Cascading Tuners For High-VSWR And Harmonic Load Pull

Authors: Steve Dudkiewicz and Roman Meierer, Maury Microwave Corporation

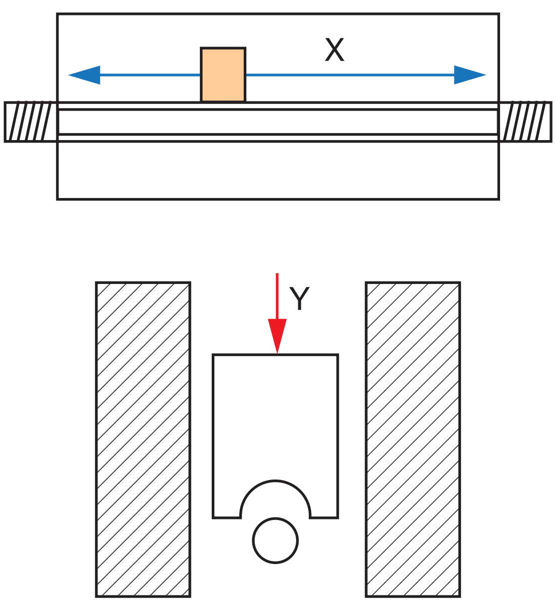
ABSTRACT:

For the first time ever, two or three tuners can be cascaded externally to achieve extremely high magnitudes of reflection (VSWR in the order of 100:1-200:1, Γ>0.98) as well as control multiple impedances at multiple frequencies (wideband harmonic tuning). Due to the use of calibrated and interpolated data for all tuners, we are able to achieve an overall system-level accuracy of greater than 40-80dB at highest Γ's.

Mechanical Slide-Screw Tuner

A mechanical slide screw-tuner consists of a 50Ω slabline and a reflective probe, referred to as a slug. Ideally, when the slug is fully retracted, the tuner presents a 50Ω impedance. As the slug is lowered into the slabline (y-direction), it interrupts the electric field and creates a capacitance, thereby increasing the magnitude of reflection. As the slug travels along the slabline (x-direction), the phase of the reflection is rotated. We are therefore able to recreate any and all impedances without the need of discrete components (lumped elements or transmission lines). (See **Figure 1**.)

The slugs used in a slide-screw tuner are wideband in nature; the response over several octaves (or even a decade) is quite linear. For instance, if we were to present a reflection coefficient of Γ=0.8 at the fundamental frequency, the reflection coefficient at the second and third harmonics would be close to Γ=0.8 with highly rotated phases. It is the frequency-dependent phase which changes rapidly and is critical when cascading tuners.



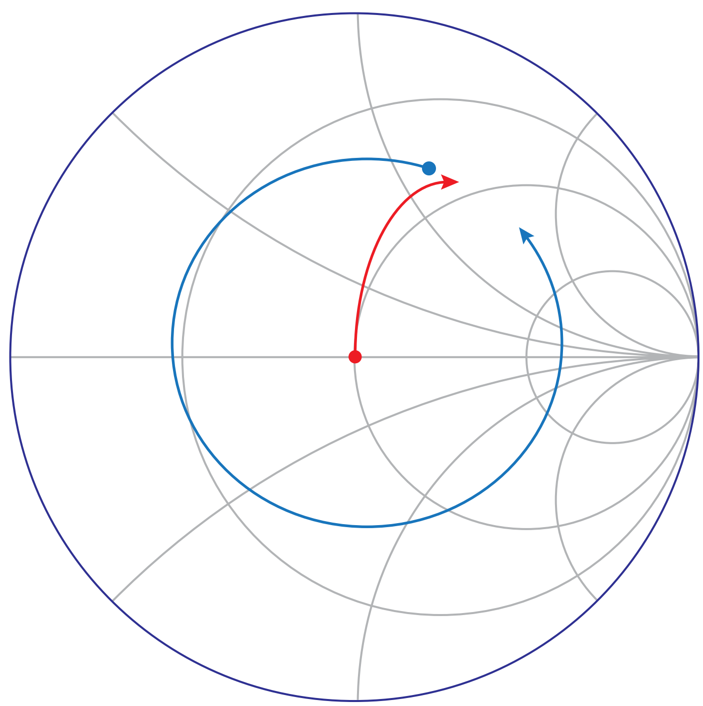


Figure 1. Representation of a Slide-Screw Tuner.

Each slug can also be looked upon as a "degree of freedom", or a vector. With a single slug, there is only one possibility of positioning so that a given impedance at a specified frequency is achieved. This physical slug position has a fixed response for the harmonics, so that each harmonic will reside at a fixed impedance with no possibility of control.

Figure 2 demonstrates the wideband magnitude response of a typical slug as read from a vector network analyzer (log magnitude of S_{11} as a function of frequency). **Figure 3** depicts the vector representation of the slug; notice that a small movement along the slabline has a large effect on the phase of harmonic frequencies.

