Harmonic Load and Source Pull Tuners For Millimeterwave Frequencies

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Abstract

A new Tuner type for "Harmonic Tuning" is presented. It generates high VSWR at 2fo and 3fo as required for harmonic load pull. The new tuners can be precalibrated and appropriate interpolation routines ensure high-resolution coverage of 360° of harmonic reflection phase. The harmonic tuners use a proprietary resonant cavity as a variable probe (1), which covers instantaneous bandwidth of ≈10% in the frequency range from 400 MHz to over 60 GHz. The new tuners can be built as "stand-alone two-harmonic frequency" units or they can be "combined with fundamental tuners". A new concept for tuner calibration allows us to fully characterize the harmonic and the "combo" tuners in about 4 to 8 minutes per frequency point (including fo, 2fo, 3fo). The new tuners permit to search and optimize the harmonic load and source impedance independently on fundamental tuning and provide test data for substantial design improvements in terms of Gain, PAE and Intermod.

(1) patent pending

Introduction

It is known since the early days of semiconductor amplifier design, using bipolar transistors, that short circuiting the second and third harmonic frequencies with the right phase at the output of the device can improve the device performance. This improvement concerns mostly the gain and in particular the efficiency (PAE = Power Added Efficiency) of the amplifier at hand.

Numerous simulations and experiments have confirmed this and there is unanimity about the following facts:

- Harmonic Tuning at 2fo is important when the device is in saturation
- The Amplitude of the Harmonic Reflection Factor shall be = 1
- Harmonic Tuning at 3fo has about 25% the effect of the second harmonic
- Harmonic Tuning effects depend on frequency for a given device
- PAE improves 10-15% from 2fo and another 1-3% from 3fo tuning at the Load.
- Linearity (Intermod) improves 3-8 dB from 2fo tuning at the Source.

These improvements, in addition to load and source impedances at fundamental and harmonic frequencies depend also strongly on

- Transistor Type
- Power Saturation Level
- Frequency
- Bias conditions

Because of all these dependencies it is obvious that, until the chase for the phantom "universal nonlinear transistor model" has succeeded, Harmonic Load Pull is the accepted experimental method for investigating and optimizing the Harmonic terminations of high power amplifier circuits.

Such a Harmonic Load Pull system has to provide

- High Reflection inside the test bandwidth
- High tuning resolution
- High power handling
- Low pass characteristics in order to avoid parasitic oscillations.

Harmonic Tuning Solutions, a critical Comparison

There are presently different methods possible for generating controllable harmonic loads and for being able to test devices under those conditions.
The table below is an attempt to summarize those methods and to provide a critical presentation of their advantages and shortcomings from a technical, practical and economical point of view:

Technique	Description	Pro	Contra	Supplier
Active Harmonic Load Pull (Active Load)	Feed fo into DUT, extract 2fo and 3fo, amplify and feed back into DUT output	$\|\Gamma\|=1$ at any Ref plane Fast for Single Tone Extendable to high frequencies	Phase Stability ?? Power Limits !! Slow for Two Tone and Modulated Signals High cost	FOCUS HP Divers Universi-ties
Active Load Pull (split signal, Takayama)	Feed fo into DUT and fo, 2fo, 3fo via split path. Combine at output and inject into DUT output	Same as above	Complex Calibrations Saturation plots a problem (new Cal) Power Limits Slow for two tones High cost	Divers Universi-Ties
Harmonic Fixture	Use $\lambda/4$ stubs at various positions	Low Cost Easy to employ	Crude method Very long No corrections	FOCUS and all others..
Wideband Tuners and Multiplexers (MUX)	Frequency discriminator for fo, 2fo, 3fo with multiple tuners	Independent tuning of harmonics High power	Low $\|\Gamma\|$ (MUX loss) Off band reflections and DUT parasitic oscillations Limited BW Complex MUX Cost?	Maury FOCUS
MUX + Tuners + Active Modules (AM)	As above but AM amplifies signal to compensate for MUX losses	As above $\|\Gamma\| = 1$	Complex MUX DUT and AM parasitic oscillations (off band) Power and limited frequency range Cost?	Maury FOCUS

