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Application Note 45

Algorithm for Automatic High Precision Residual Tuning to 50Ω using Programmable Tuners

Summary

This note describes a technique used in order to be able to employ programmable slide screw tuners (CCMT[1]) to finely tune around 50Ω. Main application is the 'on-line' correction of small residual reflection factors of standards, (such as noise sources or loads) back to 50Ω.

This note describes the problem, the difficulties associated with this type of operation and the algorithm used to accomplish this task. Experimental verification is also provided.

The Task – The Difficulties

Some metrology applications require automatic tuning of small residual impedances, like the internal impedance of a noise source, to be compensated back to 50Ω. Since we are talking about standard load or source impedances, to be used in ready setups, the basic requirement is that the system can auto-correct the residual reflections of the load for each frequency, using previously accumulated calibration data without an on-line measurement on a calibrated VNA. Figure 1 demonstrates the problem.

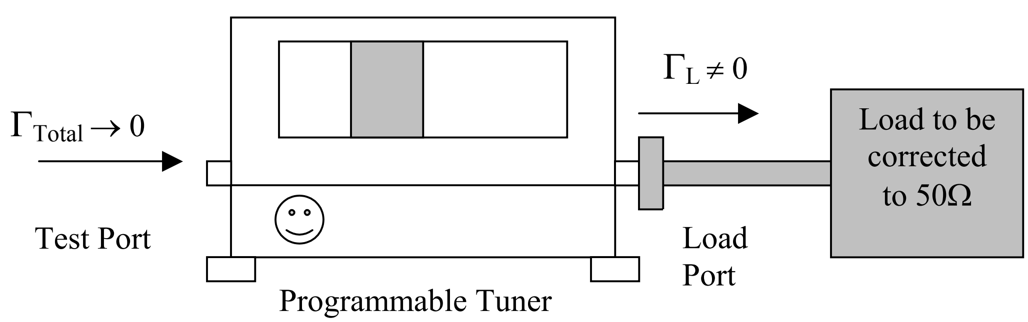

Figure 1: Typical setups using a programmable tuner to correct arbitrary residual reflections of a load back to 50Ω

It is important to realize that <u>it is not the tuner residual SWR which is at stake here</u>, but the capability of the algorithm to use the tuner, which has been previously calibrated at arbitrary points in the vicinity of the center of the Smith chart, to compensate for small reflections on the load port of the tuner (with typical return loss ~30-35dB), so that the resulting reflection factor at the test port of the tuner be corrected nearly to zero (return loss >50dB).

[1] CCMT = Computer Controlled Microwave Tuner

Slide screw tuners available on the market cannot, by their nature, be calibrated around 50Ω within reasonable time limits, in order to solve this problem; the reason is that the 50Ω point represents a singularity for this type of tuning device, where infinite tuner positions correspond to the same, or nearly the same, impedance; it would require thousands of calibration points distributed in a very small area around the center of the Smith chart to make the tuner useable for this task. This solution would neither be practical nor elegant.

It remains the alternative to use techniques existing in Focus' software, which allow ordinary tuner calibrations at a limited number of points over the whole Smith chart (typically 300-400 points) to be used in order to interpolated quite accurately all 4 S-parameters of the tuner twoport at any motor position of the tuner, also close to 50Ω. The existing software can do more than only compute the impedance at any physical tuner position; it can also synthesize impedances, i.e.: find the tuner motor positions required to build any required impedance. This routine uses two iterations of a fast phase/amplitude gradient search algorithm, which results to efficient and accurate convergence towards the required ('tuned to...') impedance points.

However, this 'tuning' technique, which has been part of Focus' software since 1988, cannot be used around 50Ω. The reason for that is the very low tangential sensitivity $\partial S11/\partial Y$ of these tuners around 50Ω, as demonstrated in figures 2 and 3.

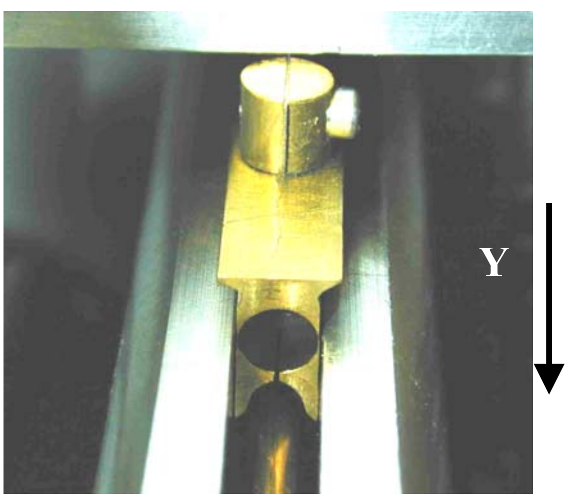

Figure 2: Principle of slide screw tuner: Lowering the RF probe creates capacitive coupling with central conductor of slabline.