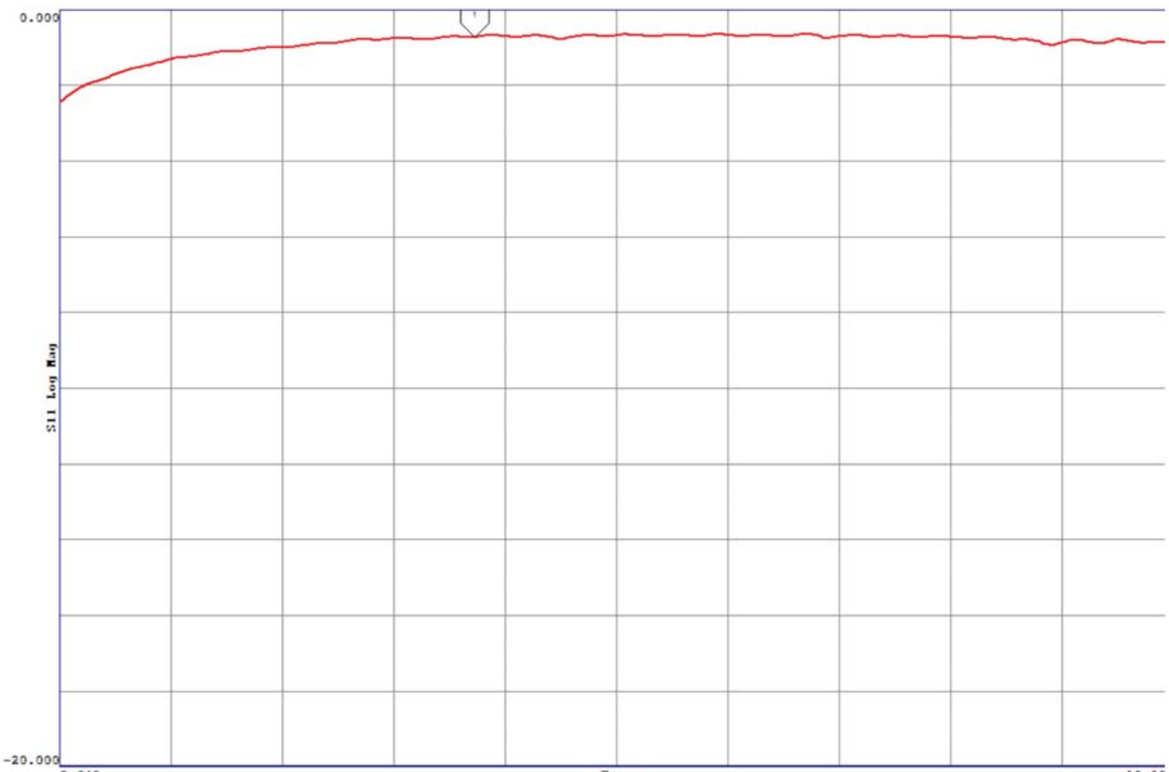


Figure 2. S_{11} (log mag) as a function of frequency (2.5-18 GHz)

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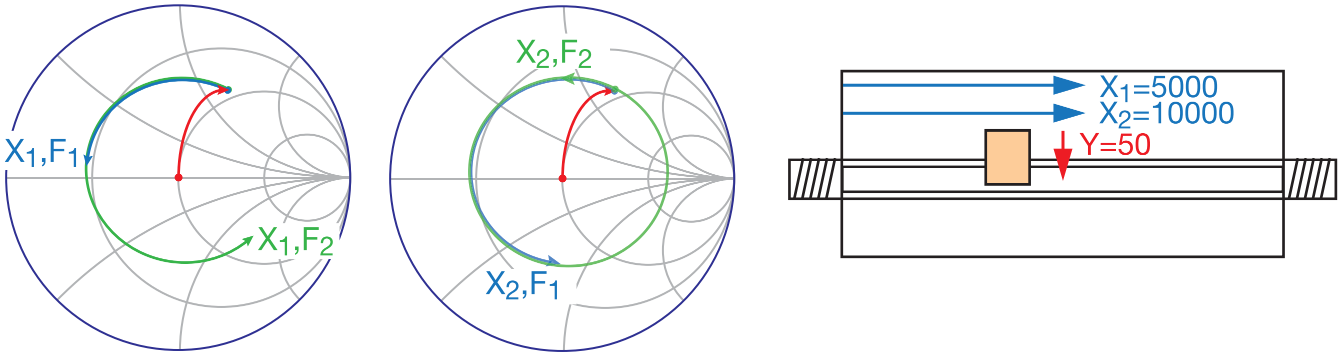

Figure 3. Reflection coefficients at second and third harmonics exhibit high linearity with highly rotated phases

If we were to cascade two tuners in series as shown in **Figure 4**, we would then have two degrees of freedom, or the ability to place two probes, or vectors, where we see fit.

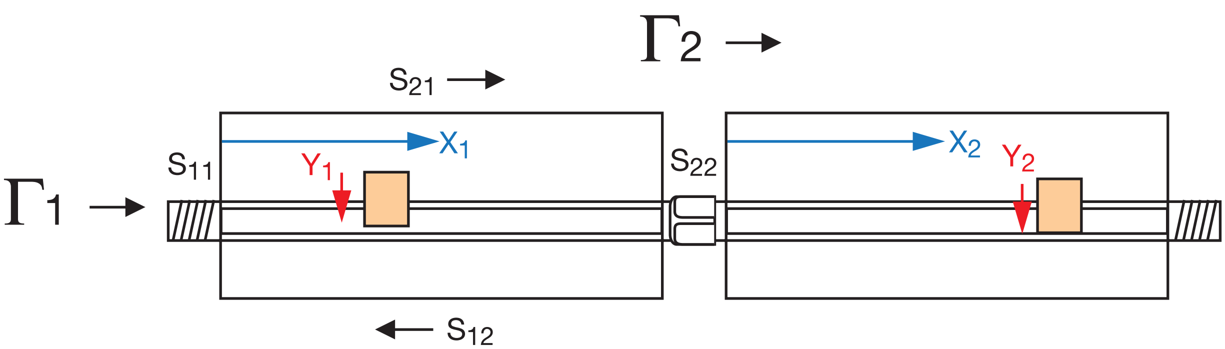

Figure 4. Two tuners in cascaded in-series

The formula that governs cascading tuners is:

$$\Gamma_1 = S_{11} + \frac{S_{12}S_{21}\Gamma_2}{1 - S_{22}\Gamma_2}$$

S_{11}, S_{21}, S_{12}, S_{22} are the s-parameters of $tuner_1$ (closest to the DUT).
Γ_2 is S_{11} looking into $tuner_2$ at a fixed termination.

