A Comparison of Harmonic Tuning Methods for Load Pull Systems

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Editor's Note: *For advances in updated harmonic tuning techniques since this paper was written, please refer to 5C-081 "Cascading Tuners For High-VSWR and harmonic Load Pull"*

Abstract: *There are three methods of harmonic tuning that have been offered commercially for load pull systems with passive automated tuners. Each method has strengths and weaknesses. This paper will examine the three methods and compare the relative advantages and disadvantages of each.*

Introduction

Load pull is widely used to characterize devices for power amplifier applications because it accurately shows what the device will do under actual operating conditions. The measurement is done with bias, RF power, and impedance conditions which are applied in the final application; so there are no data extrapolation or model validity issue.

Fundamental load pull consists of tuning the source and load impedances at the fundamental frequency of operation (F0). The fundamental impedances are the most important by far, and that is why fundamental load pull, its accuracy and repeatability, are most critical.

Harmonic load pull consists of tuning the source and/or load impedance at a harmonic frequency (F2 or F3) while measuring device performance at F0. Harmonic load pull can especially affect efficiency and linearity. The effect of harmonic tuning depends strongly on the fundamental load pull tuning as well as the device type, operating point, drive power, and other factors.

An example of harmonic tuning on power added efficiency is shown in Figure 1 (Eff). The efficiency is measured at F0 while the load impedance at F2 is varied. The result is a 16% change in efficiency, caused by changing only the harmonic load impedance, keeping the fundamental impedance constant.

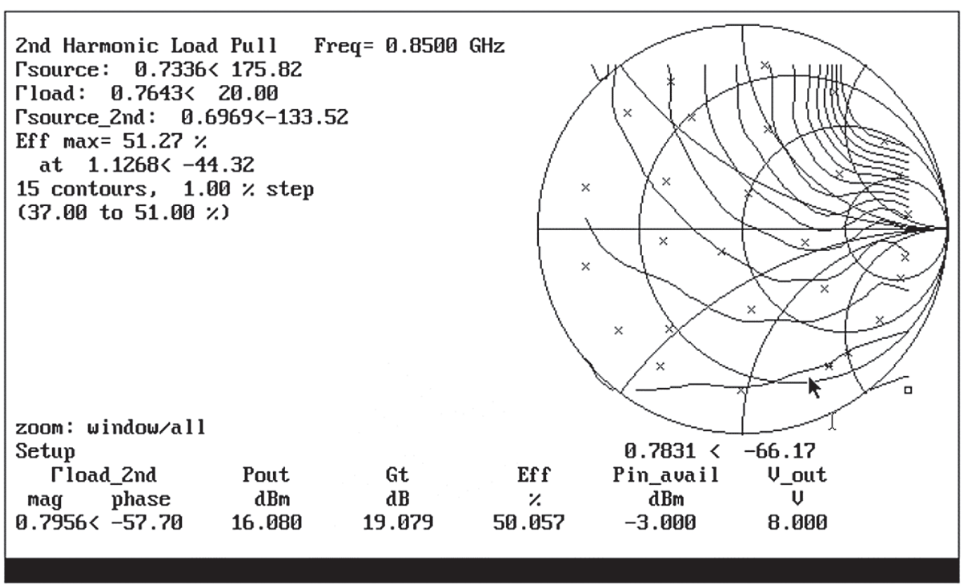

Figure 1. Power Added efficiency Contours vs. Second Harmonic Load Impedance.