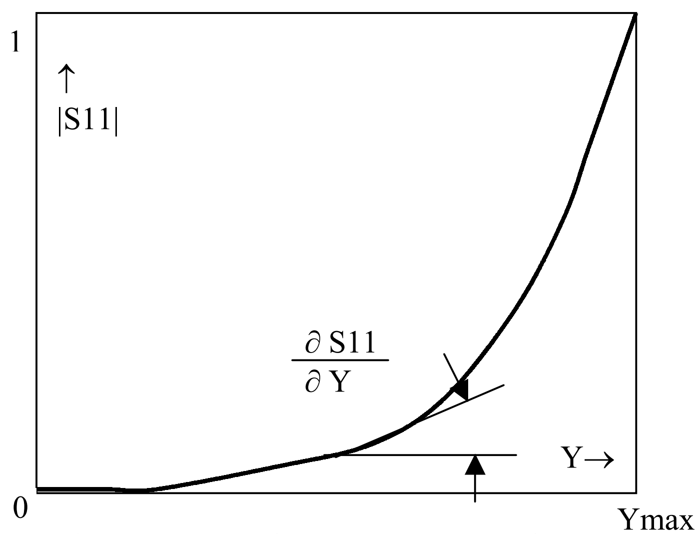

Figure 3: Dependence of |S11| from the vertical position of the probe (Y=0 →lowest capacitance, Y=MAX→highest capacitance)

The Zero Tuning Algorithm

In order to better understand the mechanism of the proposed algorithm it is useful to remind how the Focus software actually uses calibration data to interpolate the S-parameters of the tuner twoport to any physical position of the tuners. In fact, typical tuner resolution around 50Ω is of the order of 2-4 million possible positions within a circle of a radius of 0.1 around the center; the interpolation algorithm computes the correct parameters for each position, using the 9 closest calibration points to the target impedance (see figures 4 and 5 and reference [1], pages 3 and 5-6).

The way CCMT tuners work is as follows: The tuners are calibrated, for each frequency on a network analyzer at a number of regularly distributed points around the Smith chart (figure 4). For each physical position of the tuner motors (or the probe) a second order interpolation algorithm using Lagrange polynoms [1] allows exact computing the actual reflection factors at both tuner ports and gain (S-parameters). Experimental verification shows that the actual S-parameters of arbitrary interpolated tuner positions (not calibrated points) are reproduced with an accuracy exceeding 40dB (1%) [1, 2, pages 5-6]. The opposite, i.e. finding the physical position of the motors (X, Y steps in our nomenclature) for a required impedance, is much more difficult, because there are millions of nearby positions possible, due to the used high-resolution gears [2]. In Focus' approach this problem has been solved in 1988 by employing a fast gradient search algorithm, which does not try randomly all possible positions, instead it uses an iterative amplitude/phase search pattern; this search exploits to a maximum the nature of our tuners and converges within a few Milliseconds. This technique, in addition to its technical interest, is also of high practical value for allowing fine-tuning to any point of the Smith chart without re-calibrating the tuners [2].

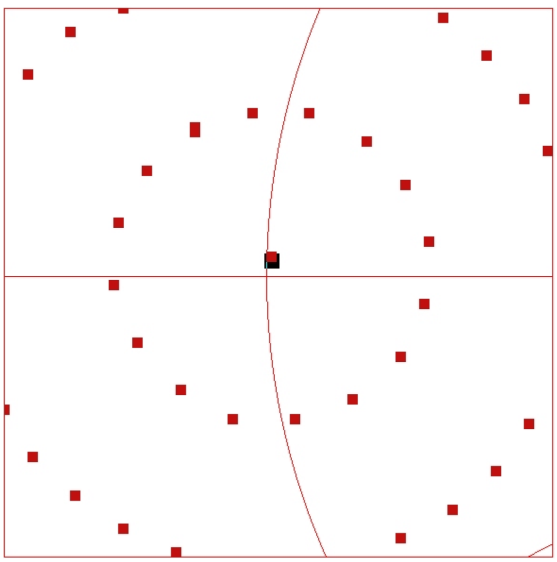

Figure 4: Typical distribution of Calibration points of a Focus CCMT connected to a perfect 50Ω load

