Differential Harmonics, Differential Mixers and IQ Mixer Measurements

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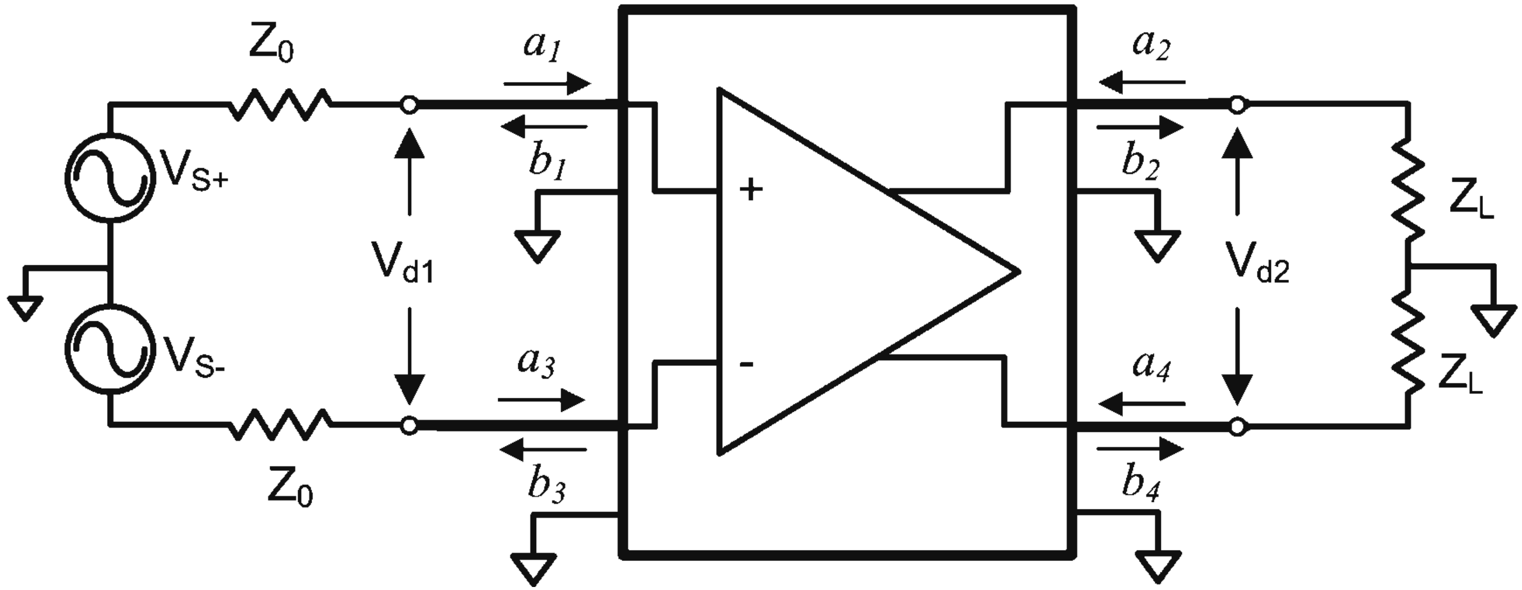
Differential and I/Q Mixer Application

- The "Swiss-Army Knife" of applications
- Set any source to:
  - Any frequency
  - Any power
  - Any phase
- Then measure
  - Any receiver
  - At any of a number of frequencies
- With match corrected power measurements

Consider the fundamentals of differential devices



$$V_d^F = \frac{1}{2}\left(V_d + I_d Z_d\right), \quad V_d^R = \frac{1}{2}\left(V_d - I_d Z_d\right)$$

$$V_d = V_1 - V_3, \quad I_d = \frac{1}{2}\left(I_1 - I_3\right) \quad I_c = I_1 + I_3, \quad V_c = \frac{1}{2}\left(V_1 + V_3\right)$$

$$Z_d = 2Z_0, \quad Z_c = \frac{Z_0}{2}$$

Differential S-parameters can be derived for this configuration, for each mode

$$a_d = \frac{V_d^F}{\sqrt{Z_d}}, \quad b_d = \frac{V_d^R}{\sqrt{Z_d}}, \quad a_c = \frac{V_c^F}{\sqrt{Z_c}}, \quad b_c = \frac{V_c^R}{\sqrt{Z_c}}$$

$$\begin{bmatrix} b_{d1} \\ b_{d2} \end{bmatrix} = \begin{bmatrix} S_{dd11} & S_{dd12} \\ S_{dd21} & S_{dd22} \end{bmatrix} \cdot \begin{bmatrix} a_{d1} \\ a_{d2} \end{bmatrix}, \quad \begin{bmatrix} b_{c1} \\ b_{c2} \end{bmatrix} = \begin{bmatrix} S_{cc11} & S_{cc12} \\ S_{cc21} & S_{cc22} \end{bmatrix} \cdot \begin{bmatrix} a_{c1} \\ a_{c2} \end{bmatrix}$$

$$\begin{bmatrix} b_{c1} \\ b_{c2} \end{bmatrix} = \begin{bmatrix} S_{cd11} & S_{cd12} \\ S_{cd21} & S_{cd22} \end{bmatrix} \cdot \begin{bmatrix} a_{d1} \\ a_{d2} \end{bmatrix}, \quad \begin{bmatrix} b_{d1} \\ b_{d2} \end{bmatrix} = \begin{bmatrix} S_{dc11} & S_{dc12} \\ S_{dc21} & S_{dc22} \end{bmatrix} \cdot \begin{bmatrix} a_{c1} \\ a_{c2} \end{bmatrix}$$

This can be configured into a single matrix

$$\begin{bmatrix} b_{d1} \\ b_{d2} \\ b_{c1} \\ b_{c2} \end{bmatrix} = \begin{bmatrix} S_{dd11} & S_{dd12} & S_{dc11} & S_{dc12} \\ S_{dd21} & S_{dd22} & S_{dc21} & S_{dc22} \\ S_{cd11} & S_{cd12} & S_{cc11} & S_{cc12} \\ S_{cd21} & S_{cd422} & S_{cc21} & S_{cc22} \end{bmatrix} \cdot \begin{bmatrix} a_{d1} \\ a_{c2} \\ a_{c1} \\ a_{c2} \end{bmatrix}$$

Thus, 16 differential S-parameters are needed to fully describe a 2-port differential device

The differential parameters can be defined in terms of single-ended measurements from first principals

$$a_{d1} = \frac{(a_1 - a_3)}{\sqrt{2}}, \quad a_{c1} = \frac{(a_1 + a_3)}{\sqrt{2}}, \quad b_{d1} = \frac{(b_1 - b_3)}{\sqrt{2}}, \quad b_{c1} = \frac{(b_1 + b_3)}{\sqrt{2}}$$

$$S_{dd11} = \left. \frac{b_{d1}}{a_{d1}} \right|_{a_{c1} = a_{d2} = a_{c2} = 0}$$

recognizing that $a_{c1} = 0$ which implies that $a_3 = -a_1$ so that $a_{d1} = 2a_1$

$$S_{dd11} = \left(\frac{b_1 - b_3}{a_1 - a_3} \right) = \left(\frac{b_1 - b_3}{a_1 - (-a_1)} \right) = \left(\frac{b_1 - b_3}{2a_1} \right)$$

From this beginning, differential S-parameters can be computed from Single-Ended S-parameters

$$S_{dd11}=\left(\frac{b_1-b_3}{2a_1}\right)=\left(\frac{[S_{11}a_1+S_{13}a_3]-[S_{31}a_1+S_{33}a_3]}{2a_1}\right)=\left(\frac{[S_{11}a_1-S_{13}a_1]-[S_{31}a_1-S_{33}a_1]}{2a_1}\right)$$

$$S_{dd11}=\frac{1}{2}\left(S_{11}-S_{13}-S_{31}+S_{33}\right)$$

And similarly for transmission:

$$S_{dd21}=\left(\frac{b_2-b_4}{a_1-a_3}\right)=\left(\frac{b_2-b_4}{a_1-(-a_1)}\right)=\left(\frac{b_2-b_4}{2a_1}\right)$$

$$S_{dd21}=\left(\frac{b_2-b_4}{2a_1}\right)=\left(\frac{[S_{21}a_1+S_{23}a_3]-[S_{41}a_1+S_{43}a_3]}{2a_1}\right)=\left(\frac{[S_{21}a_1-S_{23}a_1]-[S_{41}a_1-S_{43}a_1]}{2a_1}\right)$$

$$S_{dd21}=\frac{1}{2}\left(S_{21}-S_{23}-S_{41}+S_{43}\right)$$

We can use these definitions to define Harmonic Power, Mixer Conversion, Image Rejection, LO isolation

Diff. Input Power, Diff. Output Power, Diff. Harmonic Power

$$a_{d1} = \frac{(a_1 - a_3)}{\sqrt{2}}, \quad b_{d2} = \frac{(b_1 - b_3)}{\sqrt{2}}, \quad b_{d2,2} = \frac{(b_{2,2} - b_{4,2})}{\sqrt{2}}$$

Differential Harmonics (in dBc) are defined as:

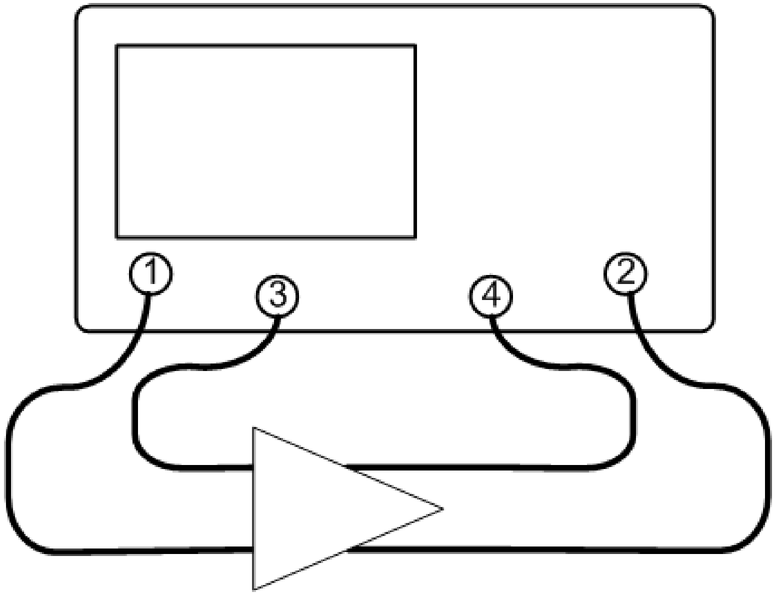
$$H2_d = \frac{(b_{2,2} - b_{4,2})}{(a_1 - a_3)}, H3_d = \frac{(b_{2,3} - b_{4,3})}{(a_1 - a_3)}, \ldots Hn_d = \frac{(b_{2,n} - b_{4,n})}{(a_1 - a_3)}$$

Differential Mixers have similarly defined signals

$$b_{d(RF)} = b_{d(LO+IF)} = \frac{(b_{2,(LO+RF)} - b_{4,(LO+RF)})}{\sqrt{2}}, \quad b_{d(Image)} = b_{d(LO+IF)} = \frac{(b_{2,(LO-RF)} - b_{4,(LO-RF)})}{\sqrt{2}}$$

$$b_{d(LO\_Isol)} = b_{d(LO)} = \frac{(b_{2,(LO)} - b_{4,(LO)})}{\sqrt{2}}, \quad b_{d(RF\_Isol)} = b_{d(LO+IF)} = \frac{(b_{2,(RF)} - b_{4,(LO-RF)})}{\sqrt{2}}$$

Use Case 1 : Measuring Harmonics of Balanced Amplifiers



Test Requirements:

- Stimulate the input with balanced, differential signal
- Measure the input differential power
- Measure the output differential power
- Measure the output differential power at N harmonics, N a small integer (5)
- Provide corrected measurements of power, provide leveled input power
- Measure with swept frequency, swept power or swept phase input
- Function in pulsed mode

Wants:

