors ($\approx 1\Omega$) and the internal impedance of the injecting source (50Ω). At very high Γ the required injection power can reach 20 times the transistor output power. This is often technically impossible and/or financially unaffordable. This high power requirement can be alleviated using an impedance transformer (pre-matching tuner) between the transistor and the load, i.e. configuring a "**hybrid"** or **"active-passive"** tuning system: this reduces the requirement for injecting power roughly by a factor of 10, i.e. in a hybrid system the injection power requirement is less than 2 times the transistor output power.

As far as the tuning speed limitations of mechanical tuners are concerned, the hybrid system can be configured to have the mechanical tuner placed permanently in a position optimized for overall reduced injection power and have all remaining tuning done electronically and extremely fast, depending essentially on the response time of the receiver (we achieved sweeping and testing load pull patterns including 50 points measured in roughly 1.5 seconds or 35ms/point). Focus promotes the hybrid solution as **HAILP** (Hybrid Active Injection Load Pull) covered by US patent 8,497,689; and pending patent applications 61/914,035; 62/042,550. If an MPT is used in HAILP, as shown in FIGURE 14, independent passive harmonic tuning can be added using the harmonic tuning capability of the MPT and is an added bonus. FIGURE 15 shows the effect of hybrid active tuning on a specific transistor: The hybrid optimum Gamma is higher (close to $|\Gamma|=1$) and the maximum output power is almost 5dB higher. The hybrid system offers an additional benefit for verifying the overall system accuracy: at the same purely passive (pre-calibrated) and purely active impedance the system must generate the same output power and gain. This can easily be done by switching between purely passive and purely active tuning to the same load impedance. FIGURE 16 shows the effect of higher Gamma tuning on power added efficiency (PAE). Higher Gamma creates more PAE and a higher PAE swing.

Conclusion

Harmonic Load Pull, as most technologies, has come a long way since introducing automatic tuners around 1985. Progress has been possible through innovation, but not only: Many ideas are excellent but, with the present means, unfeasible. For instance, the MPT-tuning algorithm would not be possible in 1998, when the PHT appeared. The computing power was simply not available to the average engineer. We have many new ideas, but we dare not predict what comes next. We may as well be surprised by our and other’s innovation (see references 14, 15).

References

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4. Tsironis, “Triple Probe Automatic Slide Screw Load Pull Tuner and Method”, US Patent 7,135,941.
5. Tsironis, “Calibration and Tuning Using Compact Multi-Frequency Range Impedance Tuners”, US Patent 13/851,607 (to be issued).
6. Tsironis, “Harmonic Impedance Tuner with Four Wideband Probes and Method”, US Patent 8,405,475.
7. “System Performs Active Load Pull Measurements”, Microwaves &RF, November 1995, pp 102-108.
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9. Ferrero, “Active load or source impedance synthesis apparatus for measurement test set of microwave components and systems”, US patent 6,509,743.
10. Tasker et al. “Methods and apparatus for time-domain measurement with a high frequency circuit analyzer”, US patent 6,639,393.
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12. Tsironis, “Hybrid Split Signal Load Pull System”, US Provisional Application 61/914,035.
13. Tsironis, “High Speed Hybrid Active Load Pull”, US Provisional Application 62/042,550.
14. Tsironis, “Compact Impedance Tuner”, US Provisional Application 62/017,930.
15. Tsironis, “Compact Two Probe Impedance Tuner”, US Provisional Application 62/034,201.