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Description of Harmonic Tuning Methods

The three harmonic tuning methods considered here are summarized in Table 1 below:

Table 1. Harmonic Tuning Methods Summarized

Harmonic Tuning Method	Description
Triplexer	Use filters to separate the fundamental and harmonic signals so that they may be tuned independently. A triplexer has a low pass filter for F0, a band pass filter for F2, and a band pass or high pass filter for F3. a block diagram with source and load harmonic tuning is shown in Figure 2.
Stub Resonator	Use open stubs, quarter-wave at the harmonic, connected to the center conductor with a sliding contact. A block diagram with load harmonic tuning is shown in Figure 3. • The F3 stub is closest to the DUT, intending to reflect all F3 signal and pass the F0 signal. • The F2 stub follows the F3 stub, intending to reflect the F2 signal and pass the F0 signal. • A normal tuner is used to tune the F0 impedance. • Dual quarter-wave stubs are typically used, since single stubs are very ineffective.
Cascaded Tuner	Use two cascaded tuners with 625 states each, producing nearly 400,000 available impedance states with the combination. With this many states, multiple states will produce any specified F0 impedance but will have a variety of F2 impedances. Second harmonic load pull, for example, consists of measuring a set of states with approximately constant F0 impedance.

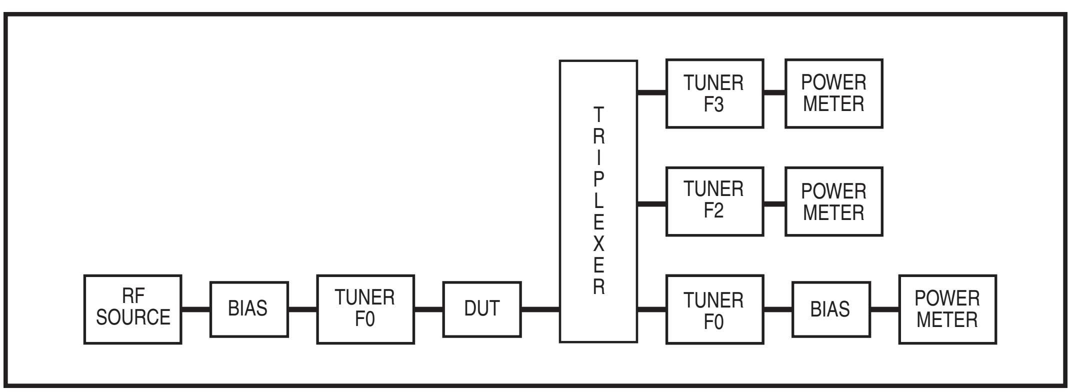

Figure 2. Load Pull Setup with Triplexer Load harmonic Tuning.

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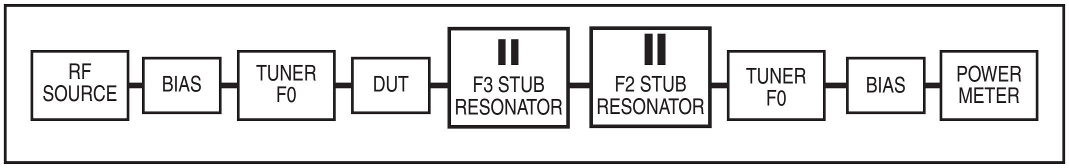

Figure 3. Load Pull Setup with Stub Resonator Load Harmonic Tuning.

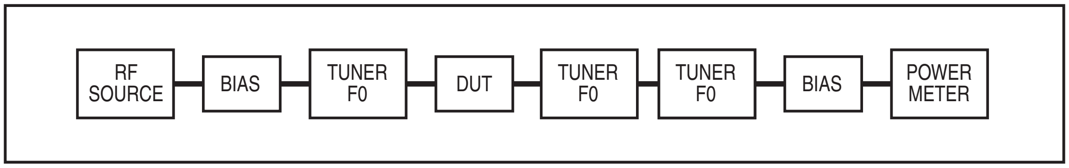

Figure 4. Load Pull Setup with Cascaded Tuner Load Harmonic Tuning.

Comparison of Harmonic Tuning Methods

The Key parameter is HIGH ISOLATION between the fundamental and harmonic tuning. It is critical since the purpose of harmonic tuning is to separate the effects of tuning F0, F2, and F3.