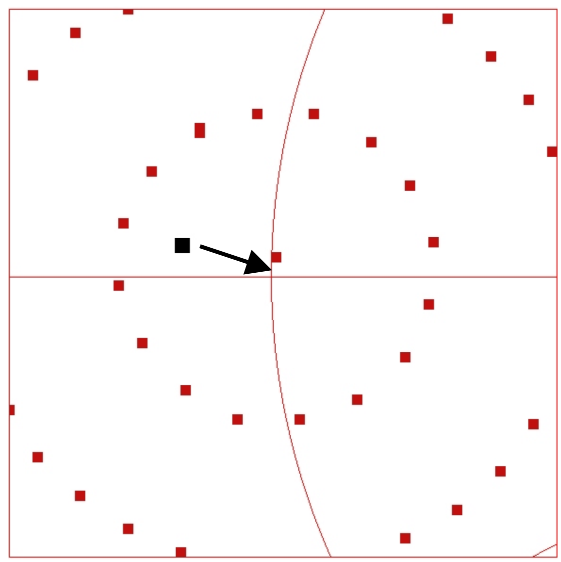

Figure 5: Non 50Ω load seen through the tuner at its test port (■). This load has to be tuned back to 50Ω.

In the actual setup of figure 1 the reflection factor seen into the test port, when the tuner is initialized, will be of the kind shown in figure 5 against the tuner calibration points. The tangential sensitivity being practically 0 in this area, the normal gradient based tuning algorithm fails to determine a set of tuner positions needed to compensate the residual reflection back to 50Ω as shown by the arrow. The load which is connected to the load port of the tuner and generates the pattern of figure 5, seen at the test port of the tuner, is Γ_L = 0.07 /-125°.

The zero tuning algorithm consists of four basic steps, which are indicated in the diagram of figure 6 (all operations are carried on in memory, no motor movement is required at this stage, until the final positions of the tuner motors are determined);

Keeping in mind that a vertical probe move will add a reflection vector and a horizontal probe move will rotate this vector around the origin X we can describe the search algorithm as follows:

1. Lower the RF probe into the slabline (Y axis, figure 2) until a measurable additional reflection factor occurs (vector XA).
2. Move the tuner carriage (X axis) until the phase of this additional reflection factor vector becomes the roughly equal to residual vector DX, which is the vector we want to compensate (course AB on the inner circle).
3. Continue lowering the RF probe (Y axis) into the slabline until the magnitude of the total additional vector (XB+BC) becomes equal to the residual reflection vector DX).
4. Continue moving the tuner carriage (X axis) along course C→E→D until the total reflection vector DE = DX + XE becomes minimum (in fact it will cross very closely to zero, which is the objective of the exercise).

At this point the routine will deliver the final horizontal and vertical positions for the tuner and the motors can be moved; since all operations are first carried out in memory, the whole routine demands only a few milliseconds giving the impression of being instantaneous. The whole mechanism works, because the horizontal movement causes the correcting reflection vectors XA and XC to rotate around the residual reflection point X.