Technique	Description	Pro	Contra	Supplier
Multifrequency – Multistate Electronic Tuners	Selection among >0.5 million diode states to simultaneously correspond to required Z @ fo, 2fo, 3fo…	High speed (once calibrated) Acceptable $\|\Gamma\|$	Very lengthy Cal Power limitations Limited isolation (not exact tuned points) Limited frequency range	ATN
Manual Harmonic Tuners (model MHMT)	≈ Independent tuning at fo, 2fo, 3fo using harmonic heads	Low cost High $\|\Gamma\|$ High Power Versatile	Limited isolation Iterative process Z(fo) needs re-adjustment when Z(2fo) varies	FOCUS
Programmable Harmonic Tuners (model PHT)	Electromechanical version of the above with Calibration and Impedance back-tuning	High $\|\Gamma\|$ (>0.9) High Power No parasitic oscillations Independent harmonic tuning Extend existing L/P systems Compatible with transformers and transforming probes	Γmax @fo lower by 0.2-0.4dB than fundamental tuners (can be compensated with Active Module)	FOCUS
Programmable Fundamental and Harmonic Tuners (model CCMT-2H)	As above but combine Harmonic and Fundamental tuning in a single housing	As above … Plus… Compact Lower loss and higher Γ at fo	Γmax @fo lower by ≈0.1dB than fundamental tuner	FOCUS

Table I: Description and Comparison of Harmonic Load Pull Techniques

Table I shows that, taken into account factors like

- Performance,
- Versatility,
- Simplicity,
- Compatibility with existing hardware,
- Cost and
- Availability

The **programmable harmonic tuners** are, at this time, the best overall solution for harmonic load pull.

Characteristics and Advantages of Harmonic Tuners

The programmable harmonic tuners (PHT, CCMT-2H) use the same proven and dependable electro-mechanical components of the wideband CCMT (Computer Controlled Microwave Tuner) of which nearly 400 units have been put in operation in the last 10 years. The selective high reflection at the harmonic frequencies is generated by harmonic heads made using a proprietary FOCUS design [1] (figures 1, 2).

The probes themselves can be manufactured for harmonic frequencies between 400 MHz and over 60 GHz, limited actually only by customer awareness. The upper frequency is defined at this time only by the use of 1.9 mm (V) connectors. Extension to over 100 GHz using 1 mm connectors is envisaged. The units presented here cover harmonic frequencies from 4 to 44 GHz (figures 1,2).

Because of the nature of the harmonic probes it is possible to inject high CW fundamental power without damage for two reasons:

- The harmonic heads present very low reflection at fo
- There are no active semiconductor devices (amplifiers, diodes) used in the setup, except the DUT.

The harmonic tuners may include one or two independent resonant heads. In calibration each cavity moves a number of steps N(2fo) and N(3fo) to cover 360° at the corresponding frequency and the "S"-parameters of the tuner are measured using a network analyzer simultaneously at fo, 2fo and 3fo and saved in binary harmonic calibration files. For higher accuracy the user can select the number of calibration points, but the software interpolates accurately between calibrated points.

An appropriate calibration algorithm allows us to construct the combined {2fo x 3fo} tuner matrix by measuring only N(2fo)+N(3fo) instead of N(2fo)*N(3fo) points. In the case of 20 steps this makes 40 points instead of 400, a time saving of 90%. This way we can calibrate the harmonic tuners in a few (5 to 8) minutes, depending on the frequency. The tuner calibration data are used to interpolate between calibrated points with a high accuracy (≈40dB, depending on the frequency).

Using the calibration data the measurement software can synthesize any harmonic tuning phase from 0° to 360°. It can sweep the harmonic phase and generate "Output (Harmonic Phase)" plots and it can search for a maximum of any preselected parameter, such as Pout, Gain, PAE, Intermod, ACPR, and P1dB as a function of the harmonic phase (figure 4).

During all harmonic-tuning operations the fundamental and the remaining harmonic impedance are automatically corrected to their original values. This makes the system extremely versatile.

An Affordable Millimeterwave Harmonic Load Pull Setup

The millimeterwave harmonic load pull setup proposed here (figure 5) could be built using a network analyzer, a test fixture (or probe station) and two programmable harmonic tuners model 4006-2H or 3002-2H. These tuners include fundamental heads from 6 to 40 GHz and 2 to 30 GHz and harmonic heads at preselected frequencies from 4 to 33 and 12 to 44 GHz correspondingly (figures 1, 2, 3). The network analyzer serves as signal source and fast receiver and for DC biasing the DUT. For Intermod tests a second synthesizer is required and the two signals are combined at port 1 of the analyzer and injected into a spectrum analyzer via an output directional coupler. The setup is calibrated using a power meter connected to port 1 of the analyzer for absolute power reference.

The system is controlled by an IBM-PC® equipped with a GPIB interface and a CC-3 tuner controller, who can position and initialize two tuners with three axes each. The tuners can be calibrated "in-situ" at fo but must be replaced by a Through line for harmonic calibrations at 2fo (or 3fo).

Some results of measurements made using such a setup are shown in figure 4.