Table 2. Harmonic Tuning Methods – Advantages vs. Disadvantages

Harmonic Tuning Method	Advantages	Disadvantages
Triplexer	• **Excellent Tuning Isolation** • Change Bans Easily (no disassembly, no tuning, no re-calibration. • Non-contacting Tuners • Harmonic impedance may be swept around edge of Smith chart, or over entire chart • Available to Millimeter Wave Frequency Range	• Small insertion loss in front of all three tuners results in slightly reduced matching range.
Stub Resonator	• No Loss in Front of F3 Tuner	• **Poor Tuning Isolation** • Small insertion loss in front of F0 and F2 tuners results in slightly reduced matching range. • Very narrow band • Complex to change bands – Disassemble Tuners – Adjust Inter-stub Spacing – Retune with VNA – Re-characterize • Sliding contact oxidizes or wears out, and is easily damaged – Result: Poor Repeatability – Result: Worse Isolation • Limited to edge of Smith chart only – no gamma control
Cascaded Tuner	• No special hardware required • Operates over full tuner BW with no setup changes • No loss in front of any tuner • Harmonic impedance may be swept over the entire Smith chart	• **Poor Tuning Isolation** • **Limited tuning range with electronic tuners**

Trade-Off Criteria

Each method has trade-offs, but some parameters are much more important to the RF designer than others.

1. **Tuning Isolation: The most important difference between the three methods:** Fundamental tuning is far more sensitive than harmonic tuning, so if a large harmonic impedance change causes even a small F0 impedance change, the results are confused. It becomes unclear whether the device performance change is due to the harmonic tuning or the unintentional F0 tuning change. Therefore, harmonic tuning must have almost ZERO AFFECT on the Fundamental impedance. **The Triplexer method is the only approach with good tuning isolation.**
2. **Insertion loss at the fundamental frequency:** This will reduce the available matching range of the tuner at F0. The F0 matching is critical because a true match to the DUT is desired. However, if the loss is low, this is not usually a practical problem. Both the Triplexer have a small loss in front of the F0 tuner, either the triplexer or the harmonic tuner. **Therefore, the Triplexer method and the Stub Resonator method are about equal in this.**
3. **Insertion loss at the harmonic frequency:** This will reduce the matching range at the harmonic frequency. This is much less important than the correct matching at the fundamental frequency for two reasons.
    a. The harmonic tuning is much less sensitive than the fundamental, so getting close is generally sufficient.
    b. In most power amplifier applications, there is no intent to actually deliver power at the harmonic frequency, but rather reflect it all back to the DUT. The question is to find the optimum reflection phase to get the best performance at the fundamental. A small loss does not hinder this.

    Although the Stub Resonator has slightly less loss, mostly at the 3rd harmonic, the Triplexer loss is small enough that there is no practical effect.
4. **Bandwidth:** The Stub Resonator method with dual stubs works over a very narrow bandwidth, so may sets of resonators and a lot of band-changing may be required. The Triplexer method is better, since the limitation is to avoid overlapping F0, F2, or F3 which are far apart. Therefore, the Triplexer method easily covers major bands of interest without band-changing. **This is a disadvantage of the Stub Resonator method.**
5. **Ease of changing tuning bands:** Both the Triplexer method and the Stub Resonator method are band limited. The Cascaded Tuner method has an advantage here, because no hardware needs to be changed. The Triplexer method also has an advantage here, since it allows quick and easy changing of measurement bands.

    The Stub Resonator method requires the following lengthy and complex procedure to change the measurement band:

    a. Disassemble the test setup to remove the harmonic tuners.
    b. Disassemble both the F2 and F3 tuners, and reassemble them with new sets of resonators inside the units. Since the parts are delicate and easily damaged, this must be done very carefully.
    c. Place the extra resonators into safe storage. This is critical to avoid damaging the critical exposed parts.
    d. Calibrate a Vector Network Analyzer, and use it to manually tune the resonator pair spacing. When finished, lock them down to hold that position. This must be done for both the F2 and F3 tuners – a total of four resonators – each time.
    e. Reinstall the tuners back into the test setup. This must be before re-characterization if the in-situ cal is to be done. Otherwise, this step would follow the characterization.
    f. Use the load pull software to run a complete tuner characterization of the reassembled tuners. This must be done for both the F2 and F3 tuners.