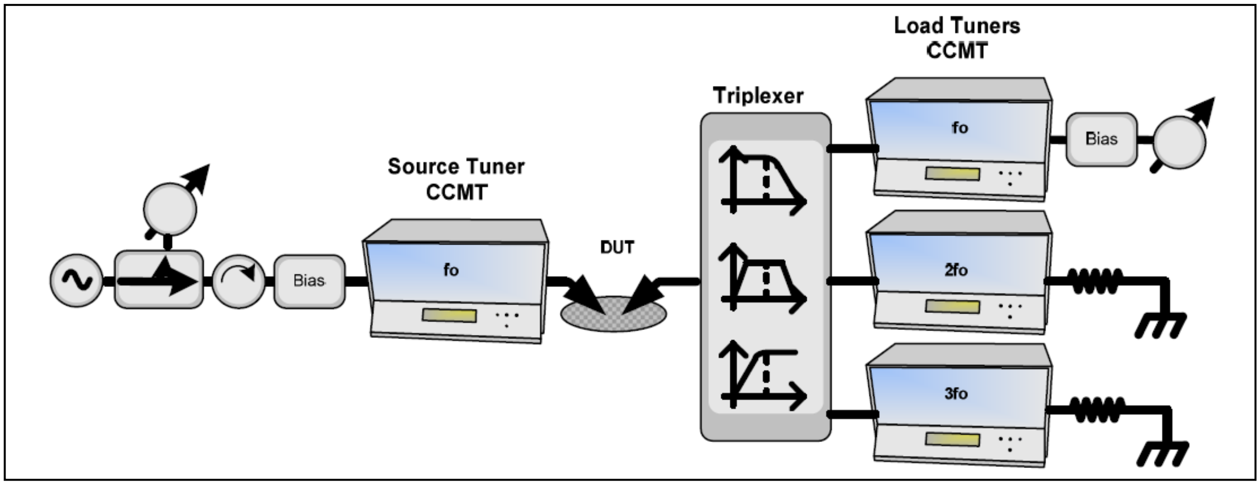


Figure 1

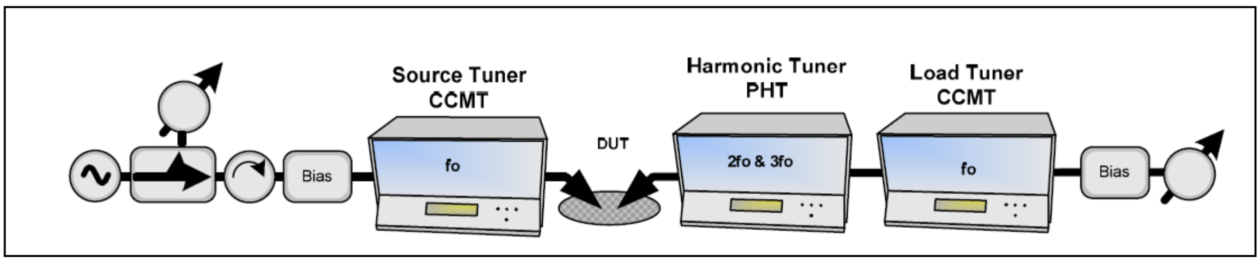


Figure 2

Figure 3

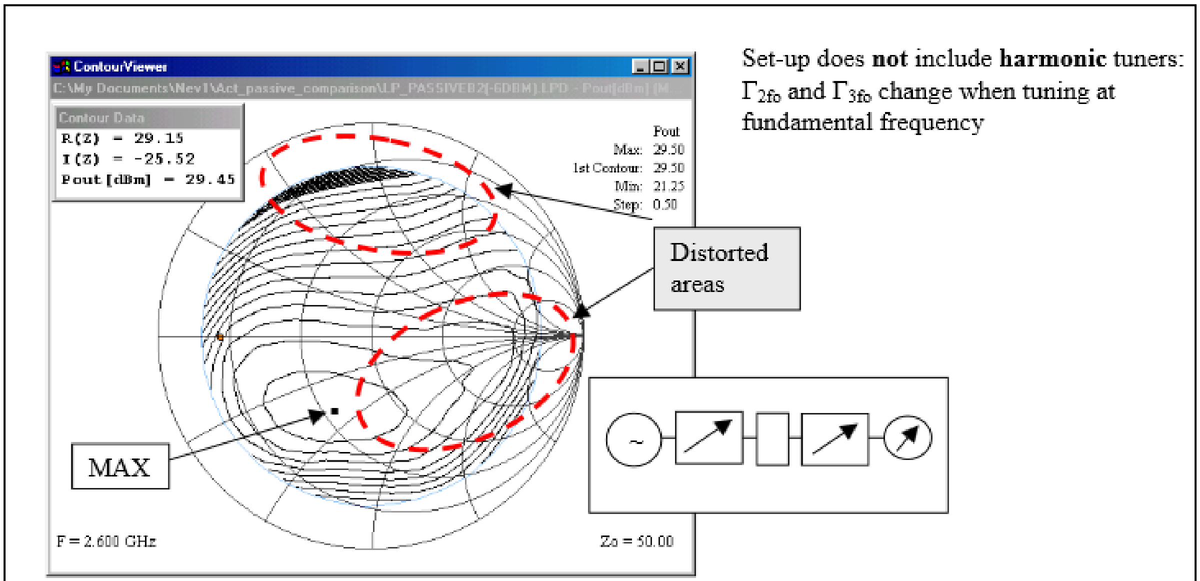


Figure 2: Load Pull contour of a power FET showing distortions on both sides of the maximum.