The overall reflection looking into the cascaded-tuner combination is equal to the complex reflection of the first tuner added to the complex reflection of the second tuner multiplied by some insertion/reflection factor. Notice that the effect of the second tuner is highly influenced by the $S_{21}S_{12}$ product of the first tuner. There are two extreme cases that best describe this effect:

- If $tuner_1$ is at a physical short circuit, $S_{21}S_{12}=0$ and $tuner_2$ would be completely masked
- If $tuner_1$ is at 50Ω initialized, S_{11}~0 and $S_{21}S_{12}$~1 and $tuner_2$ would be all that is seen.

Cascading Tuners for High VSWR

As described earlier, mechanical slide-screw tuners are used to create impedances for device characterization. A standard tuner using a simple slug has a maximum VSWR ranging from 10:1 to 30:1, which represents the ability to synthesize impedances up to 1.7Ω-5Ω. **Figure 5** shows the characterization of a tuner at 2.0 GHz with a VSWR of 25:1. Notice the uniform point distribution centered at 50Ω and the maximum tuning coverage.

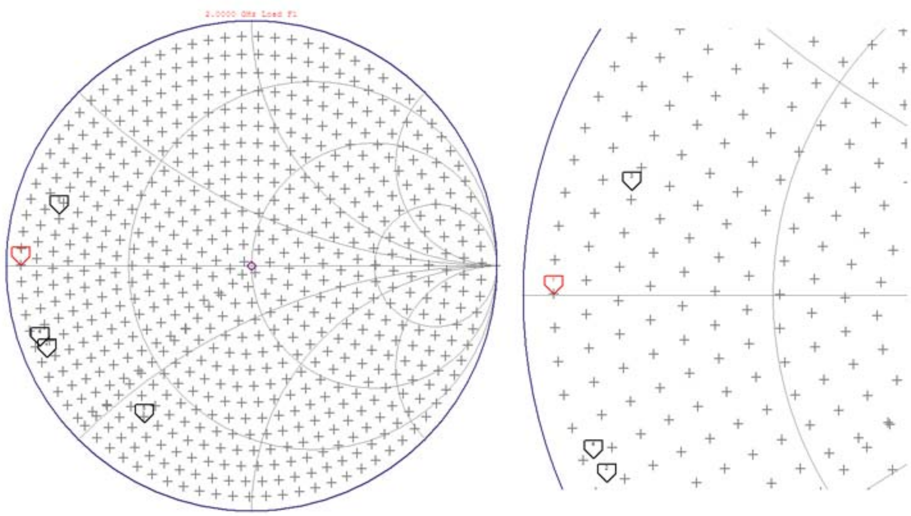

Figure 5. A single tuner with VSWR=25:1 (capable of 2Ω impedance)

Looking at the formula above, to cascade two tuners for maximum VSWR we must align the phase of the individual vectors so that the resulting vector adds perfectly. **Figure 6** shows the vector addition of two tuners resulting in Γ=0.98 (or VSWR of 100:1).