    This is a disadvantage of the Stub Resonator method.
6. **Sliding Mechanical Contacts:** This can seriously degrade performance over time. It is due to contact wear, contact oxidation, and cumulative damage from band-changing. It can lead to intermittent contact and repeatability problems, vibration problems (especially for on-wafer applications) and increased insertion loss of the tuner. The result is loss of calibration validity and accuracy. The Triplexer method and the Cascaded tuner method have been implemented with non-contacting or solid state hardware, so **only the Stub Resonator method has this problem.**
7. **Harmonic tuning over the entire Smith chart:** This allows contours vs. harmonic tuning to be drawn, providing

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better insight into DUT operation and sensitivity. However, in many applications, this is not critical, since the most important information comes from tuning in a ring near the edge of the Smith chart. **Both the Triplexer method and the Cascaded Tuner method have a small advantage here.**

8. **Availability at higher Frequencies:** As technologies evolve, the trend is to move higher in frequency. The sliding contact of the Stub Resonator is a major limitation, because the quarter wave stubs become physically small compared to the transmission line and contact size, so the stubs lose the ability to resonate. Both the Triplexer method and the Cascaded Tuner method easily extend into the millimeter wave frequencies. **This is only a problem for the Stub Resonator method.**

9. **Sensitivity to out of band oscillation:** This question is sometimes asked, mainly because a high reflection at low frequencies could cause an oscillation with high device gain. However, the Triplexer and Stub Resonator both go to 50 Ohms below the operating band, so there is not real difference from the basic load pull system without harmonic tuning. **All three methods are equal on this.**

Triplexer Performance

The Triplexer method has major advantages over the other methods, but it depends on the performance of the triplexer. The two most important parameters are isolation and insertion loss.

Because of the wide frequency separation between the fundamental and harmonic bands, the isolation is easily achieved. Also, since the only isolation effect of interest is return loss isolation, which uses a two-way path, the effective isolation is double the one-path value. **Typical return loss isolation is well over 100 dB.**

Insertion loss is important to keep a high matching range. Typical insertion loss of 0.2 to 0.3 dB maintains a high matching range, making the Triplexer method very effective. Typical triplexer performance is shown in Figure 5, with the three paths overlaid.