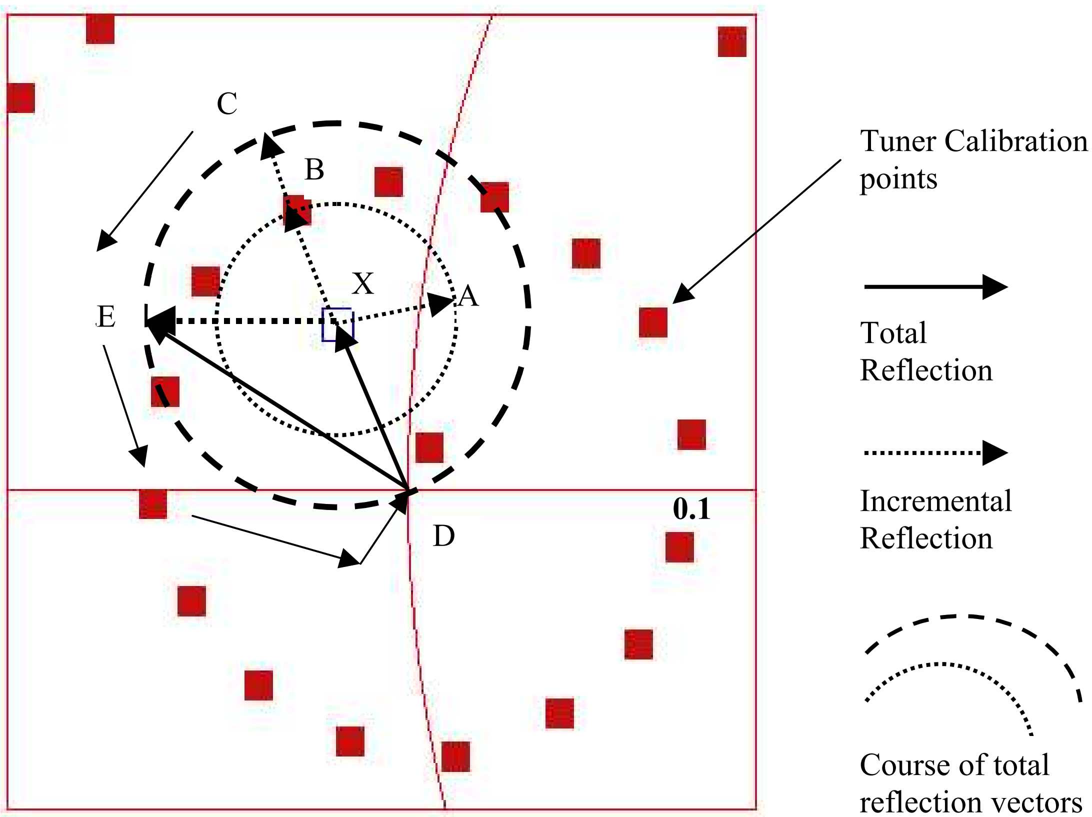

Figure 6: Graphical presentation of zero tuning search algorithm; total trajectory: XA → AB → BC → CED.

Such fine tuning around 50Ω is only possible because of the extreme resolution of the CCMT tuners and the second order interpolation algorithms of the software with accurate tuning capability, based on only a limited number of calibration points.
Figure 7 shows a tuning pattern generated automatically using the WinPower software around the center of the Smith Chart on a circle of a radius of 0.1. This impedance pattern includes 500 points which have all been generated using the 17 calibrated points shown in figures 4,5 and 6.

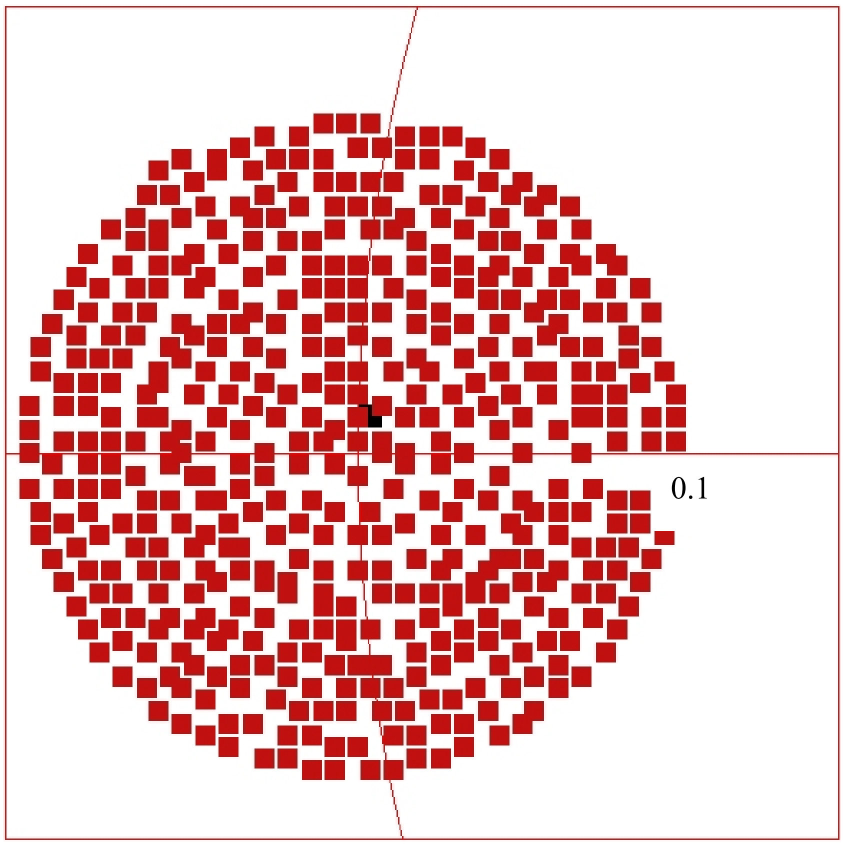

Figure 7: High-resolution impedance pattern including 500 points inside a 0.1 radius circle around 50Ω using interpolation and tuning routines.