- Provide leveled output power

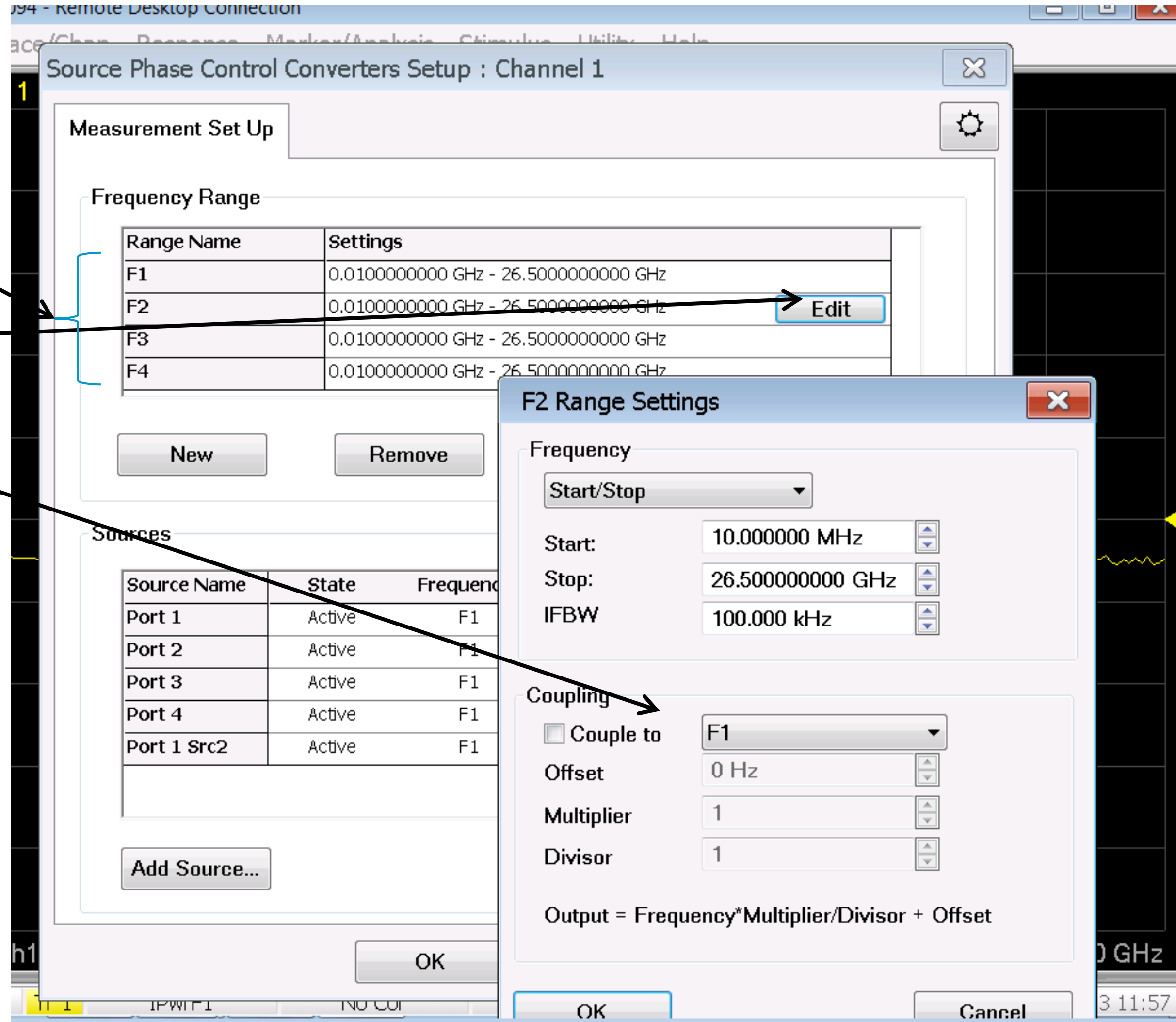
First: Define the frequency lists for source and receivers

Each frequency defined will be measured by all the receivers

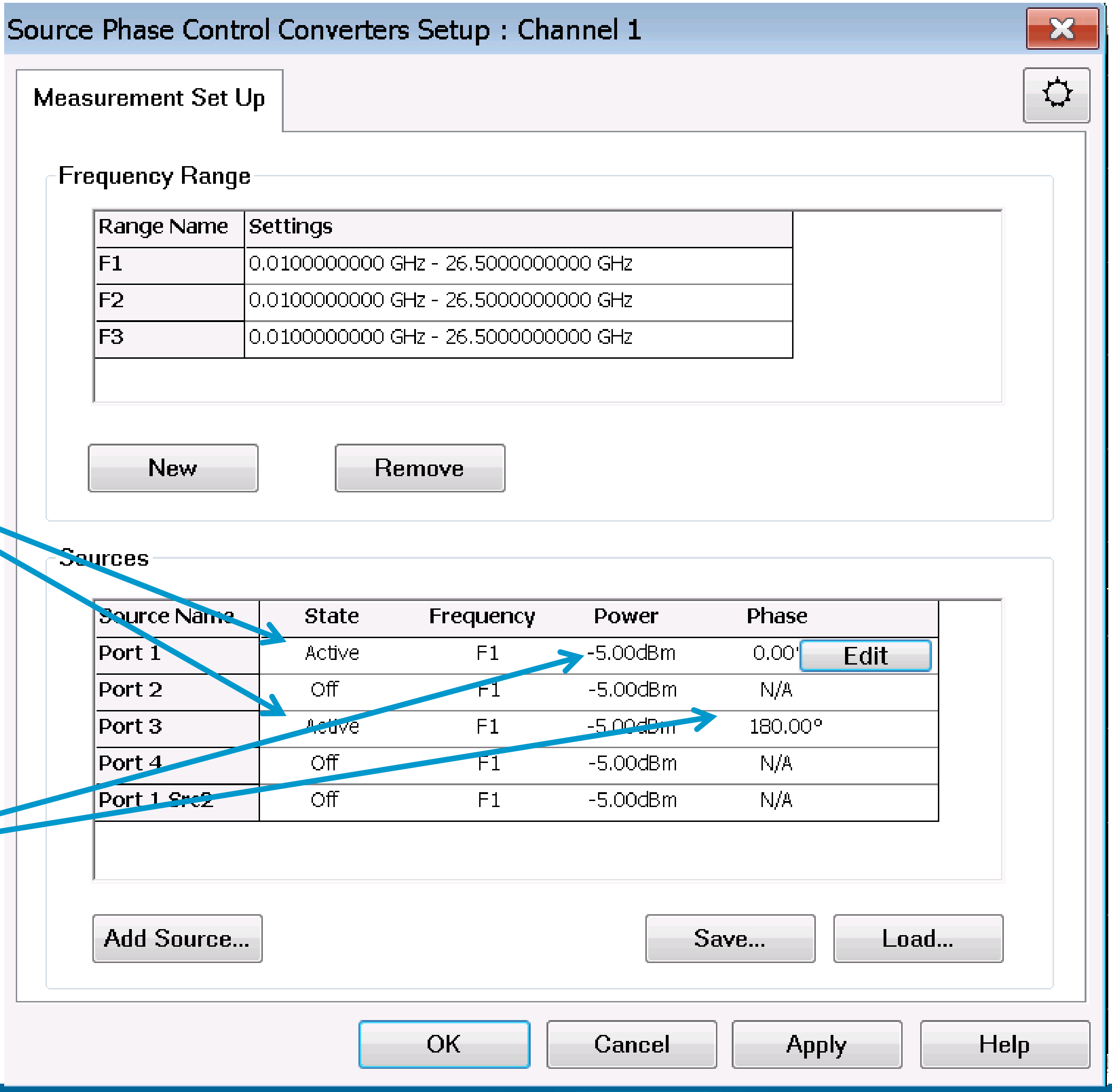
Editing a line brings up a dialog box

If coupled, some relative offset, and multiplier/divider can be set. If uncoupled, the just set start/stop.

Only linear frequencies are allowed.