Figure 4

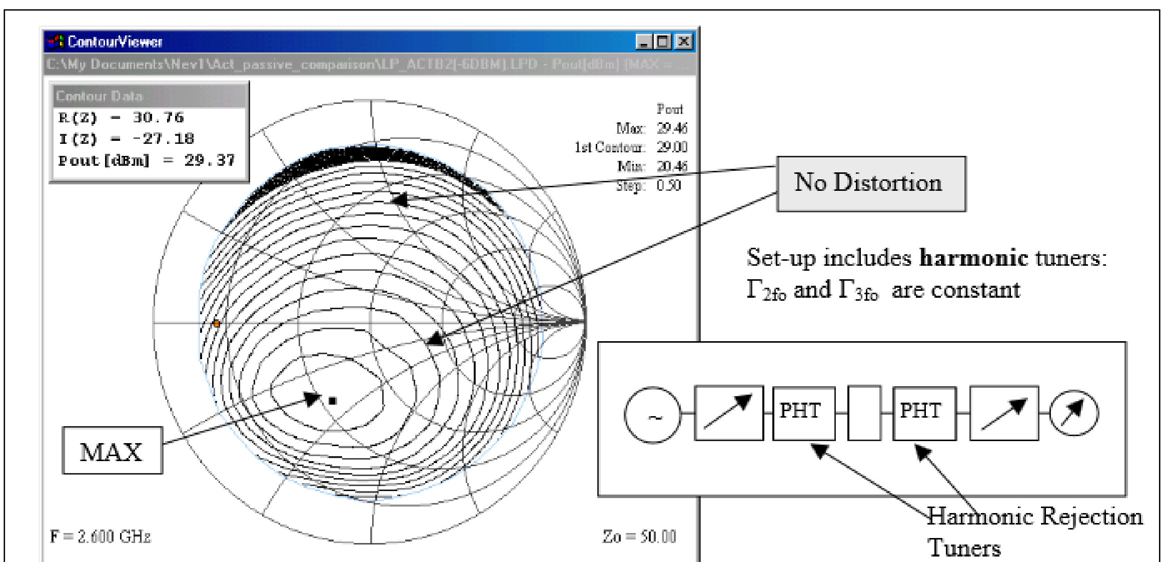
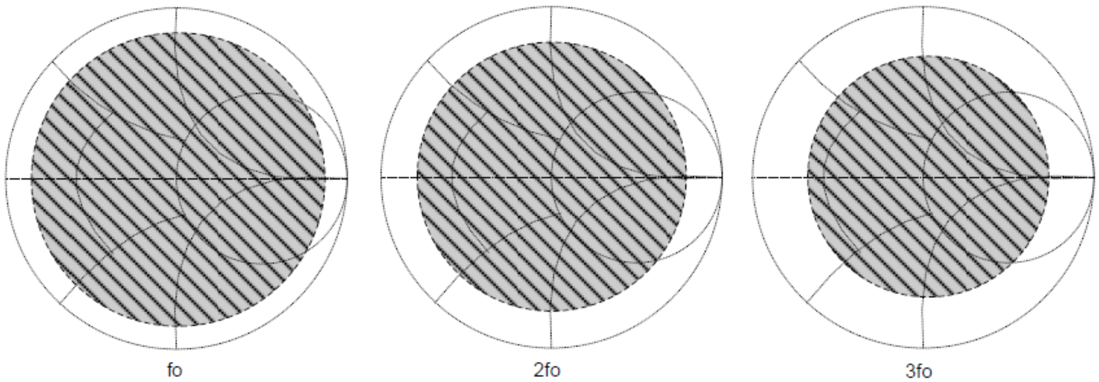
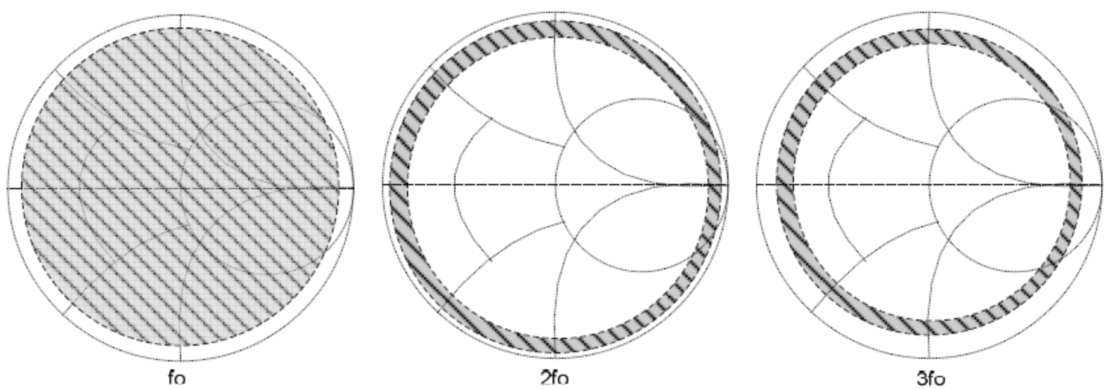