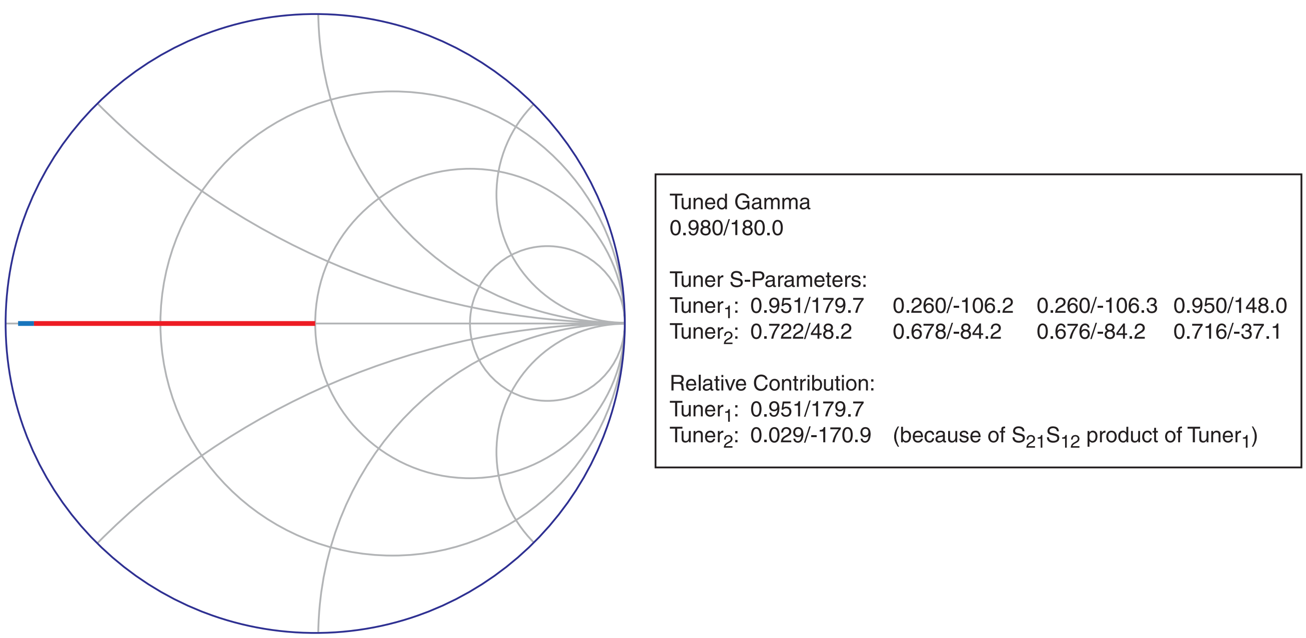

Figure 6. Vector-addition of two tuners to achieve Γ=0.98

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An additional benefit of cascading two tuners in this method is the resulting point distribution. We can achieve a much greater density of points in the region of interest which allows for a higher degree of tuning accuracy. This can be achieved by maintaining the position of $tuner_1$ (vector used to get from 50Ω to Γ=0.951) and varying the position of $tuner_2$ to perform load pull, referred to as dynamic pre-matching. **Figure 7** shows the resulting Smith Chart point distribution of a dynamic pre-matching cascaded setup with maximum VSWR of 100:1, a vast improvement over the 25:1 a single tuner was able to achieve.

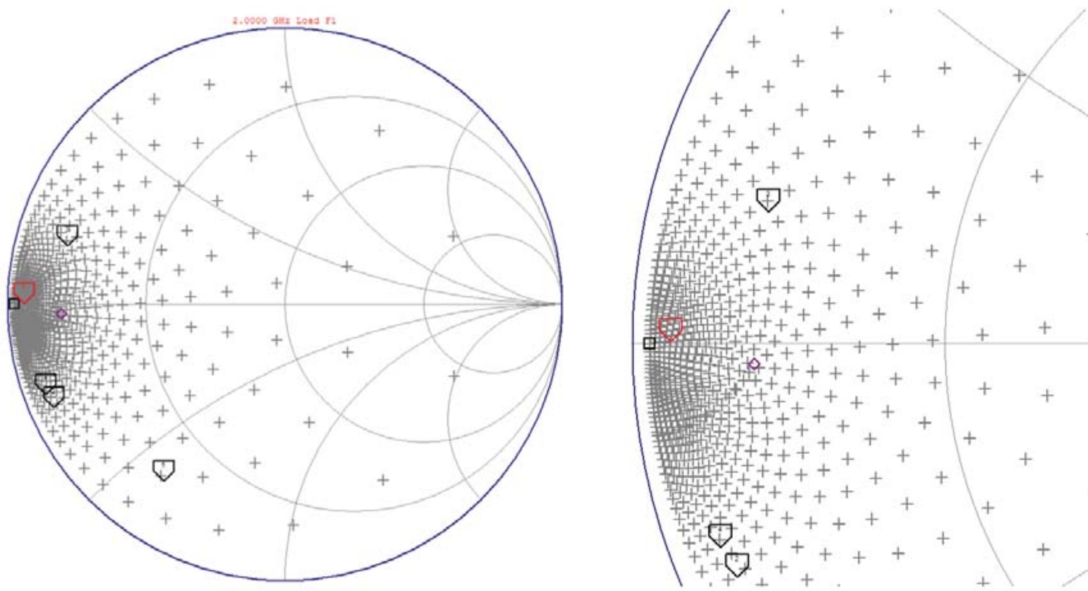

Figure 7. Two cascaded tuners with VSWR=100:1 (capable of 0.5Ω impedance)

Because of our ability to use both calibrated and interpolated points, we are able to achieve a higher accuracy than any other method, better than –50dB in most cases. **Figure 8** shows an example where Γ=0.982 (VSWR=110:1) with a resulting vector error of –67dB.