Next Define Source behavior

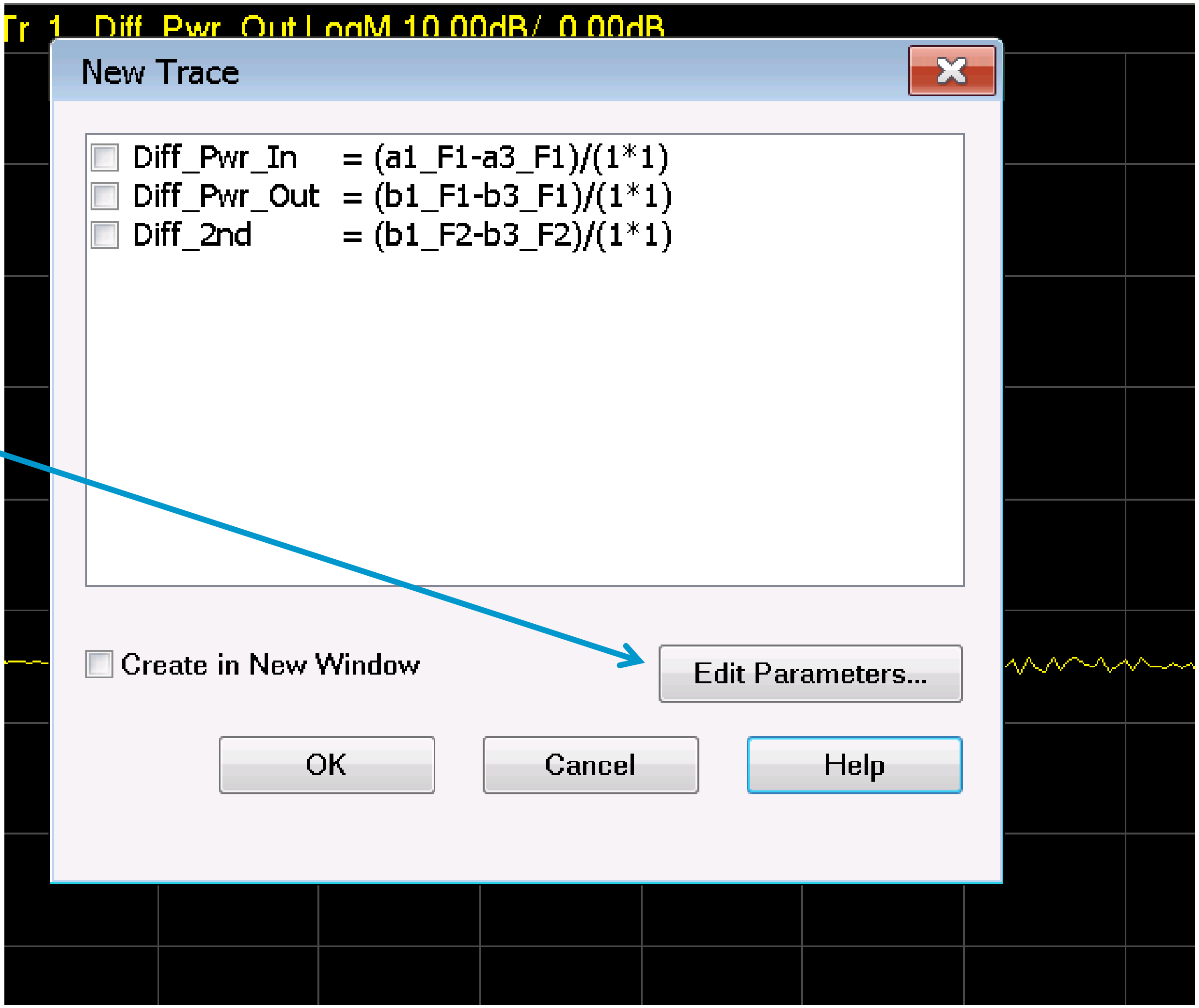


Set which sources are going to be used during the measurement

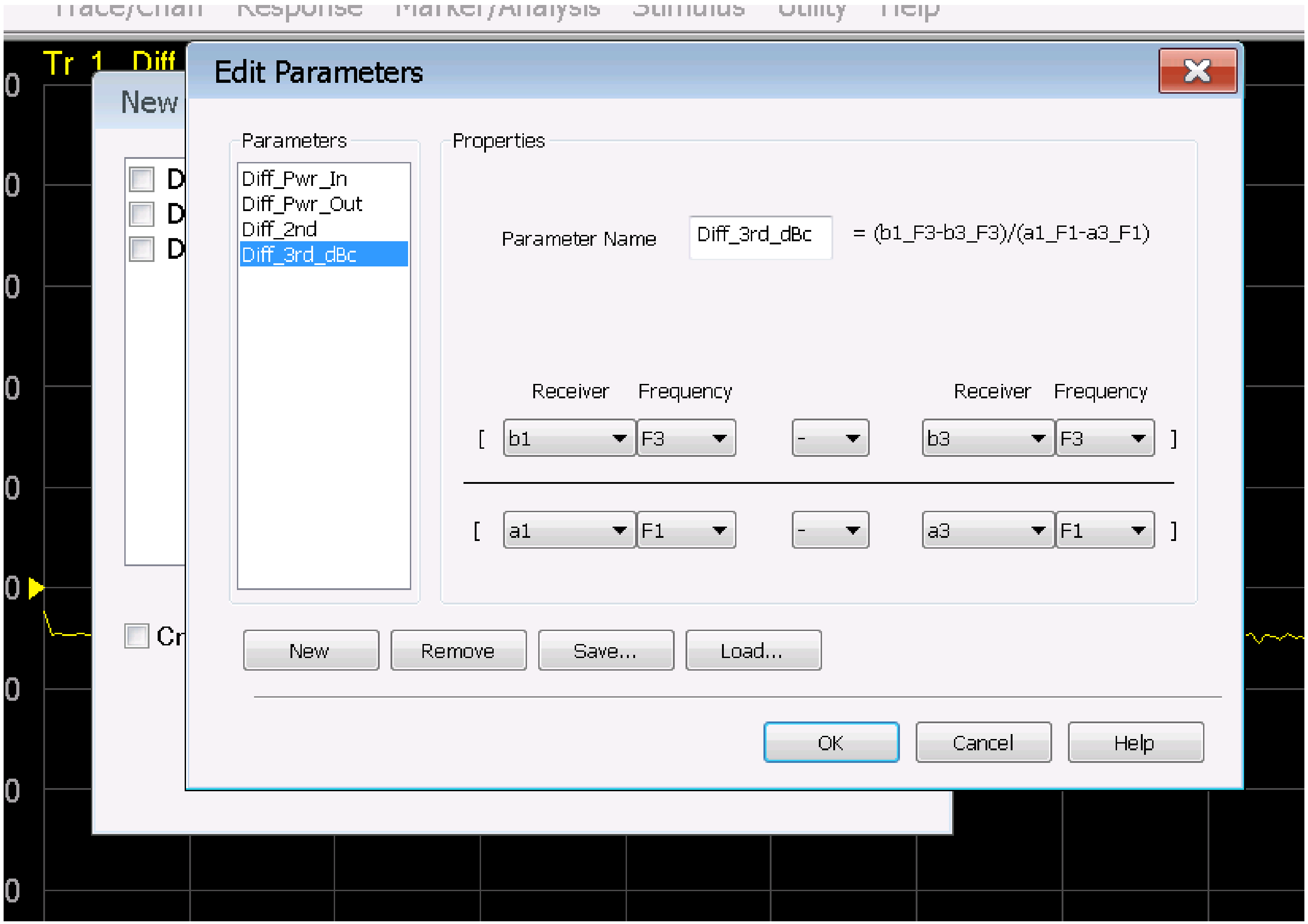
Set the Power and Phase

Finally, Define the Parameters to Measure based on receivers

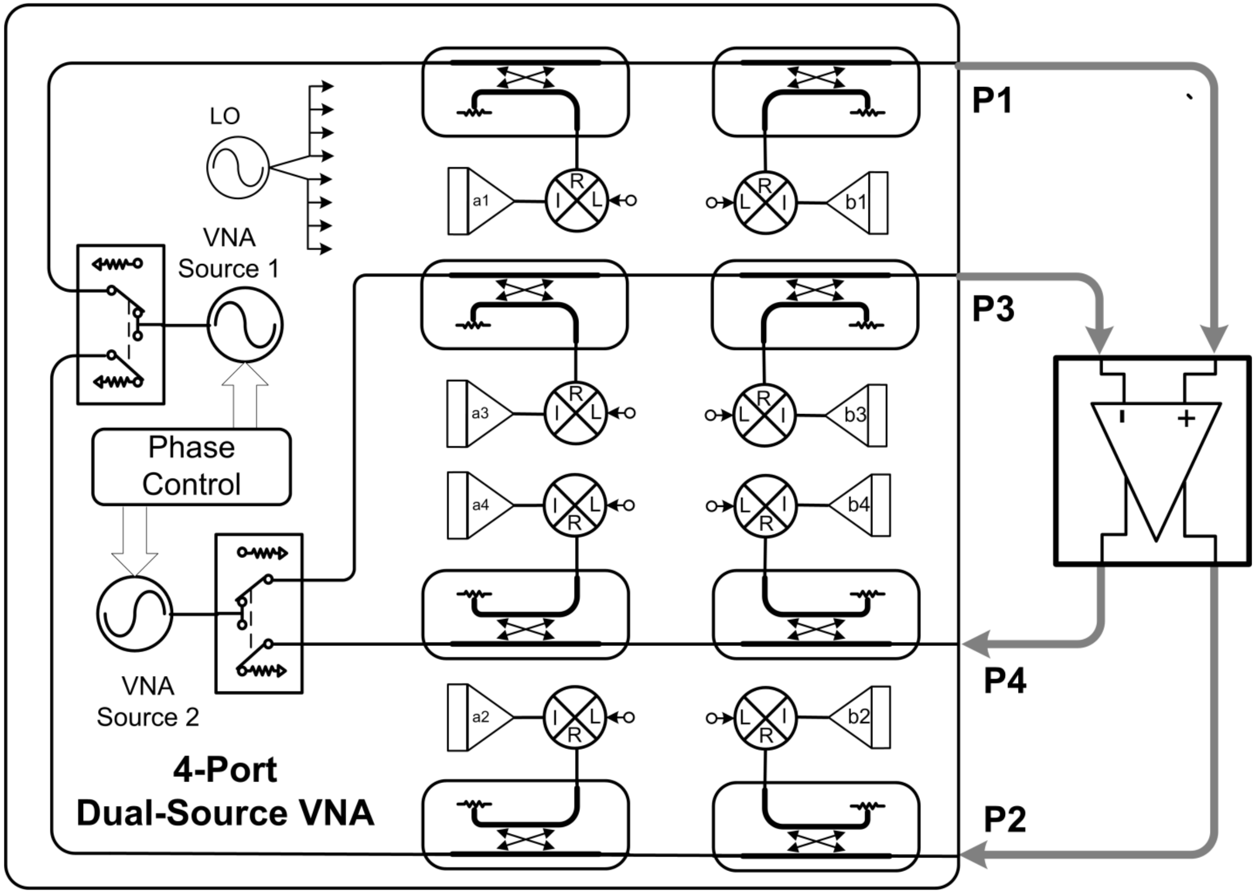
Use
“Edit Parameters”
To create new
measurements



Create New Parameters based on measurements of ANY receiver at ANY frequency



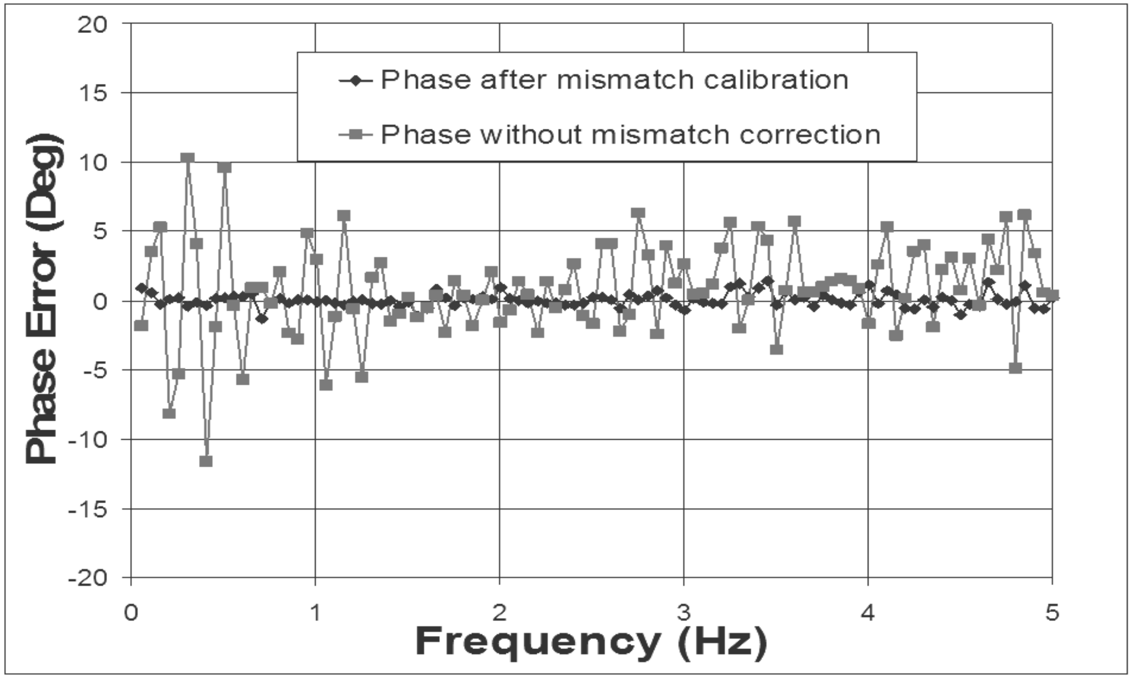
Making True-mode (true differential) measuerments



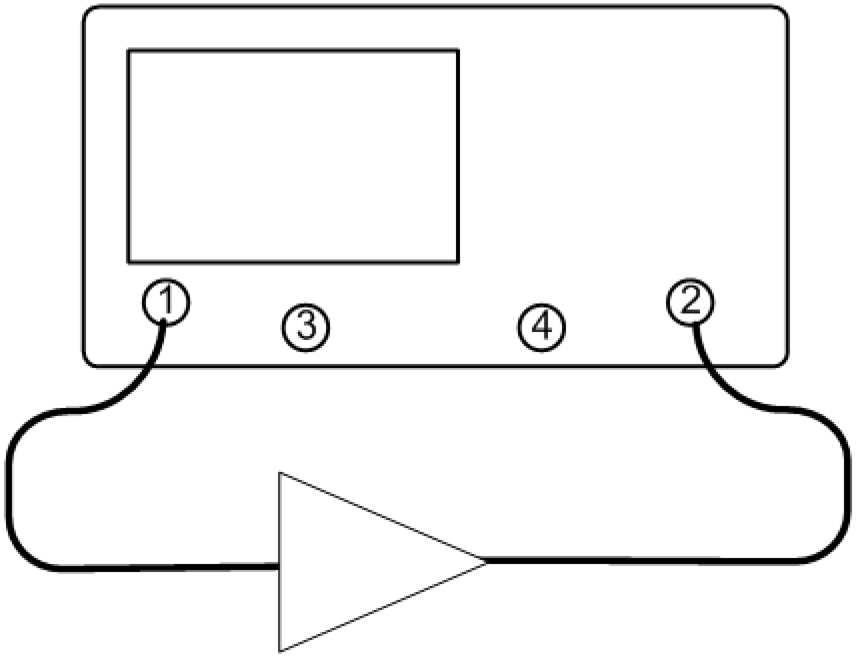
Two sources are controlled to set the differential input, and then the receivers are retuned to measure any other signal, such as output power or harmonics.

Differential signals must be actively adjusted for each new DUT S11 due to mismatch effects and requires special correction

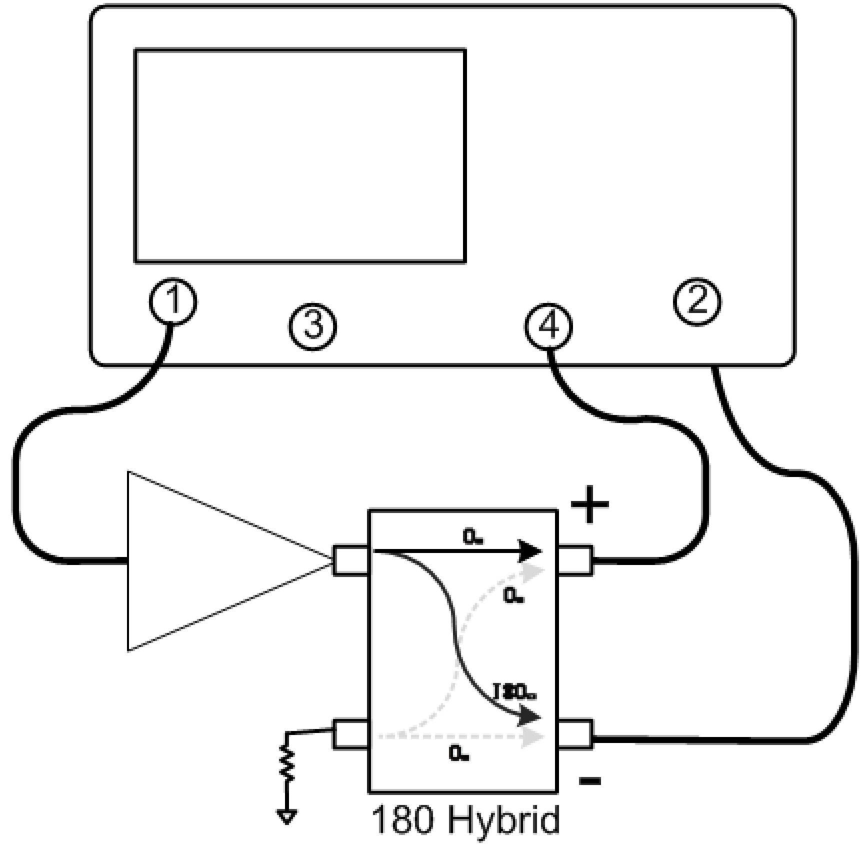
$$\frac{a_1}{a_3} = \frac{\left(a_{1M} ERF_1 + b_{1M} ESF_1 - a_{1M} ESF_1 \cdot EDF_1\right)}{\left(a_{3M} ERF_3 + b_{3M} ESF_3 - a_{3M} ESF_3 \cdot EDF_3\right)} \frac{ETF_{31}}{ERF_1}$$



To test differential harmonic measurements, measure a single-ended amp then add a balun and test again.