Figure 3: Load Pull contour of the same device under the same conditions as in figure 2, but measured using additional harmonic rejection tuners

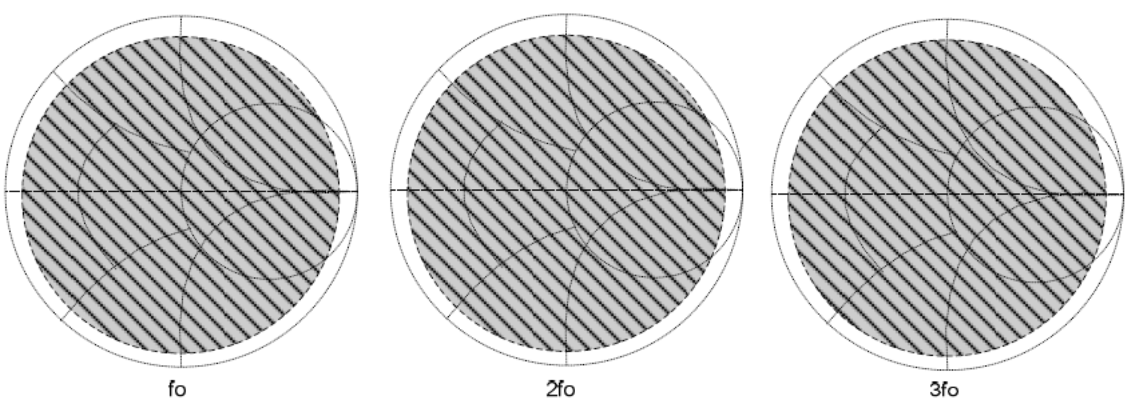
Figure 5



a)



b)



c)