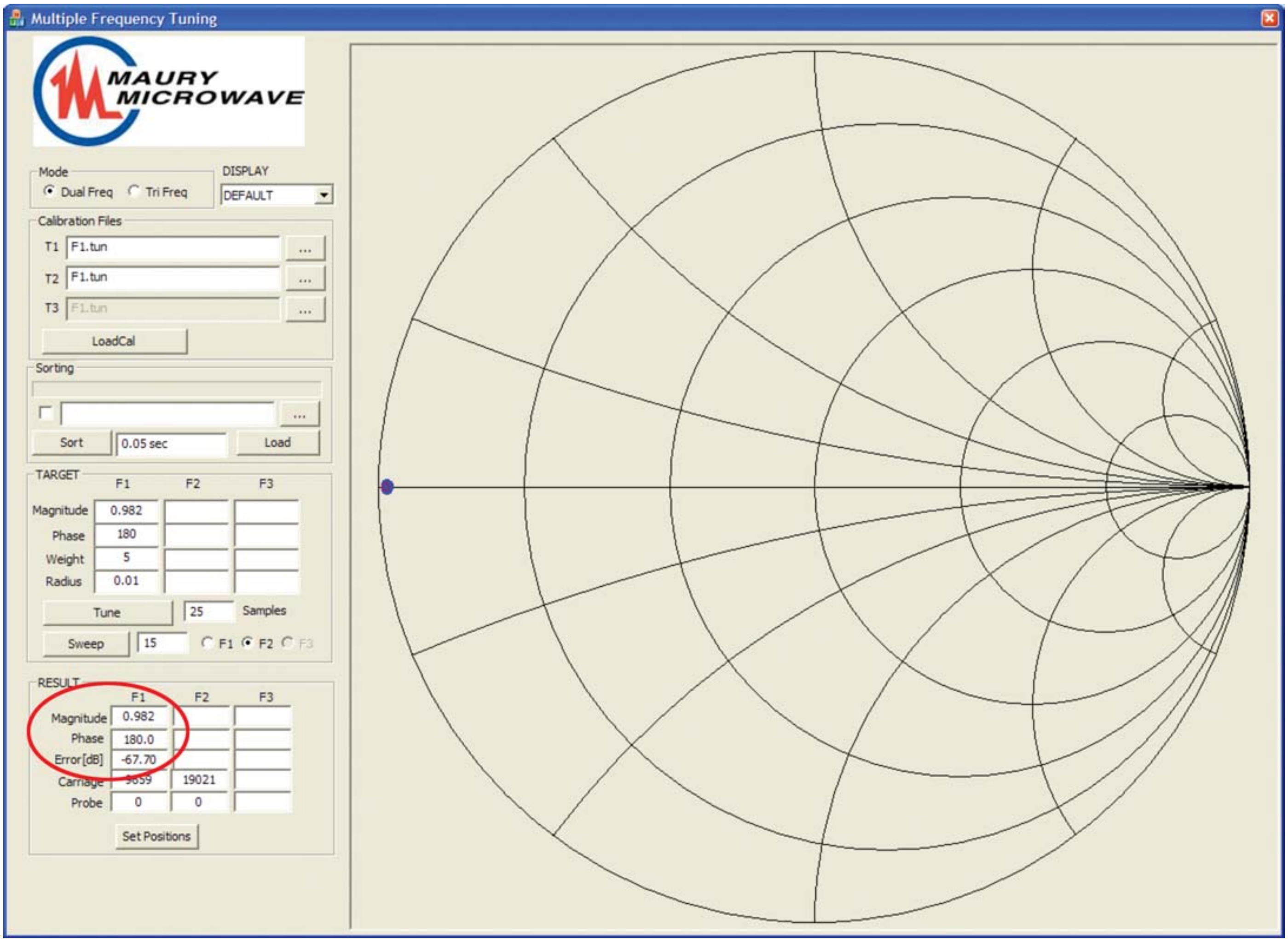

Figure 8. Accuracy of –67.70dB at Γ=0.982∠180°

When cascading tuners for High VSWR, it is essential to choose two tuners which have a strong reflection at the frequency of interest; users will normally choose two similar tuners for this application. Maury ATS software will transparently determine slug positions for each tuner which will create vectors that align in order to increase the overall reflection.

It is therefore possible to achieve the higher than normal reflection that is essential for modern device characterization where impedances around 0.5 to 2Ω are required.

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Cascading Tuners for Multi-Harmonic Tuning

The previous formula considers two tuners at the fundamental frequency. We can further expand our formula to multiple frequencies by considering simultaneous equations as follows:

$$\Gamma_{1fn} = S_{11fn} + \frac{S_{12fn}, S_{21fn}, \Gamma_{2fn}}{1 - S_{22fn}, \Gamma_{2fn}}$$ where n is the number of frequencies required.

When tuning impedances with two tuners, therefore two degrees of freedom, we are able to achieve the same fundamental impedance with various combinations of vectors. We can use the first tuner and disregard the second tuner, or we can use the second tuner and disregard the first, or we can use more of the first tuner and less of the second, and so forth. Each solution will result in the same fundamental impedance but very different harmonic impedances. **Figure 9** shows multiple vectors to the same fundamental impedance, while **Figure 10** shows the resulting 2Fo impedance. (For simplicity, higher-order harmonics have been left off the diagram, but are still very much present.)