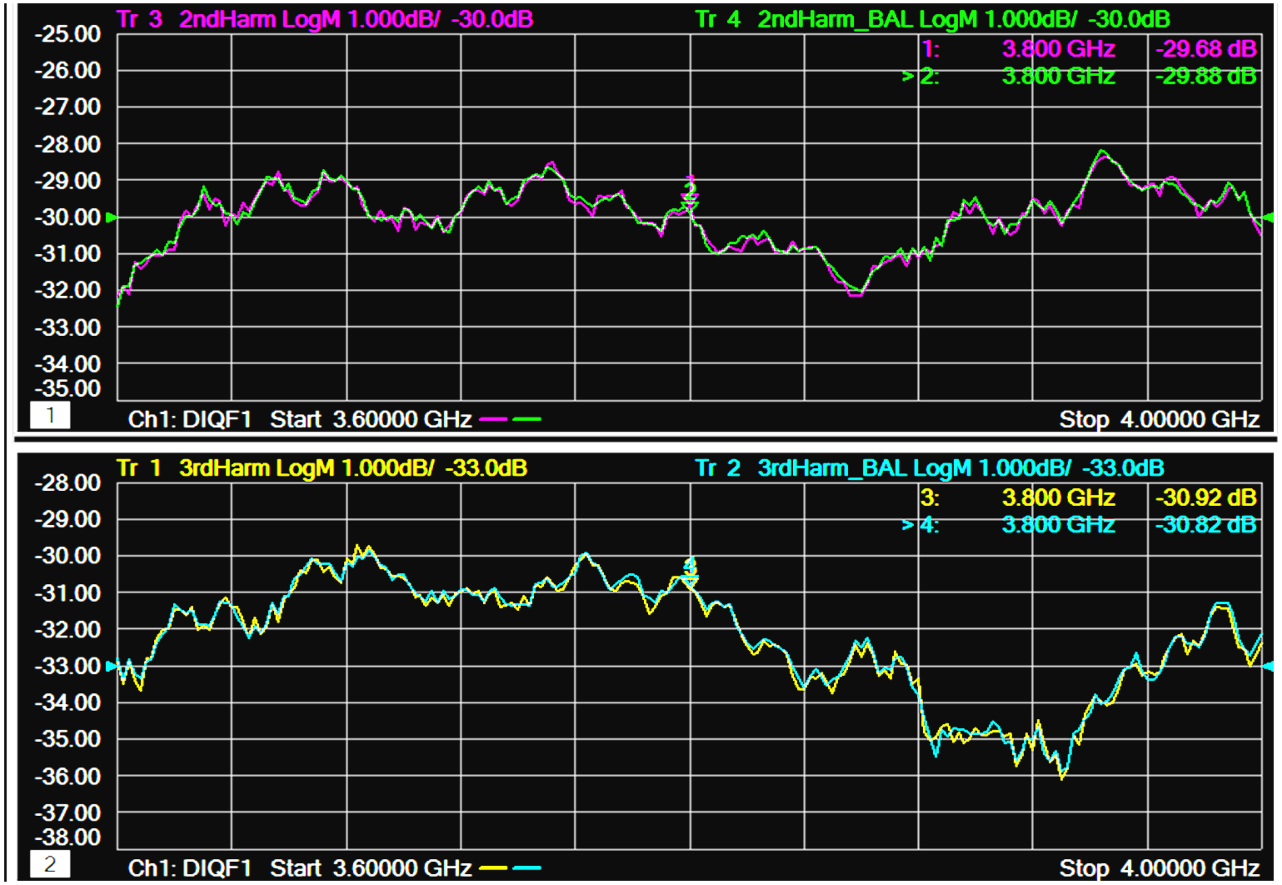


Test1: Harmonics of an SE amp



Test2: Measure Harmonics using Differential Receivers

Example Measurement: Differential Output and Harmonics

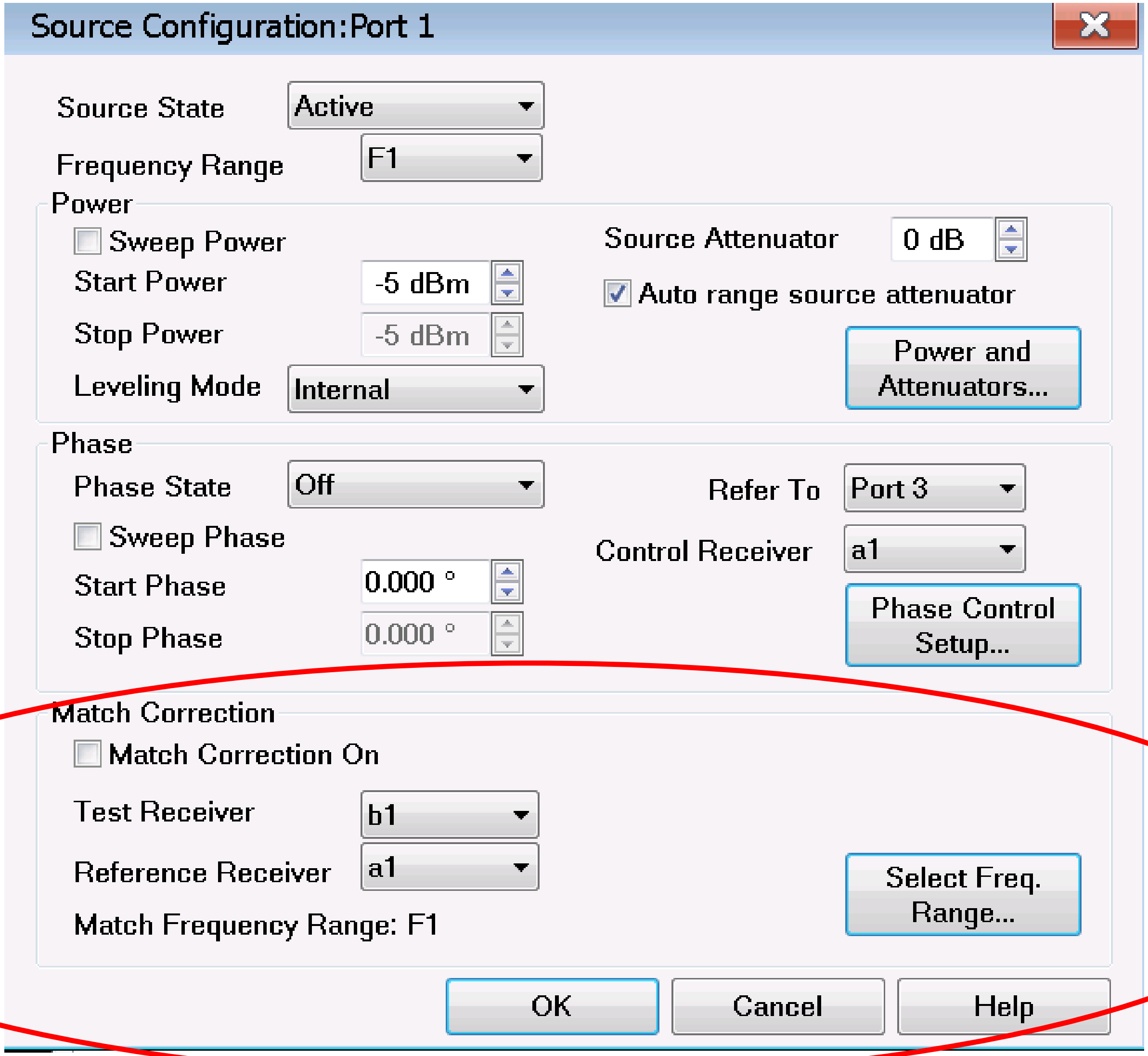


Upper Compares 2nd Harmonic Result; Lower Compares 3rd Harmonic Result.
Difference maybe due to hybrid effects (different loss at fundamental and harmonic

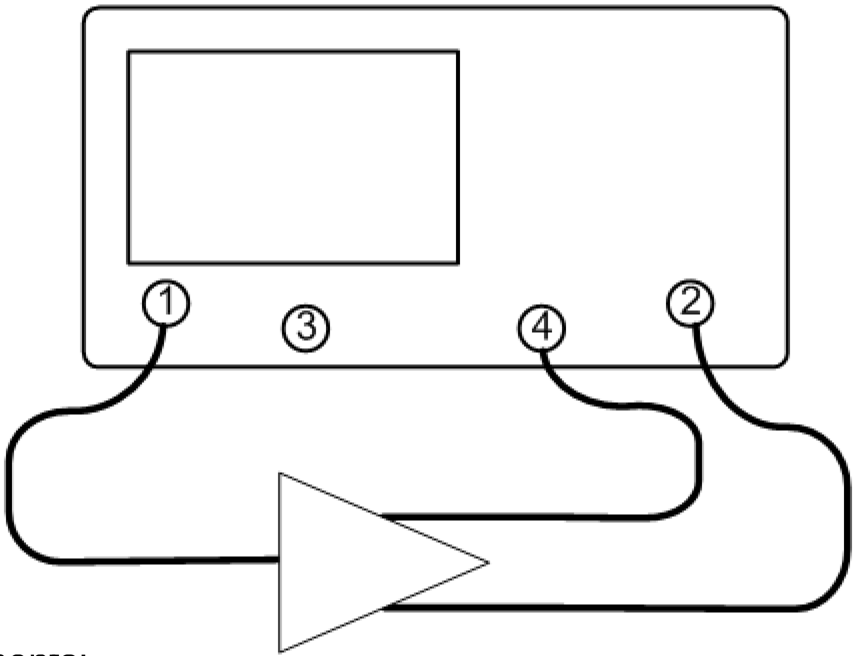
Calibration for Differential Output Power:

- Calibration for mismatch and response must use stimulus source for characterizing error terms
- During the measurement, output power mismatch terms (S22) need to be characterized with the input source off
- Match correction can be independently selected for any source, using any receivers, and any frequency range
  - User defined receivers allows match correction on a variety of complex situations such as sources passed through high-power amplifiers and using external couplers; and external sources applied through the test set.

Source definition page includes match correction choices



Planned: Use Case 2 : Measuring Harmonics of SE- Balanced Amplifiers



Test Requirements:

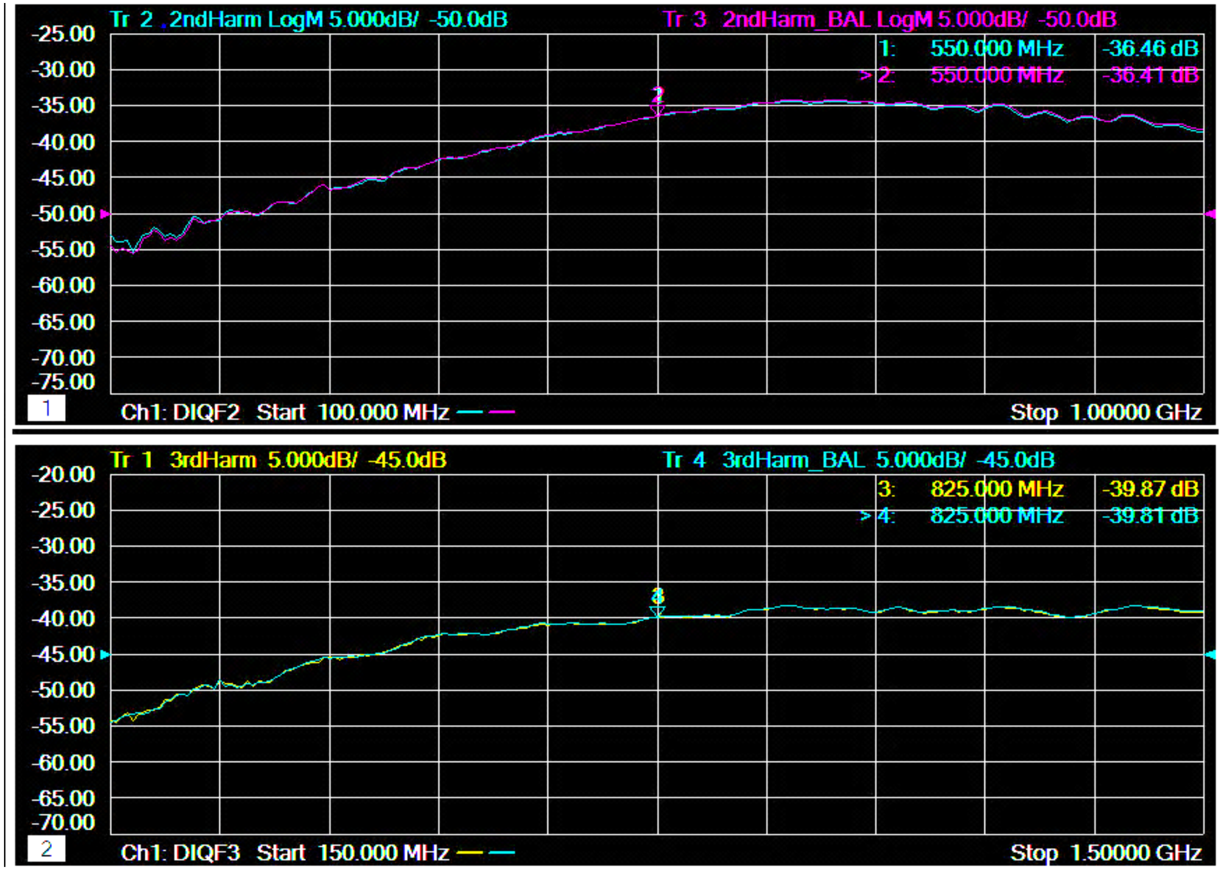
- Stimulate the input with leveled input signal
- Measure the input power
- Measure the output differential power
- Measure the output differential power at N harmonics, N a small integer (5)
- Provide corrected measurements of power, provide leveled input power
- Measure with swept frequency, swept power or swept phase input
- Function in pulsed mode

Wants:

- Provide leveled output power

Notes: In this case there is NO phase controlled source, just offset harmonics and balanced power

Example Measurement: Single-ended and Differential Mixer, with Harmonics



Harmonics are in dBc Values

Use Case: Dual Mixer;

Key measurement difficulty is relative phase response between the two paths of the mixer.