Conclusions

Programmable millimeterwave "Harmonic" and Fundamental-Harmonic "Combo" Tuners have been presented for the first time. Various models cover 0.4 to over 60 GHz of which units from 2 to 44 GHz have been described here. An affordable Millimeter-wave Harmonic Load Pull setup has been described. It can be built using only two harmonic tuners and one network analyzer as signal source and fast receiver.

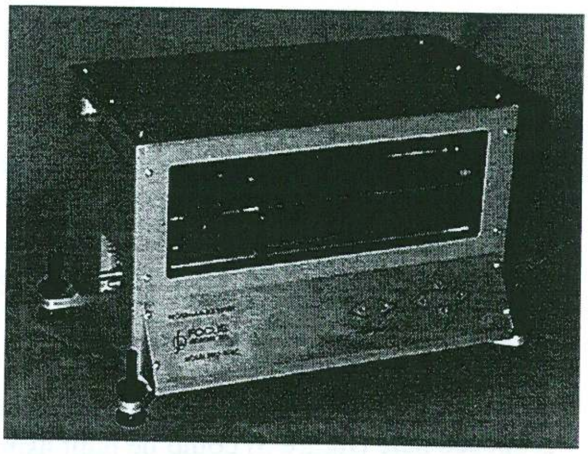

Figure 1: Programmable Harmonic Tuner
Model 3002-2H
for fo=2-30 GHz, 2fo=4-33 GHz.

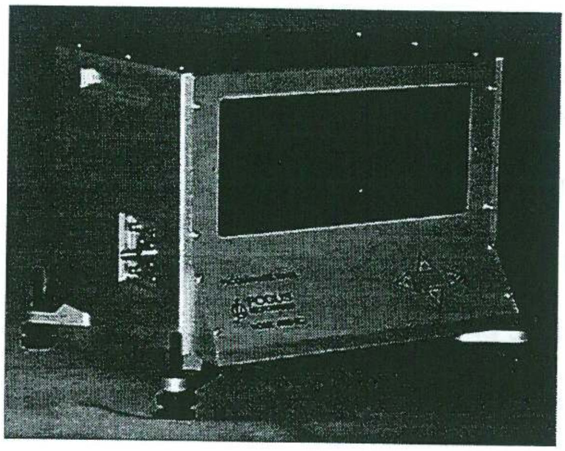

Figure 2: Programmable Harmonic
Tuner Model 4006-2H
For fo=6-40 GHz, 2fo=12-44 GHz