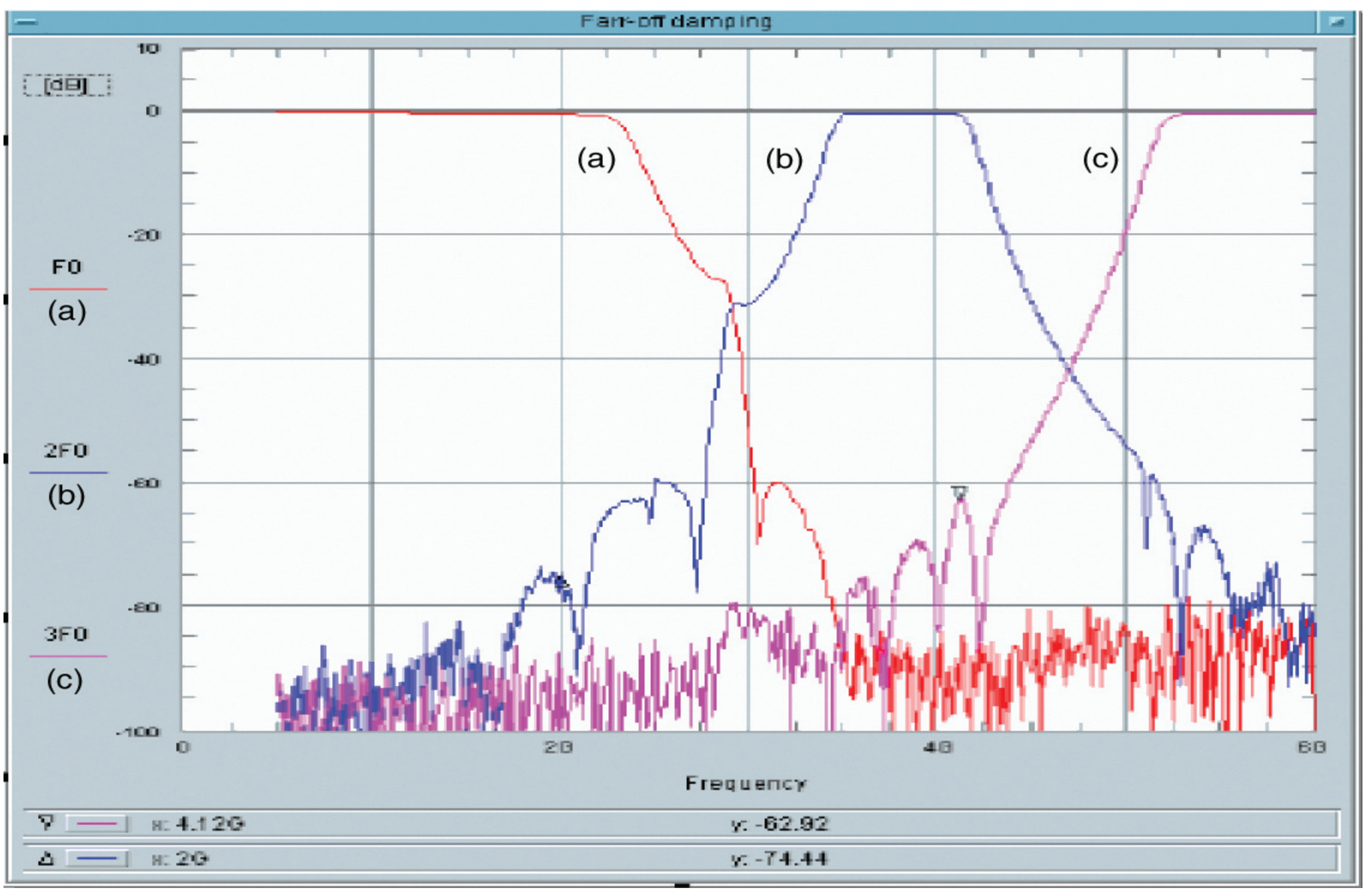

Figure 5. Typical Insertion Loss and Isolation of the Triplexer (a = Fundamental Path, b = 2nd Harmonic Path, c = 3rd Harmonic Path).

Analysis of Harmonic Resonator Pulling on Fundamental Impedance

Since automated tuner systems rely on presenting a stable and repeatable impedance, Maury has chosen the di/triplexer method for harmonic tuning, due to the very high isolation between the fundamental and harmonic impedances. Uncontrolled perturbation of the fundamental impedance due to harmonic tuner pulling results in a significant increase in fundamental impedance uncertainty, which is equivalent to adopting a low performance VNA calibration.

To examine the effect of poor harmonic resonator isolation on fundamental impedance, consider the effect of varying the phase of a perfect reflection at the second-harmonic on a fundamental tuner presenting 1 W. This tuning scenario would be consistent with, for example, characterizing a transistor for GSM operation. Typical harmonic resonator isolation specifications of 22 dB and 35 dB are assumed, which represent worst-case isolation without fundamental correction and worst-case isolation with fundamental correction, respectively. These numbers were recently published by developers of an automated loadpull system using harmonic resonators.

It is important to note that the same developers equate harmonic resonator isolation with di/triplexer isolation. They are not the same, since, with a di/triplexer, the signal is attenuated twice. Hence, a di/triplexer with an isolation o5, say 35 dB, actually has 70 dB of harmonic isolation, due to the round-trip isolation being 2x the one-way isolation. The same is not true for a harmonic isolator, however.

Figures 6a-6c show the actual fundamental impedance for 22 dB and 35 dB, respectively, versus varying harmonic impedance phase. Also shown are typical uncertainty ranges for 3.5 mm SOLT VNA calibration and 7 mm TRL calibration. In addition, limits are shown for the worst-case 70 dB isolation afforded by Maury's diplexer method.