Drive both mixers with identical signals, measure the relative output (magnitude and phase)

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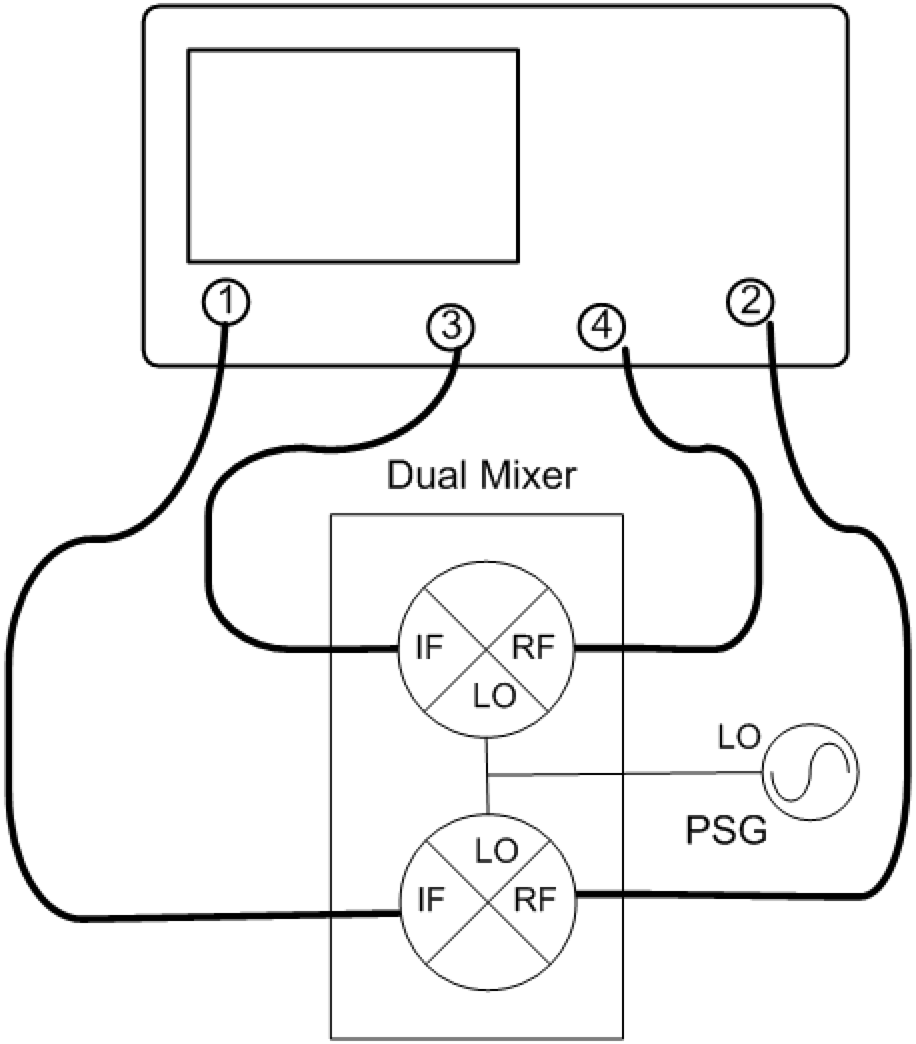
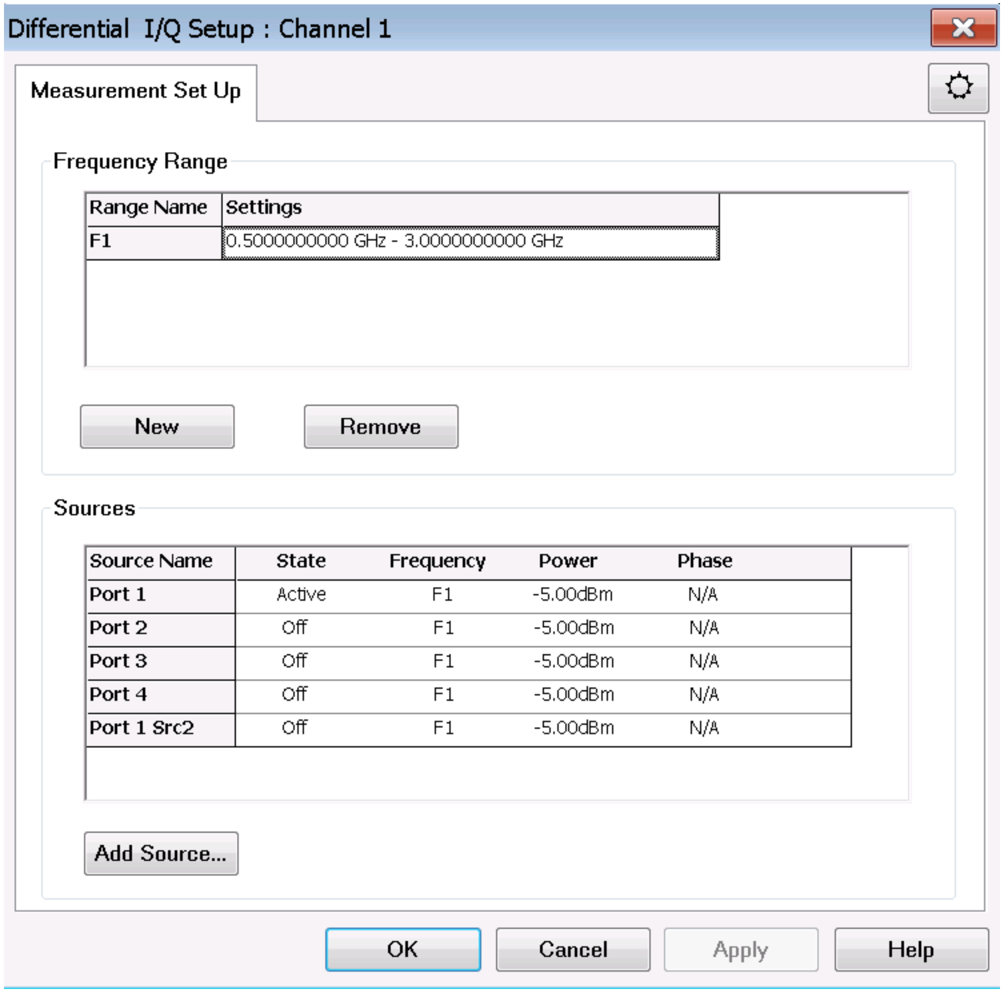
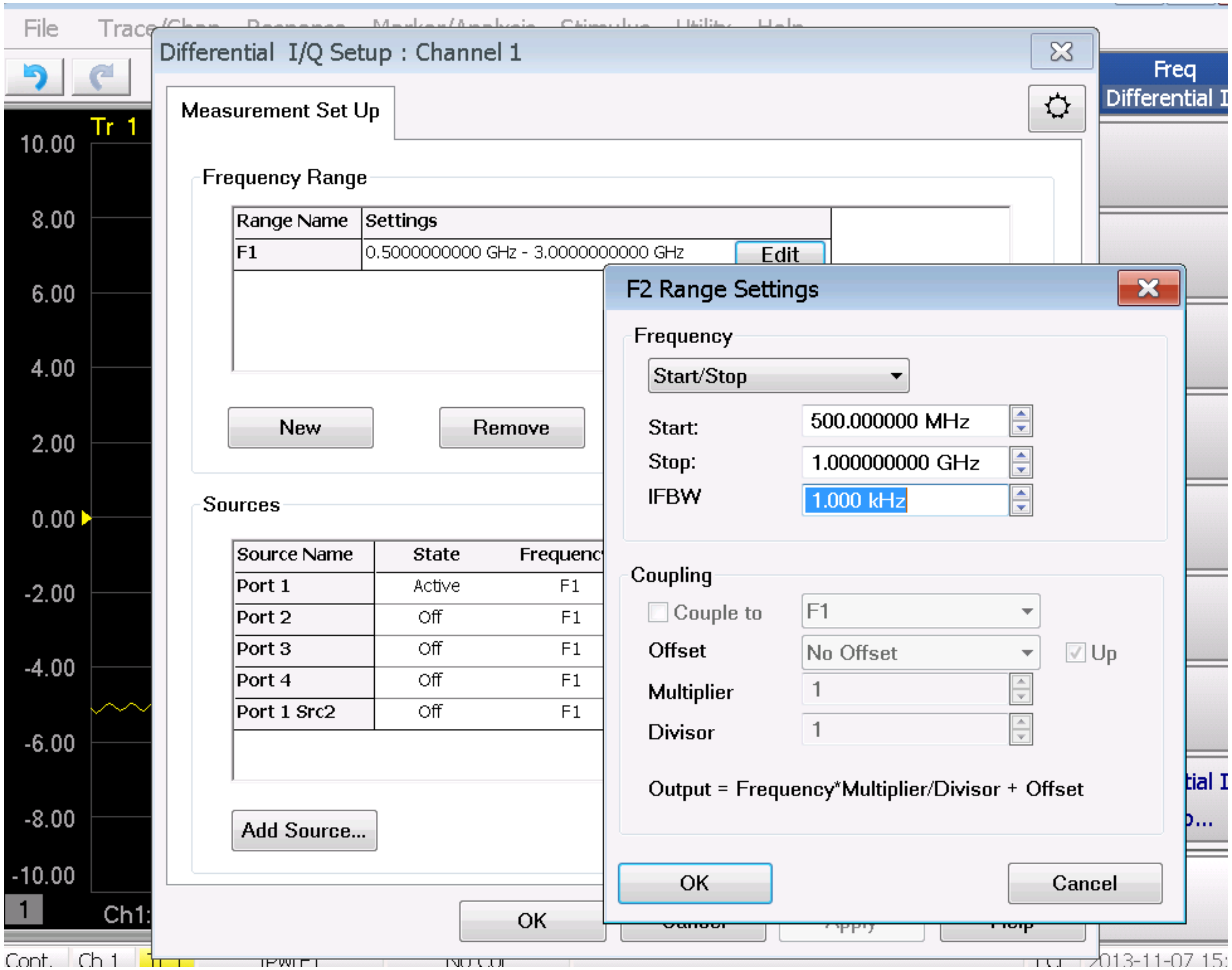