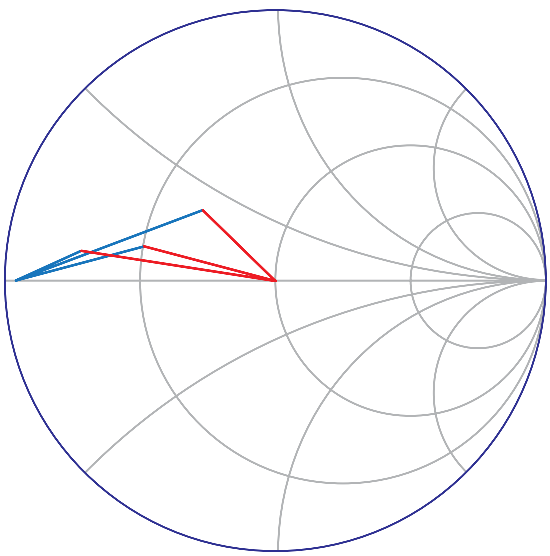

Figure 9. Multiple paths to Γ_{Fo}=0.95∠180°

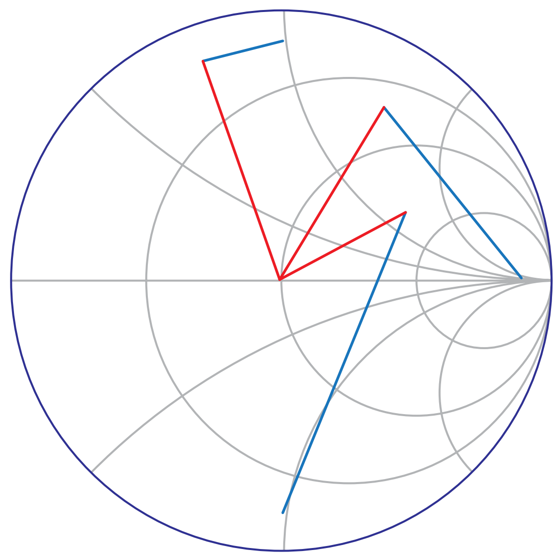

Figure 10. Resulting Γ_{2Fo} positions (0.9∠0, 90, 270°)

Please note the tuners are not frequency separated; each tuner will have an influence on each frequency. We must rely on advanced software algorithms to determine the proper positioning of each tuner for the desired fundamental and harmonic impedances. The actual tuning algorithm must take into account the losses through the tuner at each combination of positions and choose the solution out of thousands of possibilities which gives the lowest insertion loss and most accurate result. Because of our ability to use both calibrated and interpolated points, we are able to achieve a higher accuracy than any other method, better than –50dB in most cases. **Figure 11** shows an example where Γ_{Fo}=0.95∠180° and $\Gamma2_{Fo}$=0.95∠0° with resulting vector errors of –57dB and –73dB respectively. Notice we show data at Γ=0.95 and not Γ=0.8 like others. The cascaded tuning method just as easily determines the slug positions required to set one frequency to a high

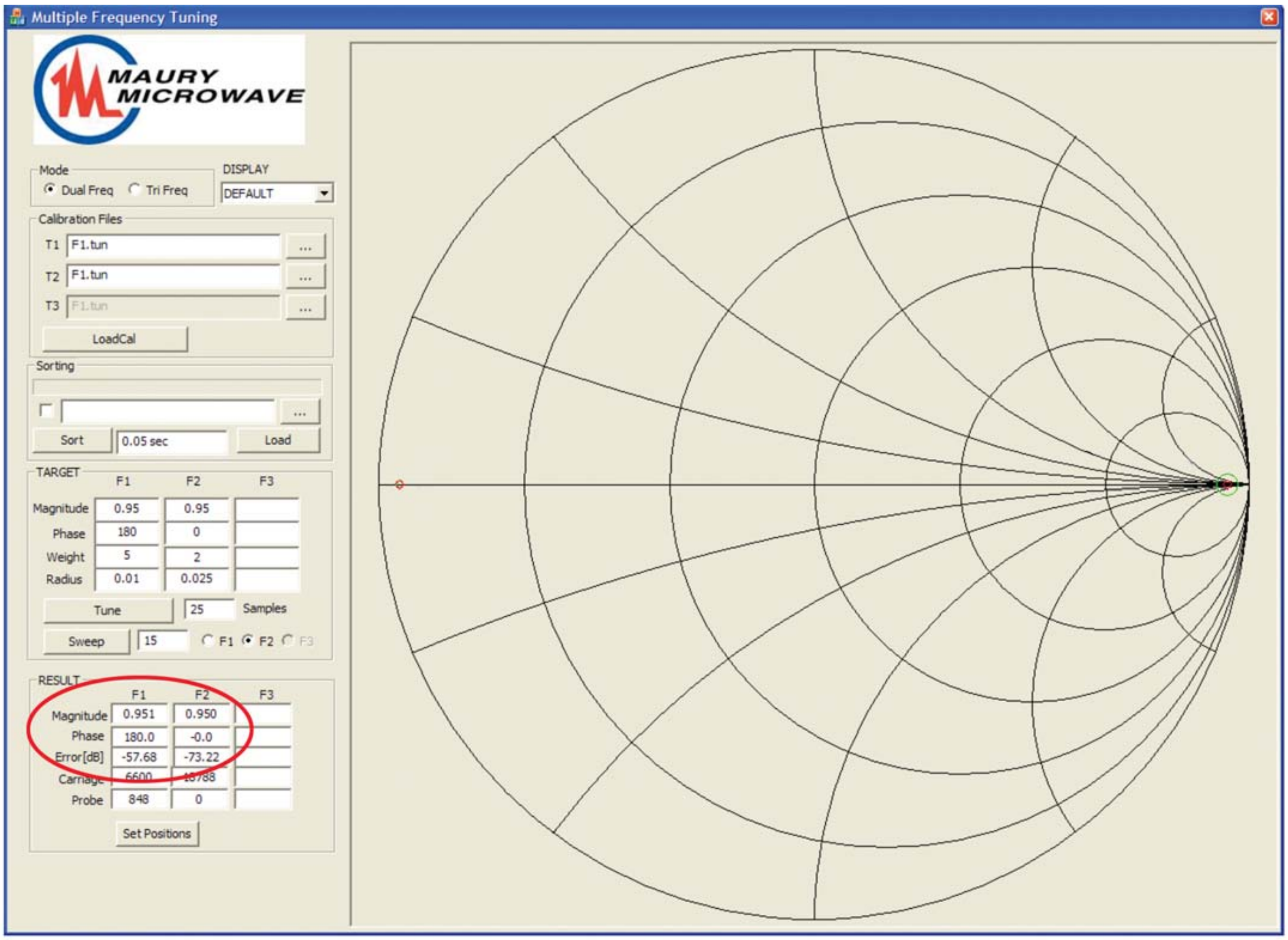

Figure 11. Γ_{Fo}**=0.95∠180° and** Γ_{2Fo}**=0.95∠0° with accuracy of –57dB and –73dB respectively**

reflection factor and the other to low reflections. In **Figure 12** we set Γ_{Fo}=0.95 with multiple phases, and Γ_{2Fo}=0.01 (50Ω) with resulting vector errors better than –50dB.