There are several immediate consequences of the poor harmonic resonator isolation. First, as Figure 6a shows, the resultant fundamental impedance pulling exceeds by a wide margin the uncertainty associated with a 7 mm TRL calibration. Thus, left uncorrected, the harmonic resonator method is similar to performing tuner characterization with a SOLT calibration, something that should be avoided at all costs. For reference, typical uncertainty for a 3.5 mm

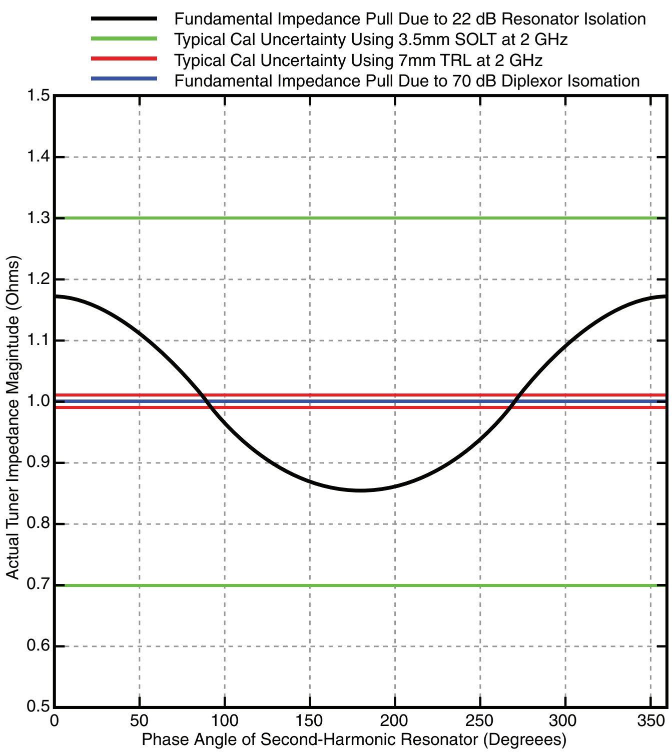

Figure 6a.

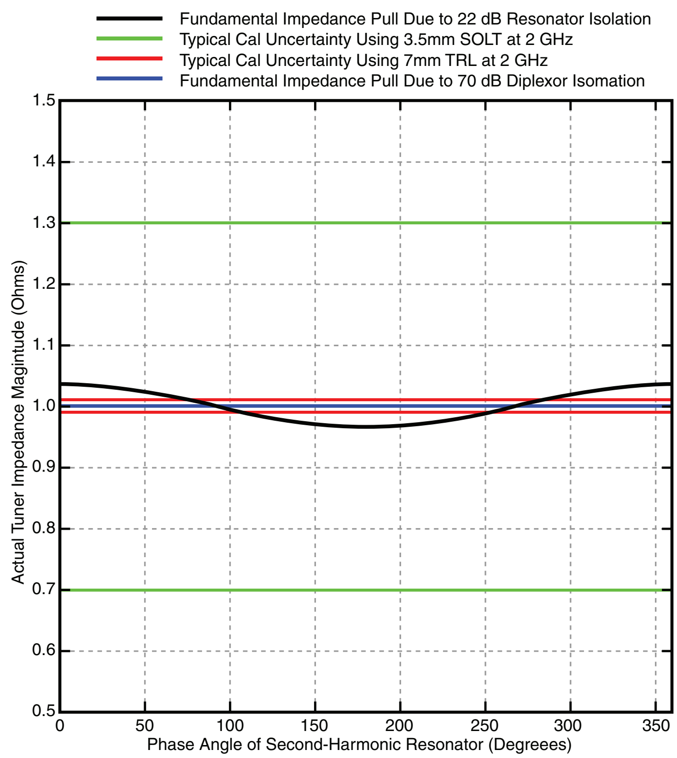

Figure 6b.