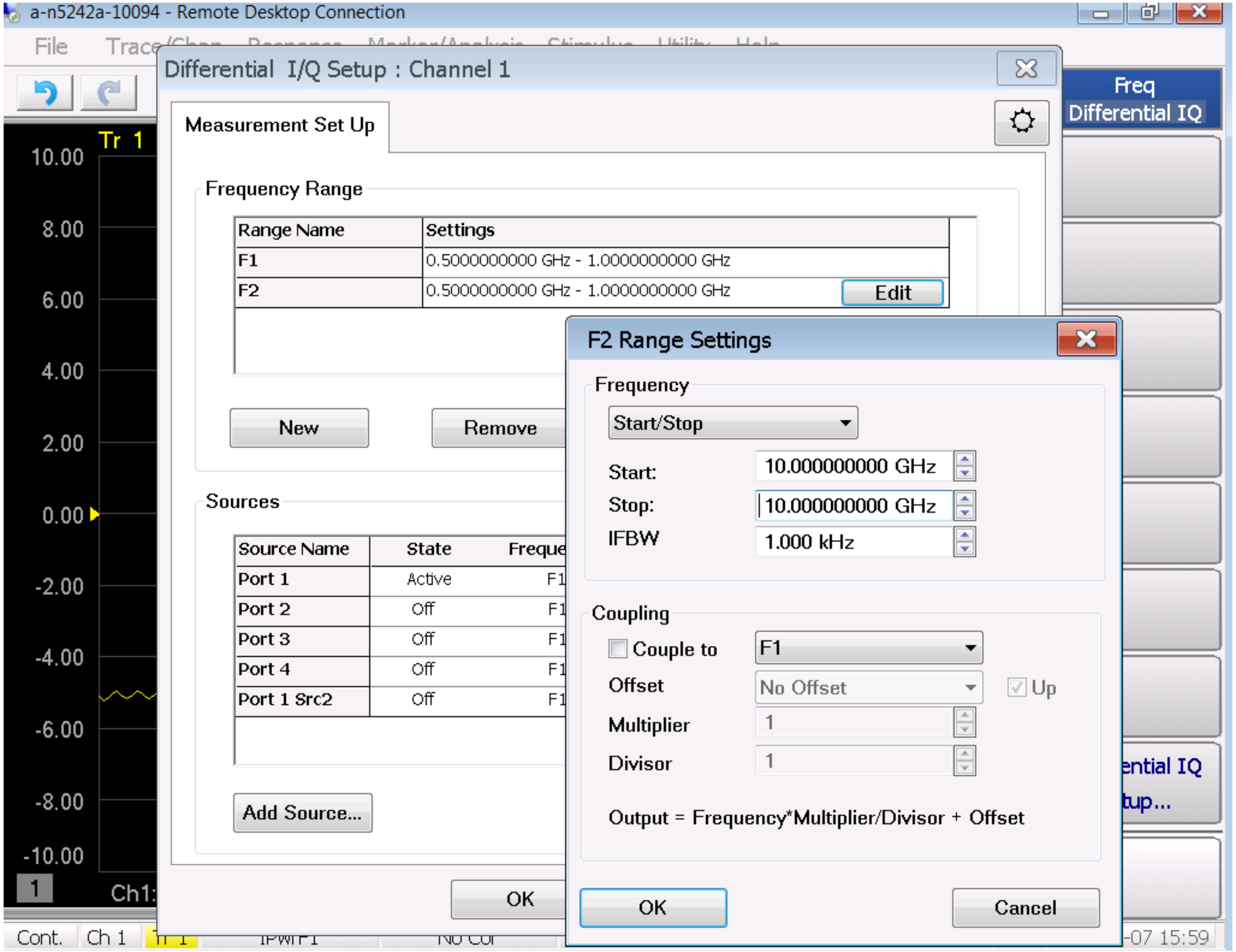
Dual Mixer: Creating the Frequency Plan - start



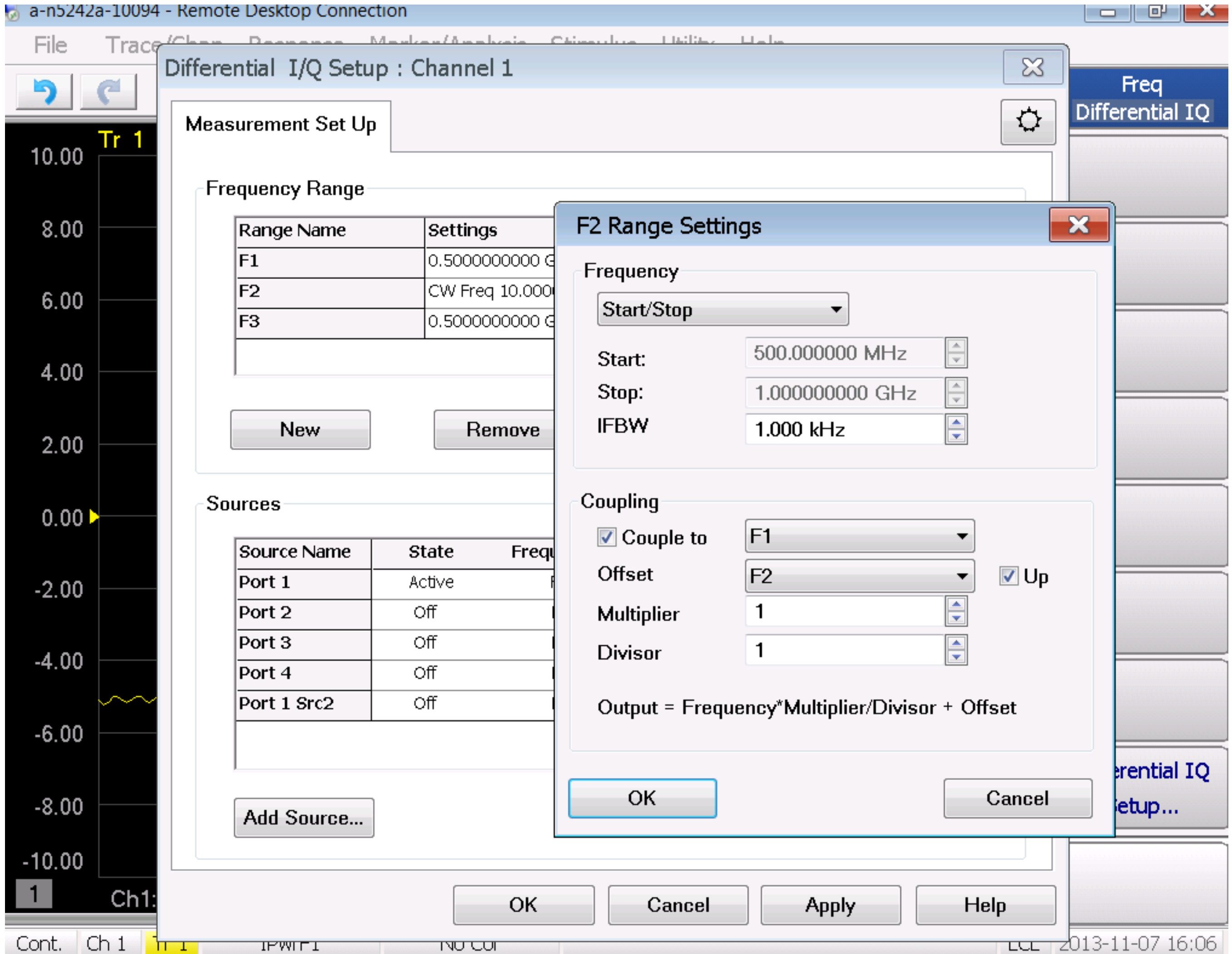
Dual Mixer: Creating the Frequency Plan – set the input frequencies



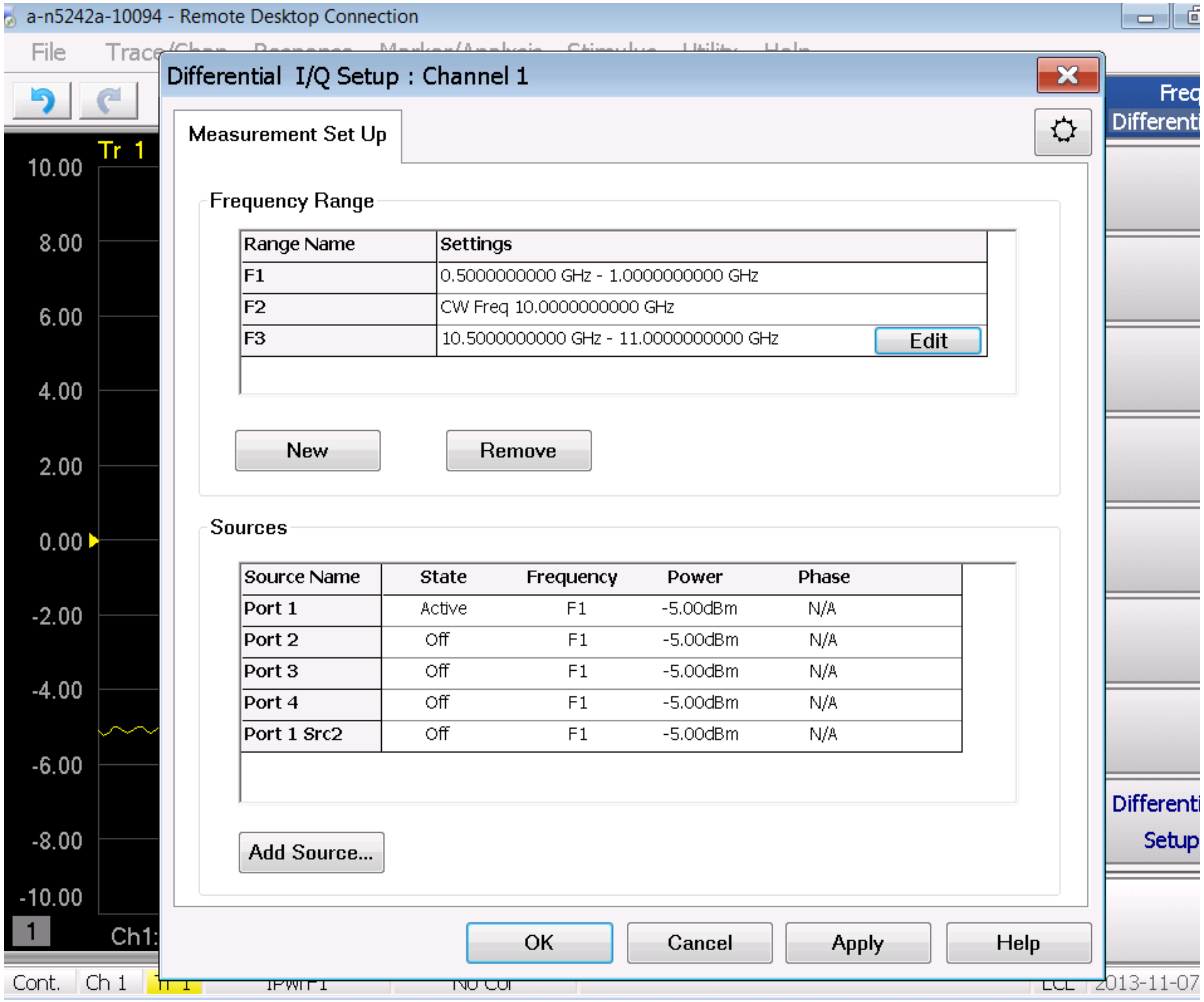
Dual Mixer: Creating the Frequency Plan – add the LO, fixed 10 GHz



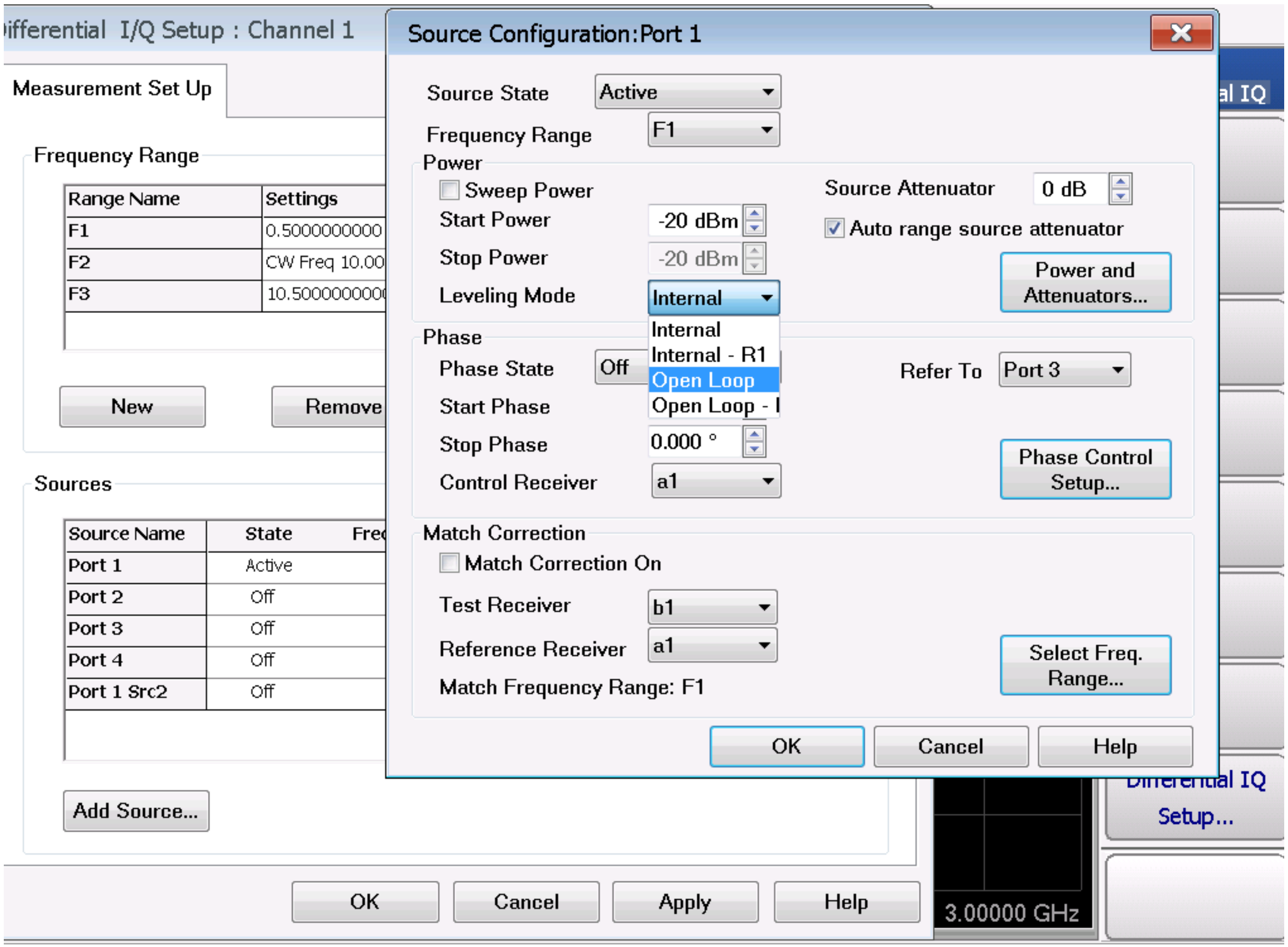
Dual Mixer: Creating the Frequency Plan – Add the output receiver frequencies