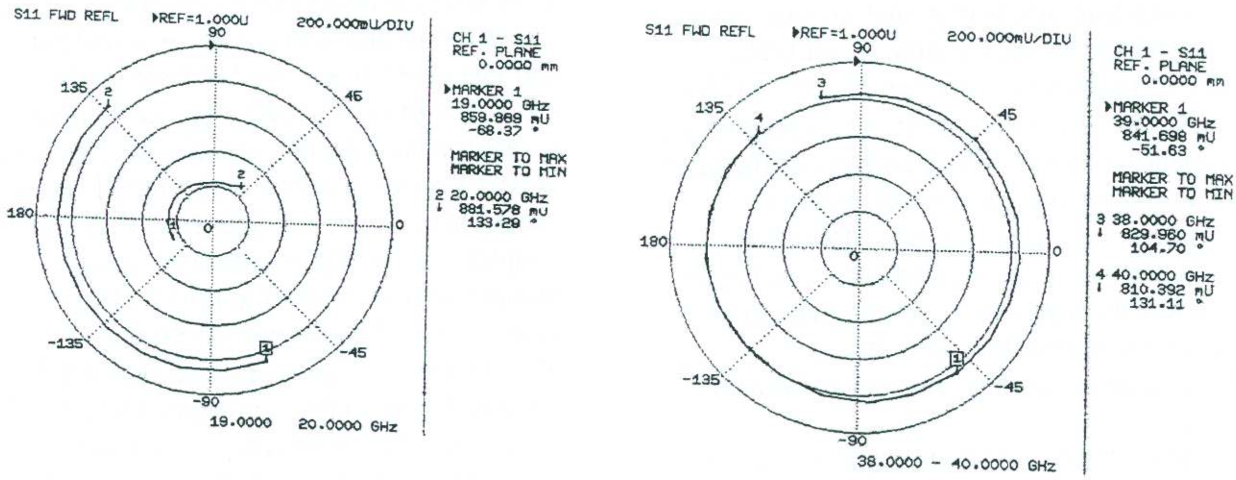

Figure 3: Γmin/Γmax of 3002-2H from 19 to 20 GHz and Γmax from 38 to 40 GHz

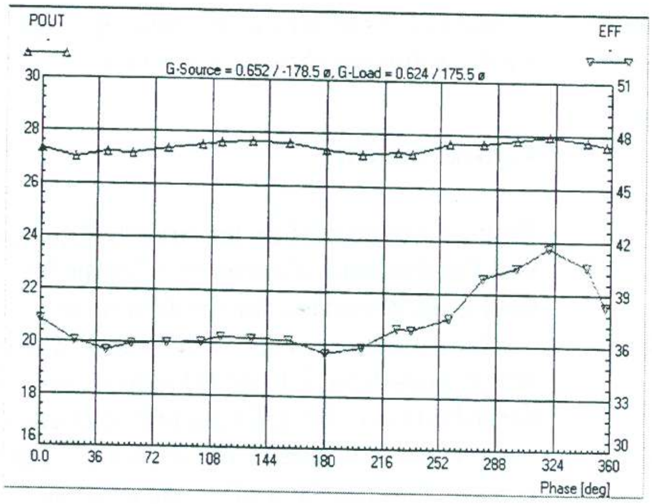

Figure 4: PAE and Pout as a function of
the Phase of Second Harmonic
at 2fo=38 GHz.

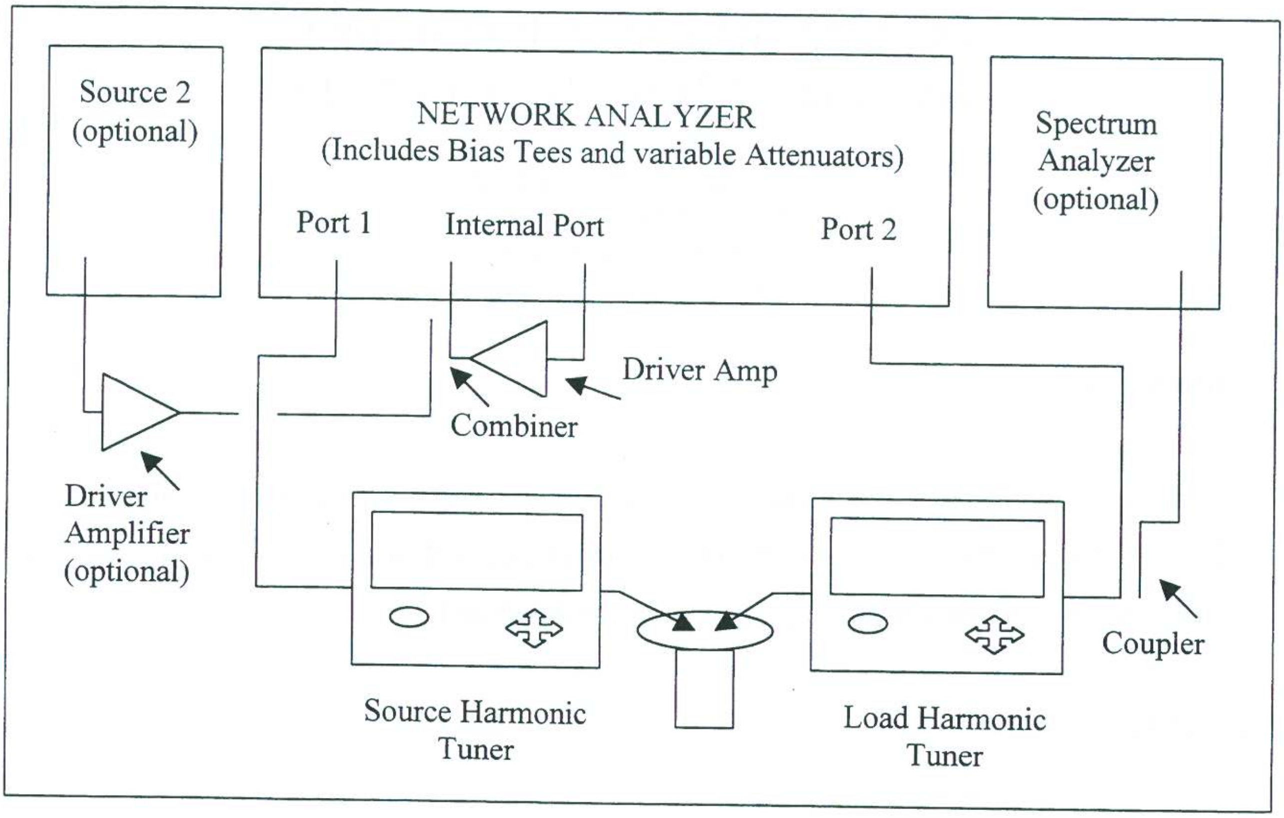

Figure 5: Millimeterwave harmonic Load Pull System. The Combiner and the other optional components must be included in order to measure Intermod or ACPR.

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The experimental load pull setup has been tested using a Wiltron 37000 network analyzer supplied temporarily for this purpose by Anritsu-Wiltron Canada.