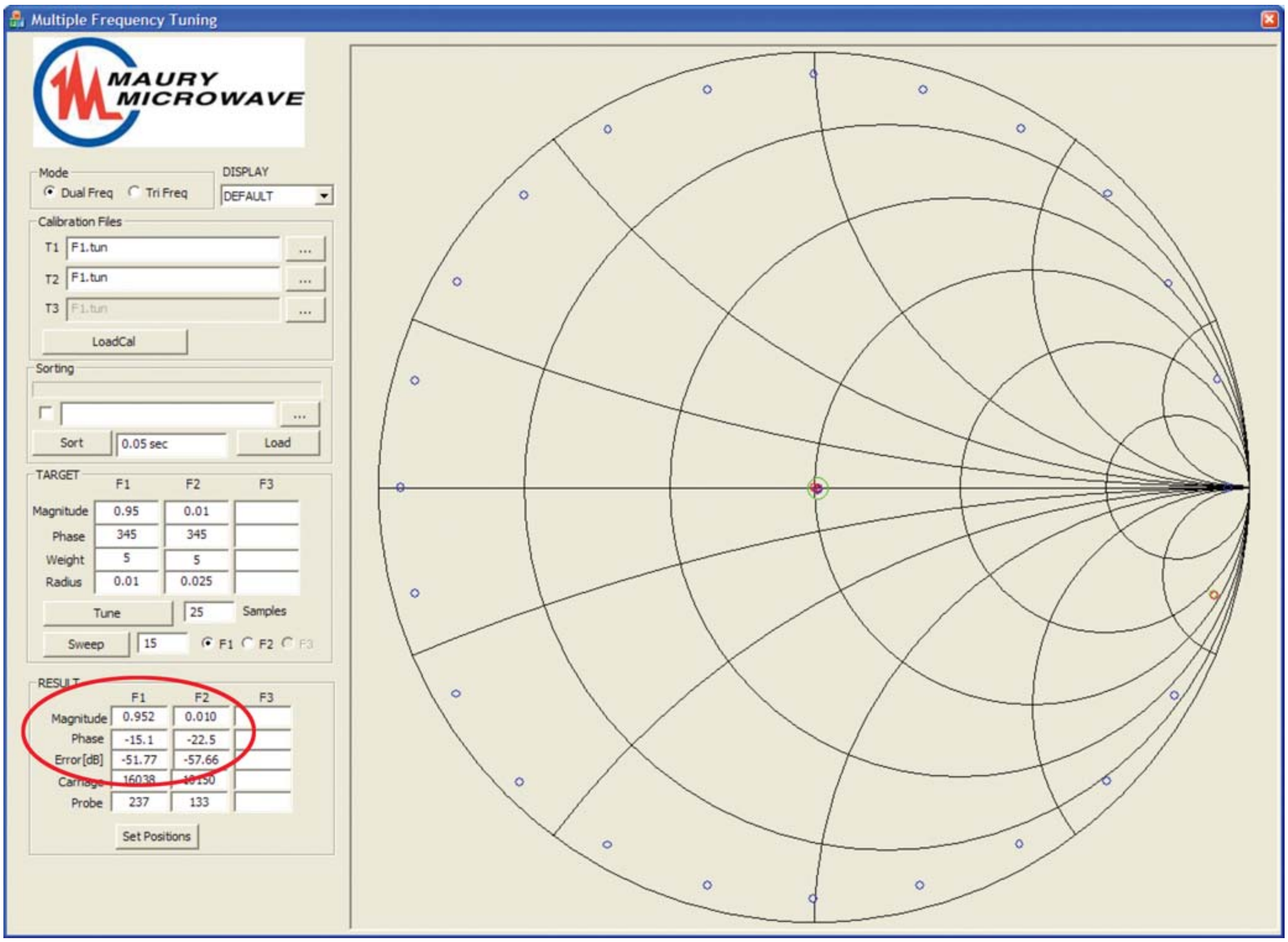

Figure 12. Γ_{Fo}=0.95 with multiple phases, and Γ_{2Fo}=0.01 (50Ω) with accuracy better than –50dB

Cascading Tuners for High-VSWR and Harmonic Tuning Simultaneously

The ultimate goal in many cases is to achieve both high reflection coefficients (low impedances in the order of 0.5Ω to 1Ω or less) and the ability to perform harmonic tuning simultaneously. As explained throughout this document, the power of cascading tuners lies in the proper positioning of vectors to achieve the desired results. Specifying low impedances at both the fundamental and harmonic frequencies relies on the existence of a combination of tuner probe positions where the resulting vectors can meet those values. While it may be possible to achieve this with standard tuners, there is no guarantee that every combination of low impedance at the fundamental and harmonic frequencies will be available at all times. Two standard tuners each capable of Γ=0.90 to 0.95 can achieve either extremely low impedances (**Figure 8** shows vector addition to Γ=0.98) or harmonic tuning (**Figure 11** shows Γ=0.95 at both Fo and 2Fo) or a combination of the two.