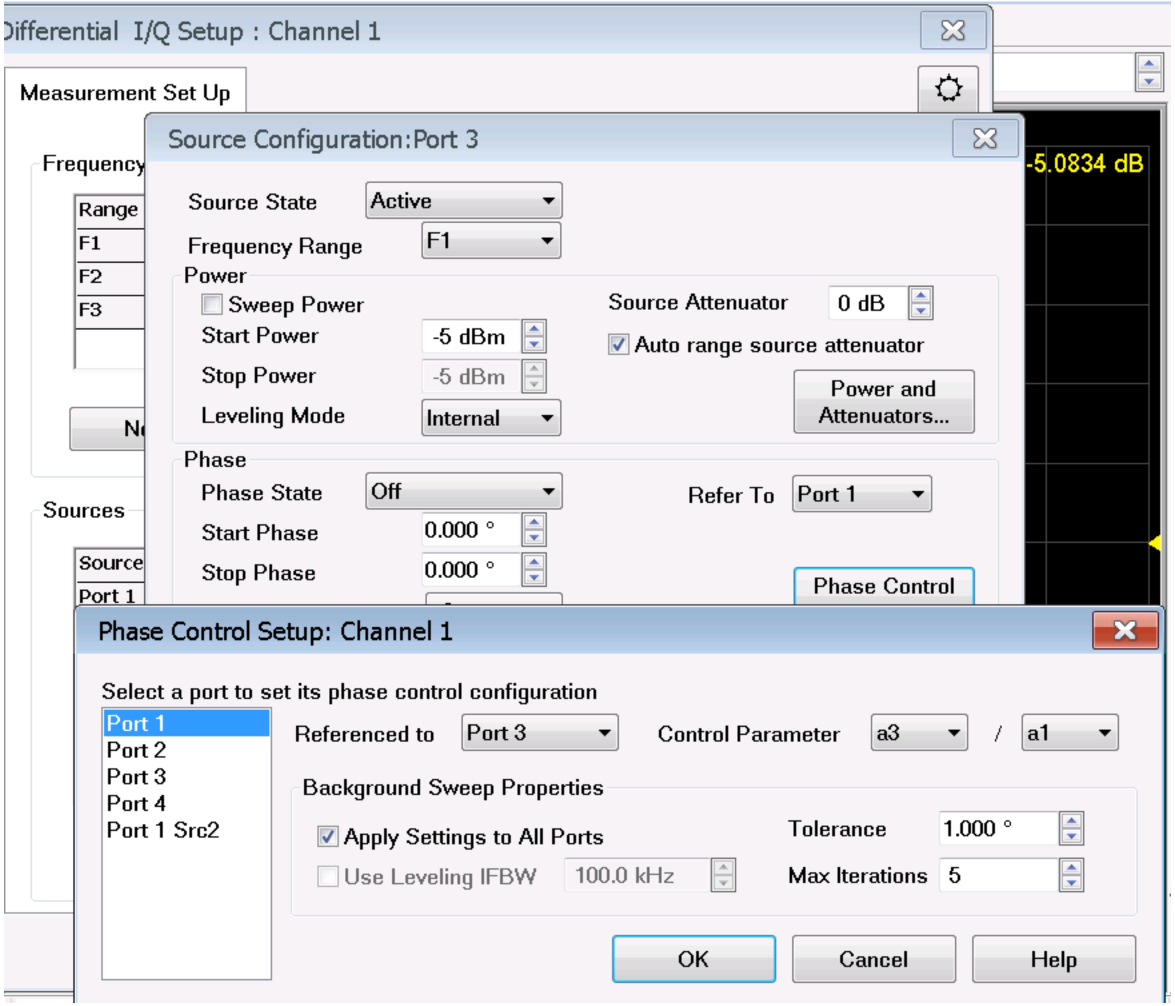
Dual Mixer: Creating the Frequency Plan – Final frequency Plan



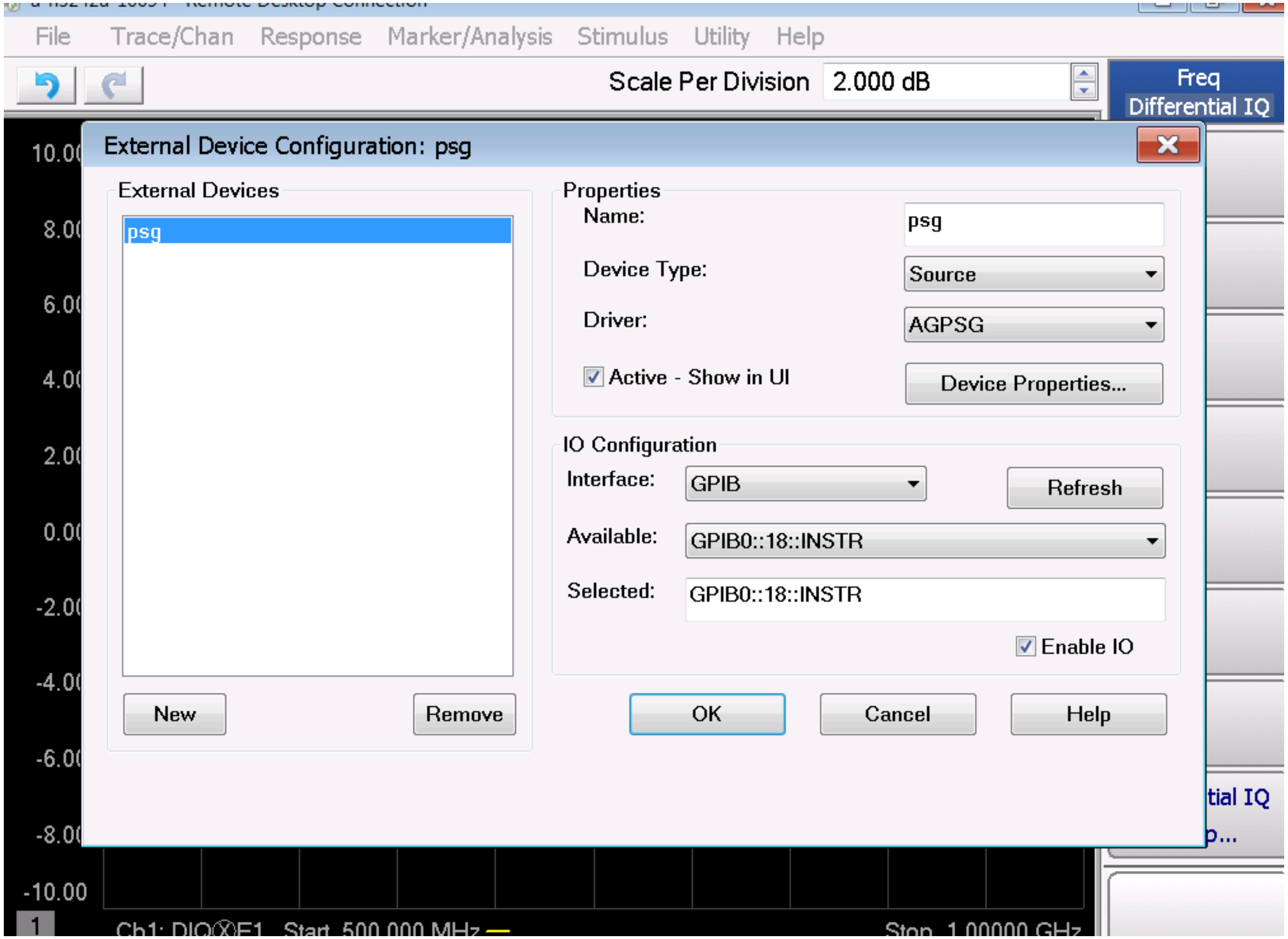
Dual Mixer: Setup the sources, start with port 1



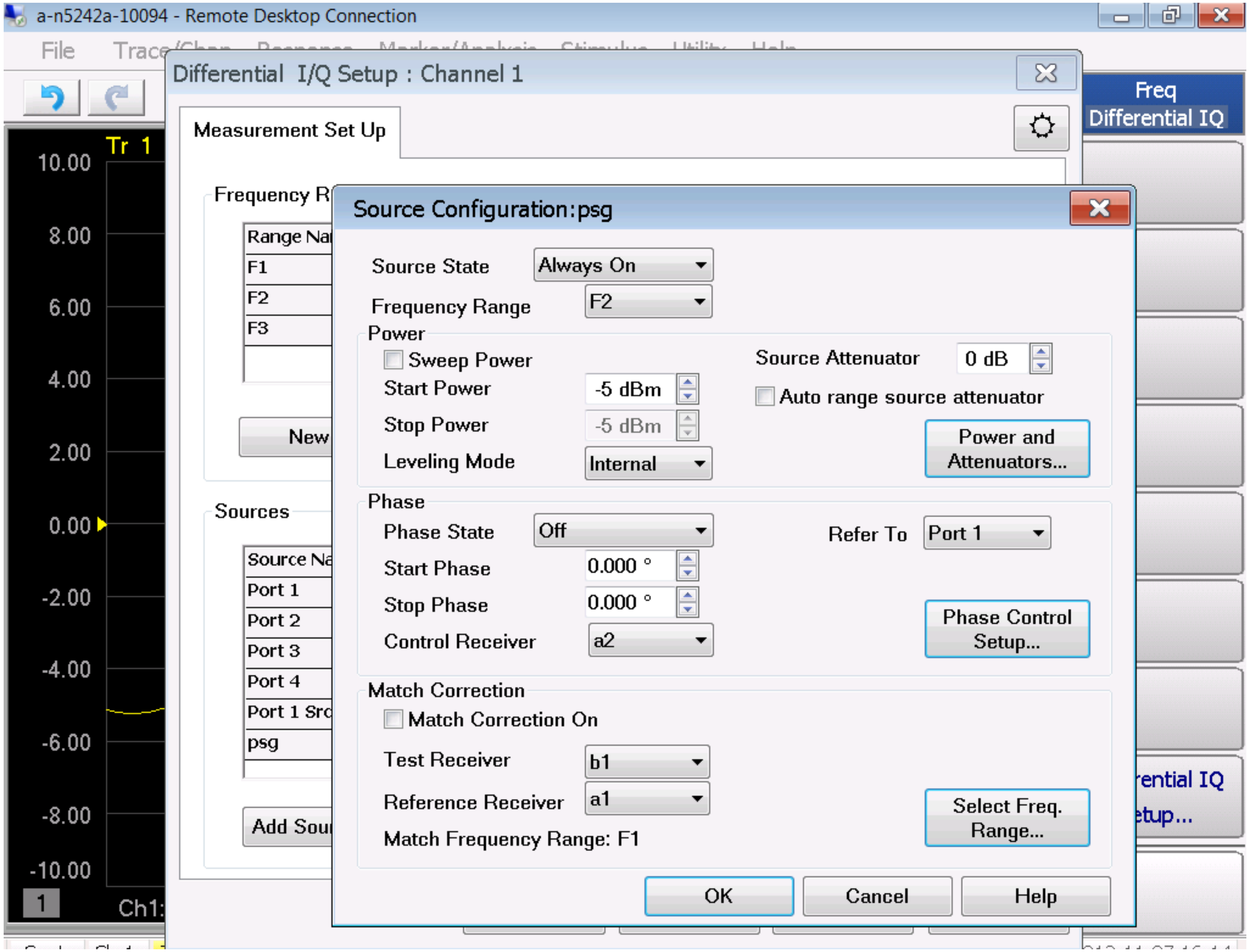
Dual Mixer: Setup the sources, add port 3, and make it match P1 phase.