Experimental Verification

The zero tune algorithm can been verified experimentally in the following setup:

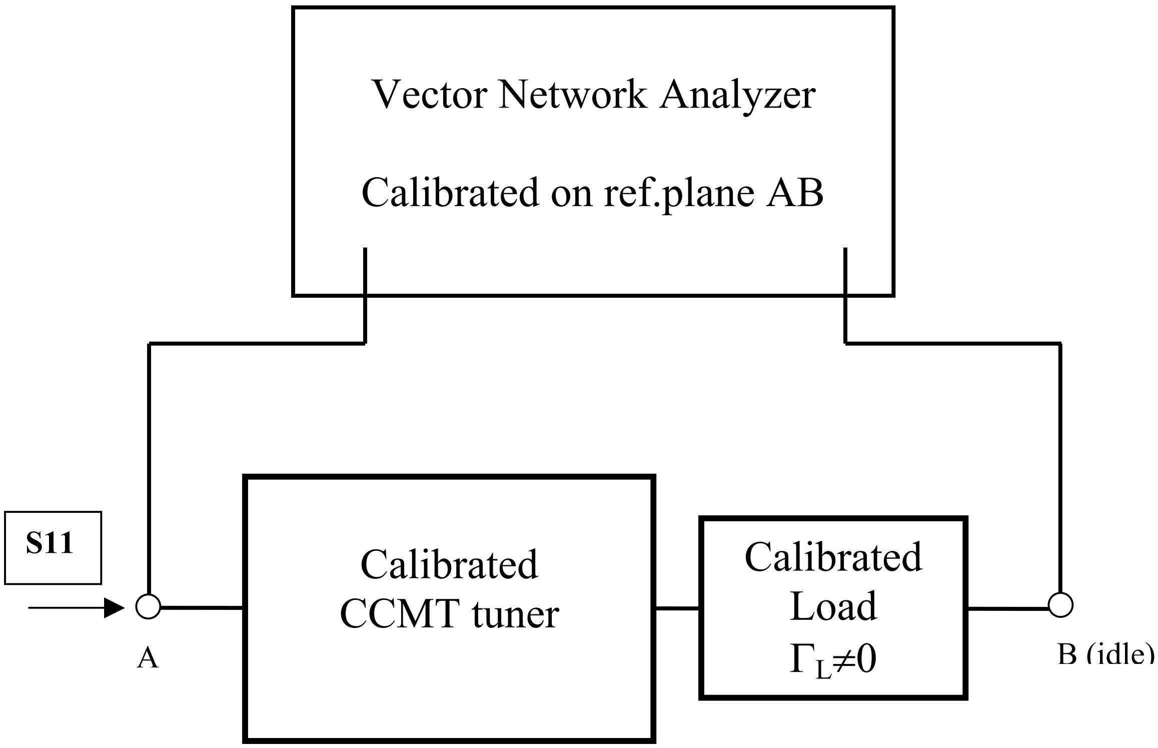

Figure 8: Setup for verification of Zero Tune algorithm.

The (arbitrary) load is being calibrated at a number of frequencies and the data are been saved in a S2P format (ASCII) file, ready to be used by the 'setup configuration' utility of the software. This utility cascades the scattering parameters of the load with the calibration parameters of the tuner at each frequency point and displays on the Smith chart the total reflection into the tuner test port (figure 1), which should be equal to S11, as measured by the VNA.
Table I shows examples of such automatic tests at three frequencies.

Frequency [GHz]	Γ-Load	$S11_c$ (Return Loss)	$\delta S11=20\log\lvert S11_m - S11_c\rvert^2$
1.000	0.051 ∠+95.5°	0.0025∠98.3°(52dB)	-44.9dB
1.500	0.067∠124.6°	0.003∠175.2°(50.5dB)	-51.5dB
2.000	0.072∠-45.7°	0.004∠-66.3°(48dB)	-49.8dB

Table I: Results of Zero Tuning routine. $S11_c$ = Calculated S11, $S11_m$= Measured S11.

Literature

[1] "High Resolution Tuners Eliminate Load Pull Performance Errors", Application Note 15, Focus Microwaves, January 1995
[2] "Computer Controlled Microwave Tuner", Product Note 41, Focus Microwaves, January 1998