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SOLT calibration is also shown in Figure 6a. Also shown is the fundamental uncertainty exhibited by the Maury di/triplexer method, showing that even at the worst-case isolation of 70 dB that uncertainty is dominated by VNA calibration uncertainty.

Figure 6b shows the resultant fundamental impedance pulling with a harmonic resonator isolation of 35 dB. Even in this case, with fundamental correction, the uncertainty exceeds typical 7 mm TRL calibration performance.

Figure 6c shows figure 6b with the y-axis magnified to show the details of di/triplexer fundamental impedance pulling. As clearly illustrated, even at a worst-case isolation of 70 dB, the resultant fundamental impedance pulling is far less than the uncertainty of a typical 7 mm TRL calibration. Hence, the Maury di/triplexer method is completely transparent.

- Maury has adopted the di/triplexer method of harmonic tuning due to its superior isolation, resulting in nonexistent fundamental impedance pulling. Isolation far exceds the ability to even measure it using conventional VNA methods.

- The accuracy expected from using a high-performance calibration method, like TRL, is maintained, with the Maury di/triplexer harmonic tuning method.

- The harmonic resonator method for harmonic tuning, under worst-case corrected conditions, is equivalent to adopting a VNA calibration method with higher uncertainty than TRL, which virtually all automated tuner system developers agree is the preferred method.

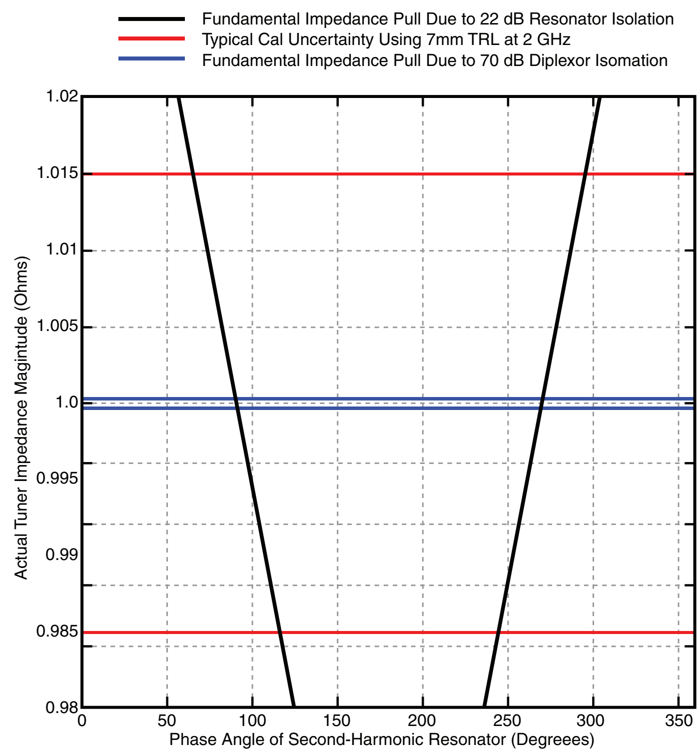

Figure 6c.

Summary of Comparison

1. The **Triplexer** method excels at the most important factor for accurate measurements, which is the tuning isolation. The small loss causes slightly less tuning range at the 3rd harmonic, but this has no practical effect on the measurement. This method trades off an unimportant factor to gain the critical tuning isolation factor.
2. The Cascaded Tuner method is the only one that does not require band limited hardware. However, it has very poor tuning isolation.
3. The Stub Resonator method has slightly less loss at the 3rd harmonic, but this does not have much practical measurement advantage. This small advantage is overwhelmed by the poor tuning isolation, complexity in changing bands, and degradation with use due to the sliding mechanical contacts.

Maury Microwave selected the Triplexer method because of the major advantages over the other methods.

Due to advances in harmonic tuning algorithms and the implementation of new software features, MMC's method of cascaded tuners for harmonic tuning has become a viable and recommended option and has overcome any and all issues related to tuning isolation.

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