Figure 6

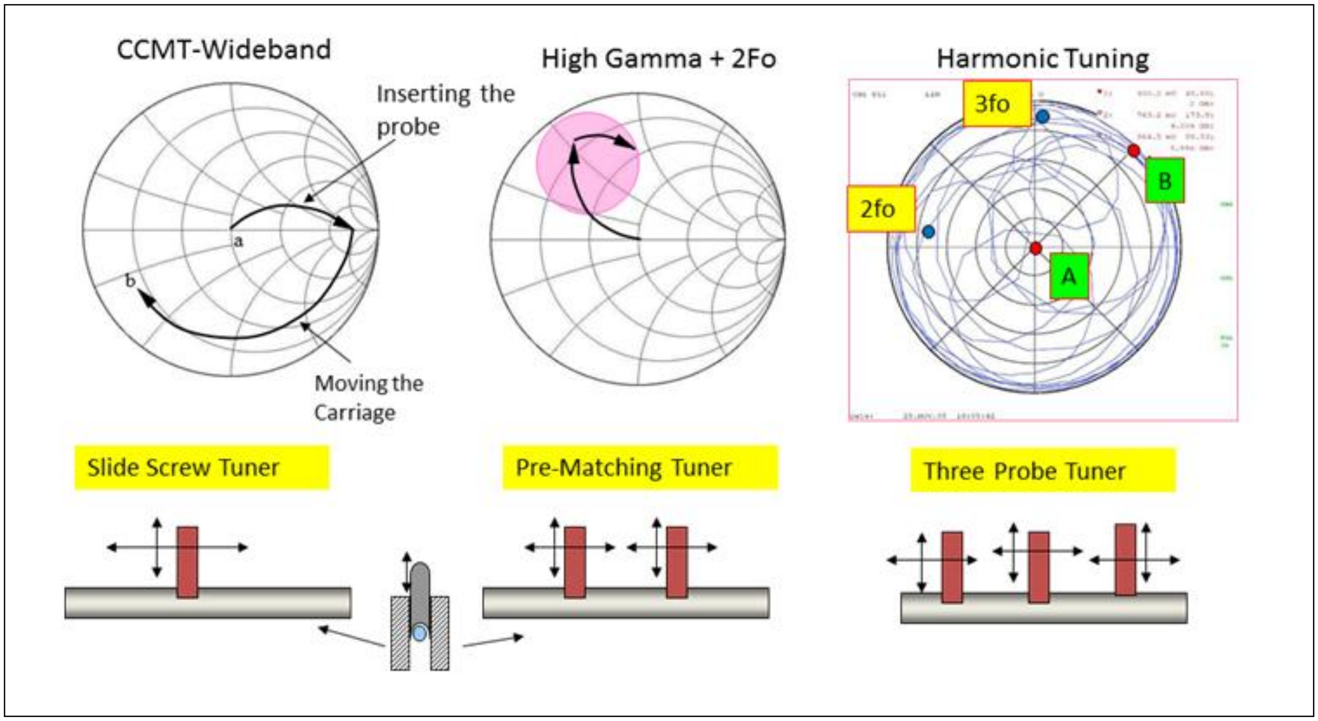


Figure 7

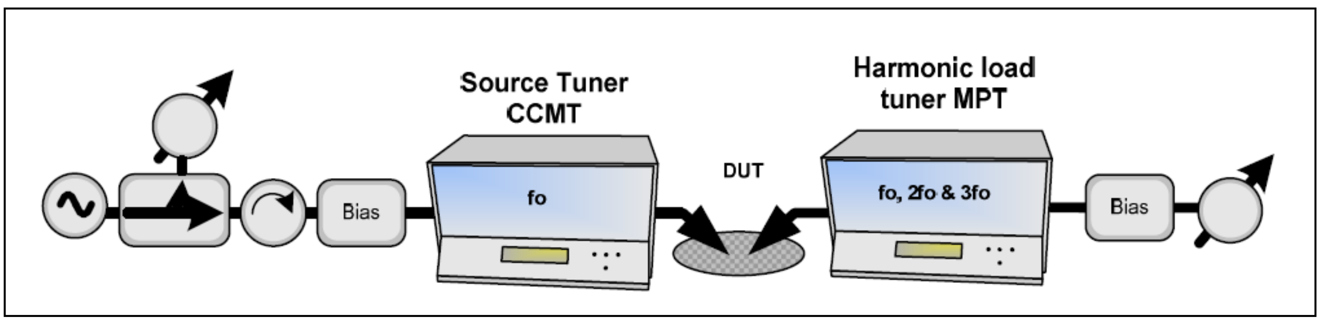


Figure 8


C1
C2
C3
FOCUS MICROWAVES
PWR
LNK
ACT
Step=3.18um
iTuner
MODEL : MPT- 5080
C.Xmax=19250, C1.Ymax=2250, C2.Ymax=2250,