Achieving both high-VSWR and harmonic impedance control simultaneously is possible if tuners that can independently achieve a VSWR~100:1 (Γ=0.98) are used. The software algorithm no longer needs to search for vector combinations that achieve low impedances, since each tuner is capable of low impedances independently. By cascading high-gamma tuners, we can achieve fundamental and harmonic impedance values in the order of 1Ω or less. **Figure 13** shows a case where two MT981HU13 High-Gamma Tuners™ each capable of 100:1 to 200:1 VSWR are cascaded in series to achieve both high-gamma and harmonic tuning simultaneously.

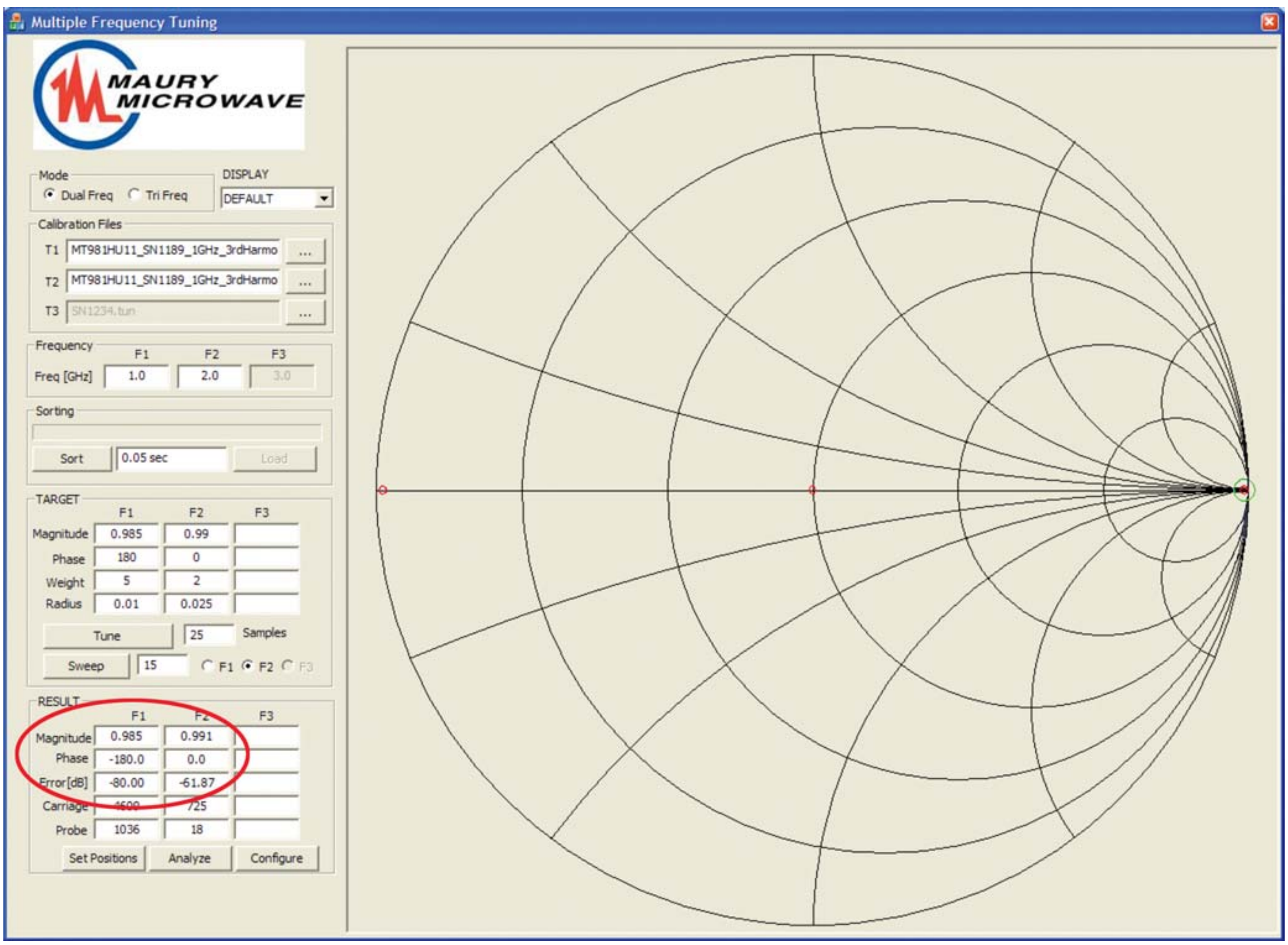

Figure 13. Γ_{Fo}=0.985∠180° and Γ_{2Fo}=0.99∠0° using HGT™

Conclusion

Maury Microwave Corporation has proven through explanation, mathematics and measurement results that it is not only feasible to cascade multiple tuners for high-VSWR and multiple-frequency tuning (harmonics), but that the results achieved are unmatched in the industry. Cascading tuners gives the flexibility to upgrade existing systems, allows greater variety in the usage of tuners (independent single-frequency tuning on multiple workstations), and offers a more wideband harmonic solution than any other method.

References

For information about Maury ATS software and/or the MT981HU series of High-Gamma Tuners™ click on the links below, or go to maurymw.com:

- ATS Version 5 Automated Tuner System Software (URL: http://www.maurymw.com/atsv5.htm)
- Application Note 4T-070A High-Gamma™ Automated Tuners (HGT™) – Models MT981HU13, 23, 33.