Figure 9

Figure 10

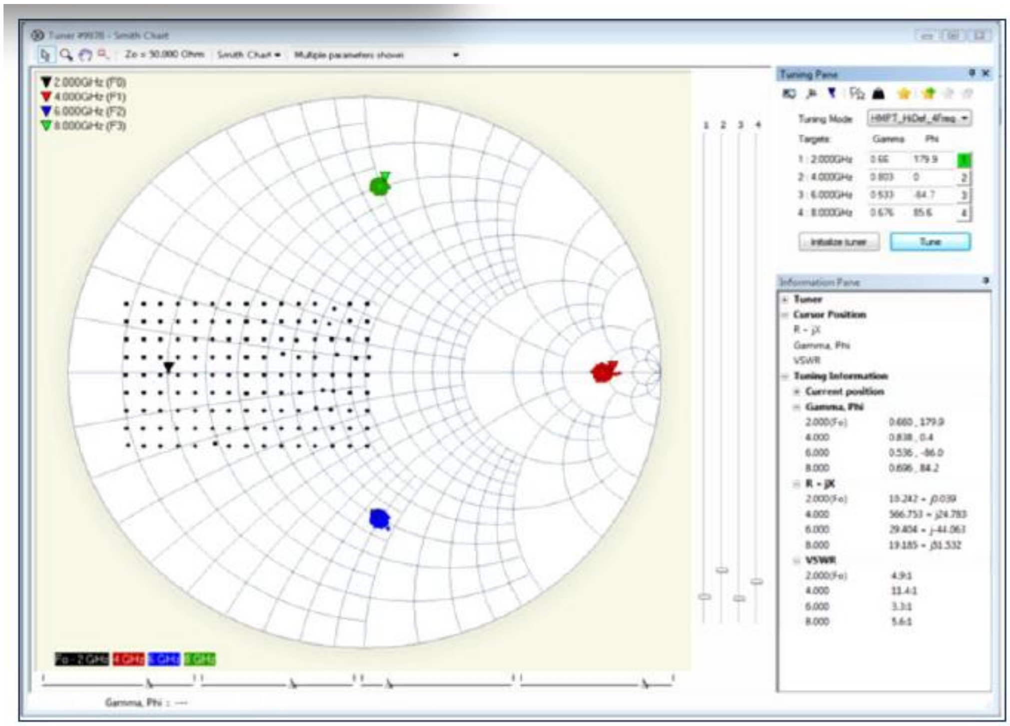


Figure 11

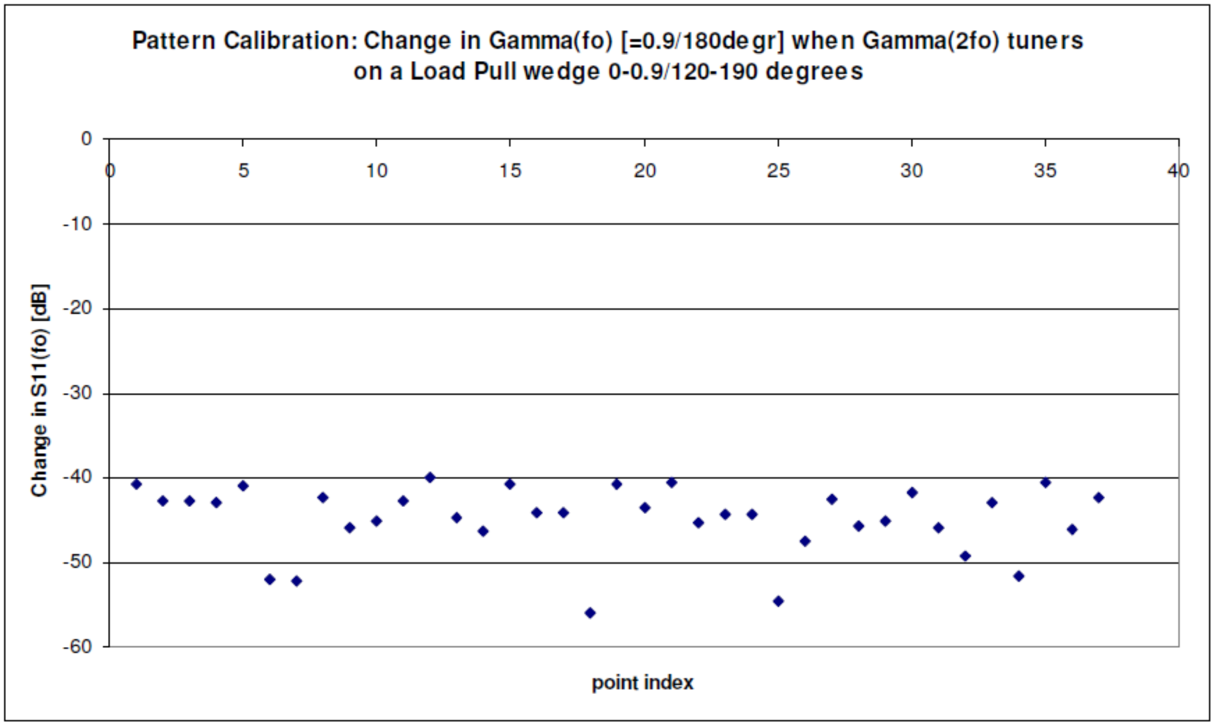


Figure 12

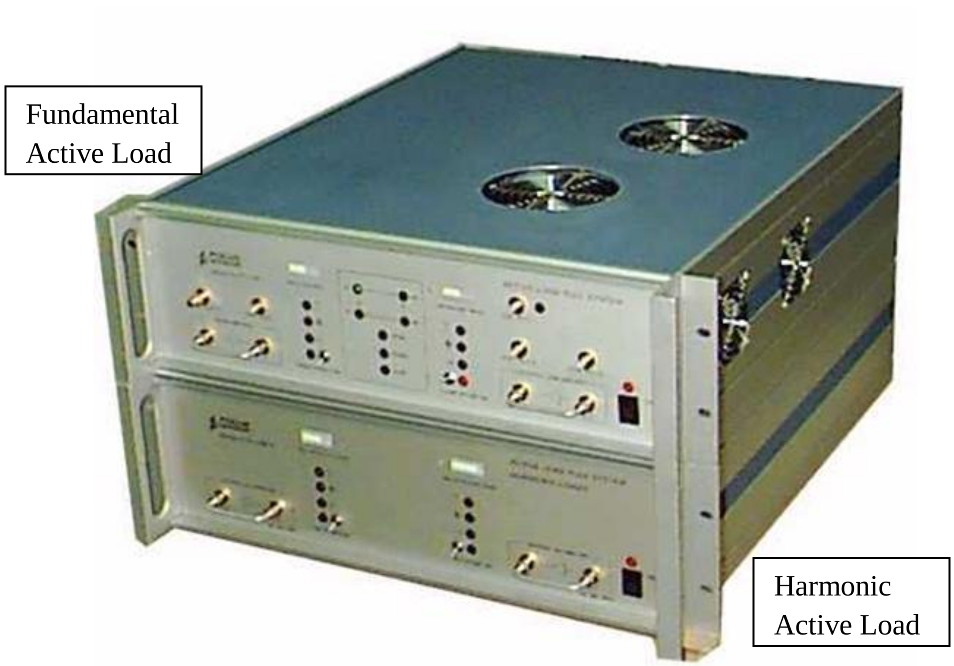


Figure 13

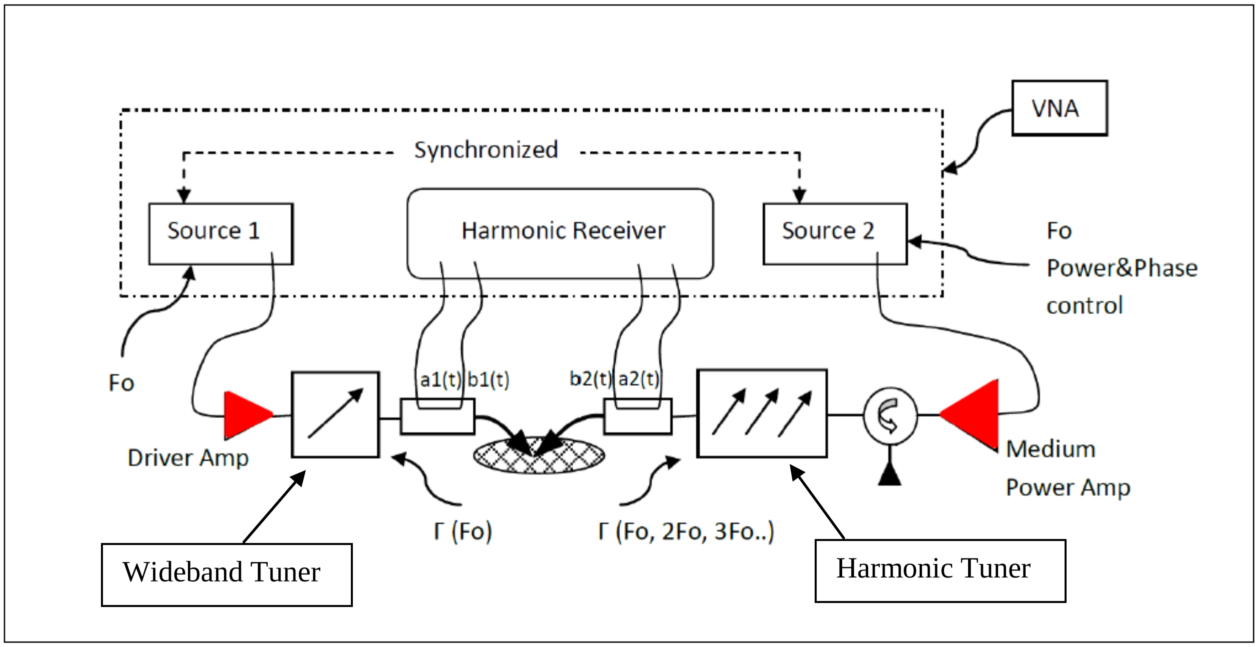


Figure 14

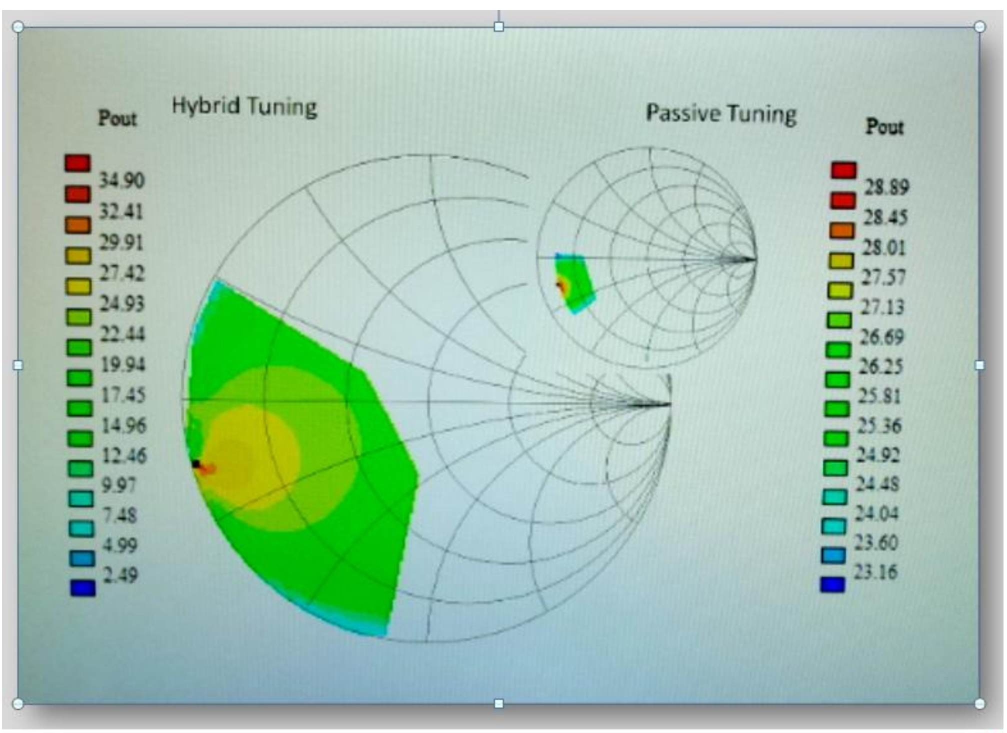


Figure 15

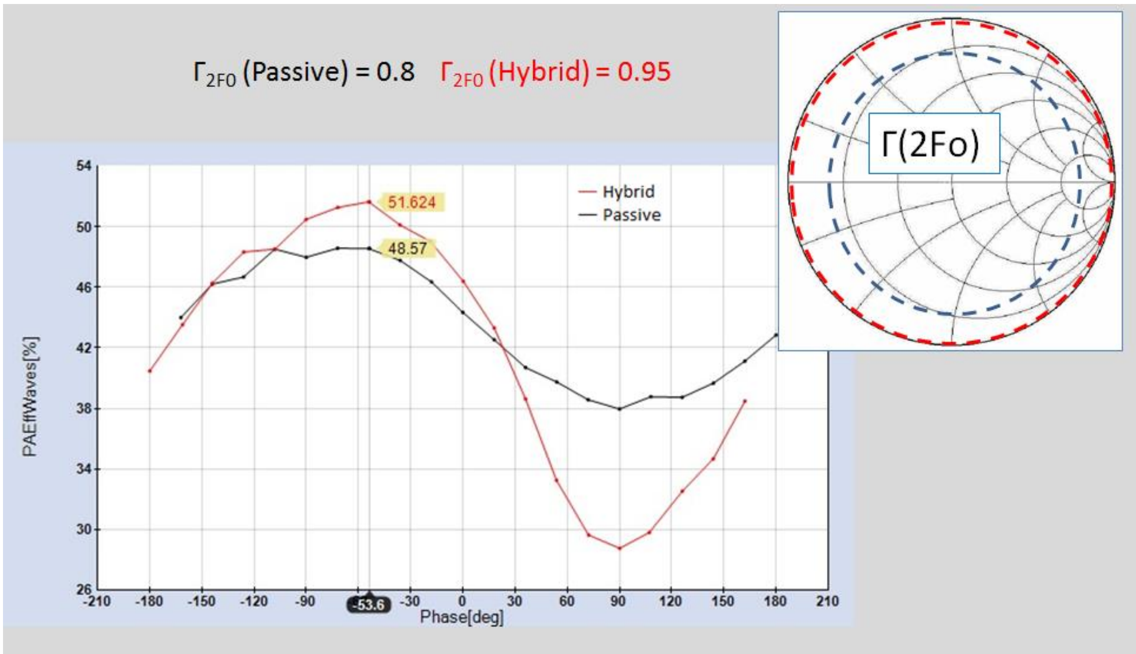

Γ2F0 (Passive) = 0.8
Γ2F0 (Hybrid) = 0.95
Γ(2Fo)
Hybrid
Passive
51.624
48.57
-53.6
PAEffWaves[%]
Phase[deg]
54
50
46
42
38
34
30
26
-210
-180
-150
-120
-90
-30
0
30
60
90
120
150
180
210

Figure 16