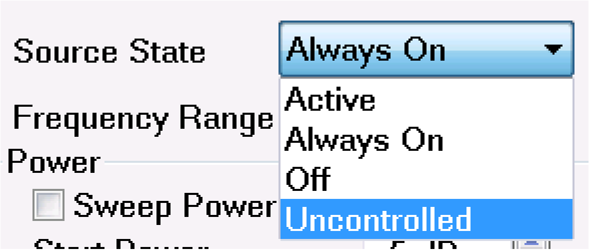
Dual Mixer: Setup the sources, add the PSG



Dual Mixer: Setup the sources, add the PSG



Let's try to understand Source State: It's flexible but maybe a little confusing



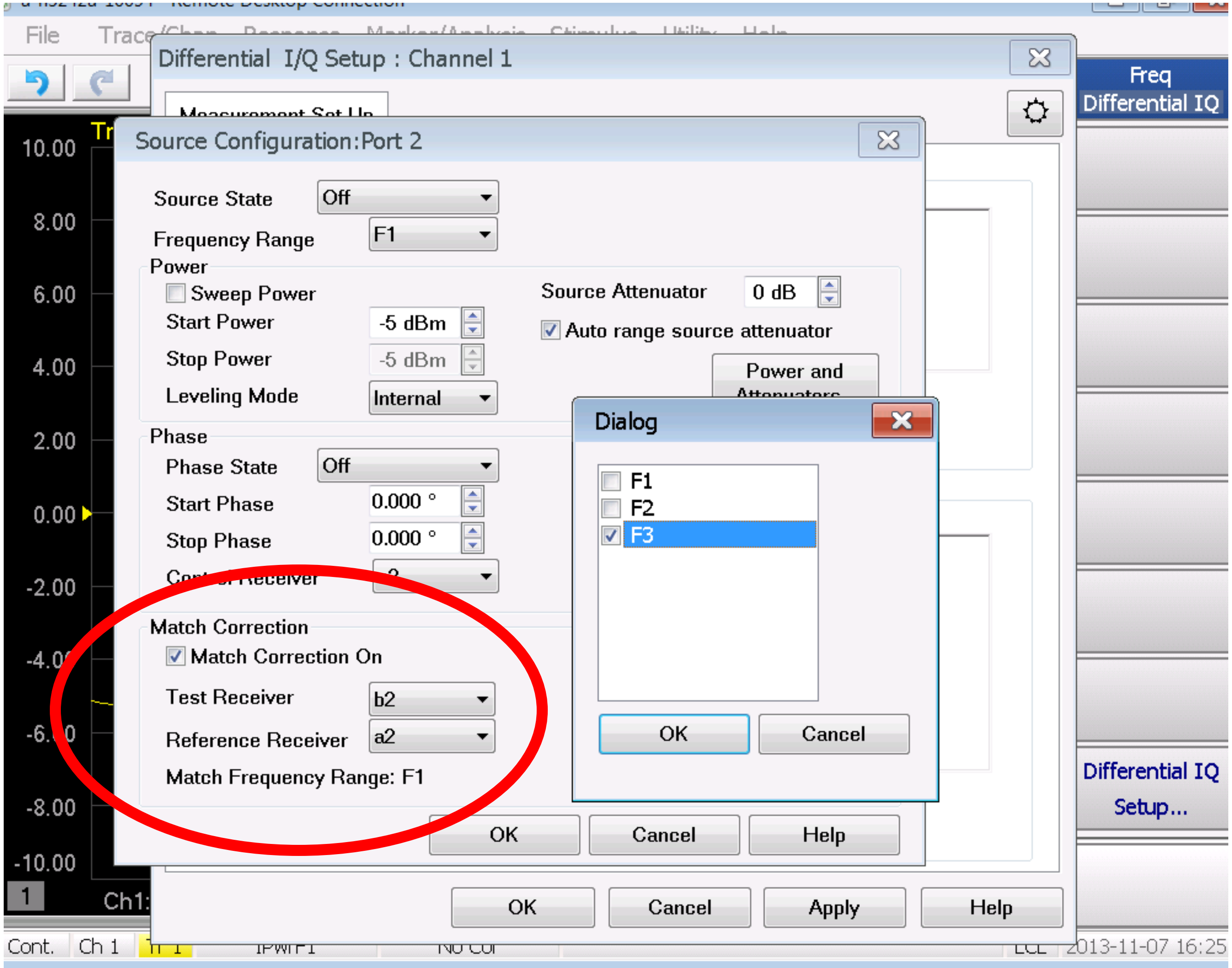
Always On: Always On

Active: turn on during measurement sweep

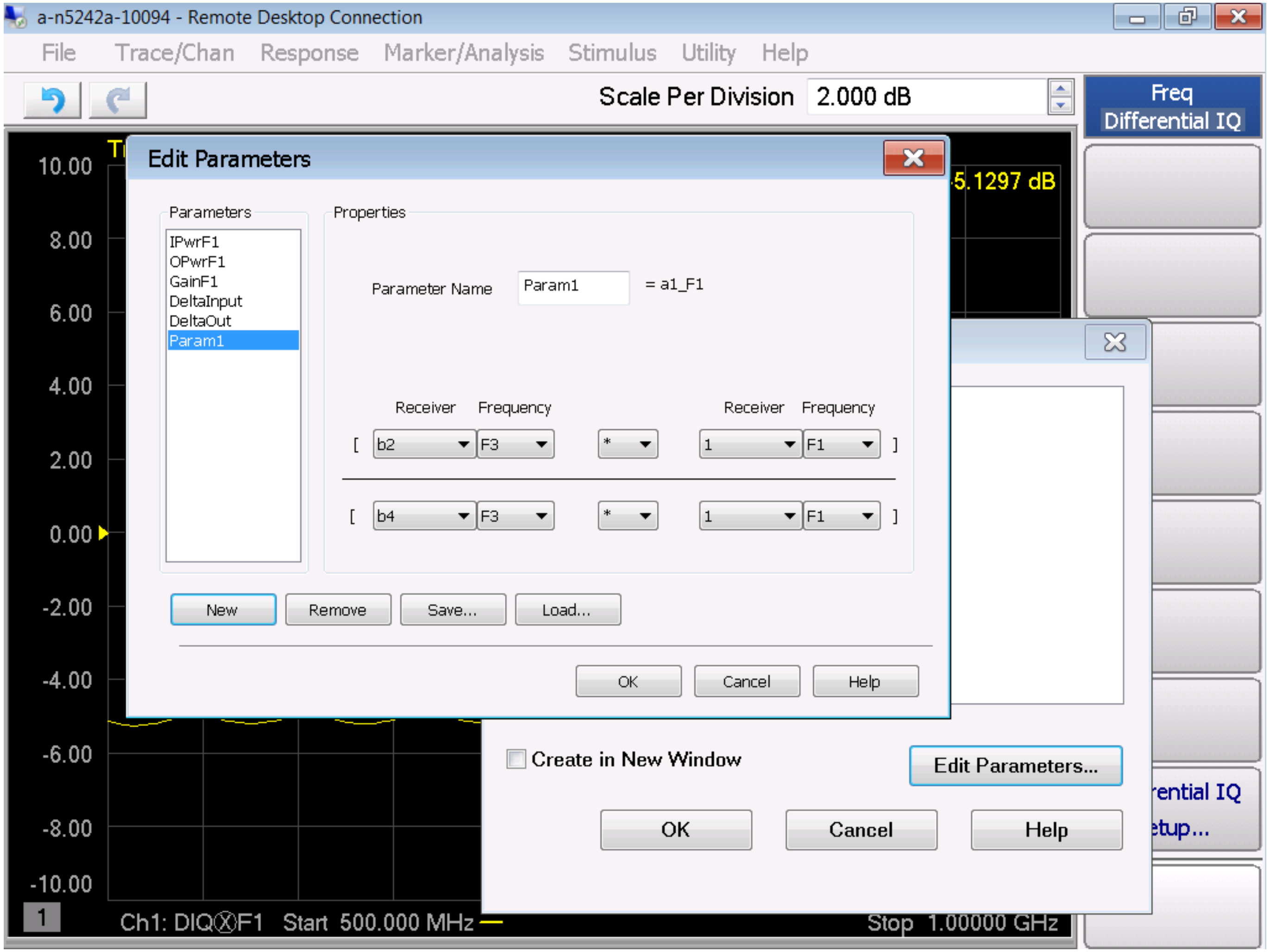
Uncontrolled: don't write to the source at all.

Off: Sometimes OFF unless the source is needed for match correction on that port.

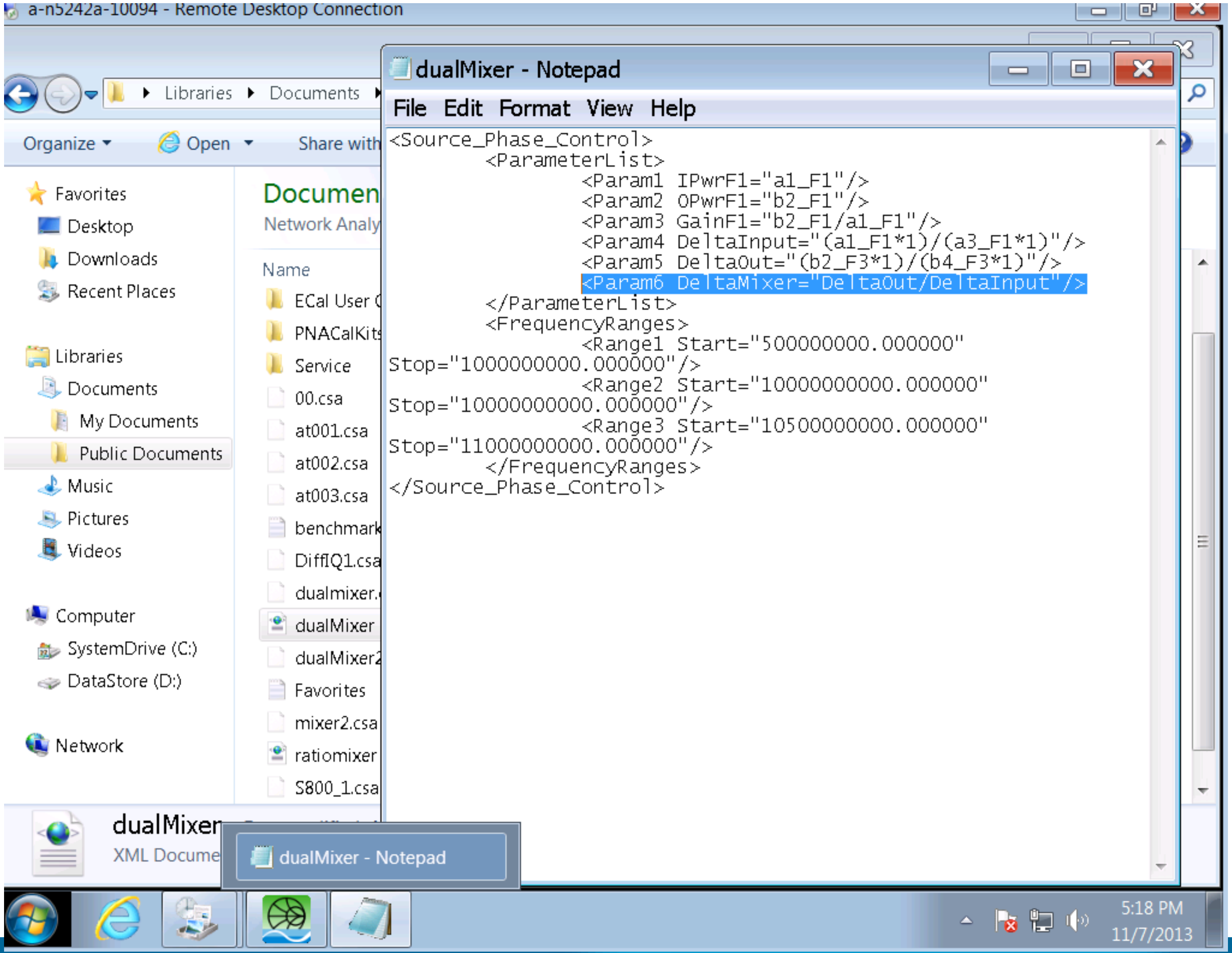
We need match correction for the RF output of the dual mixer



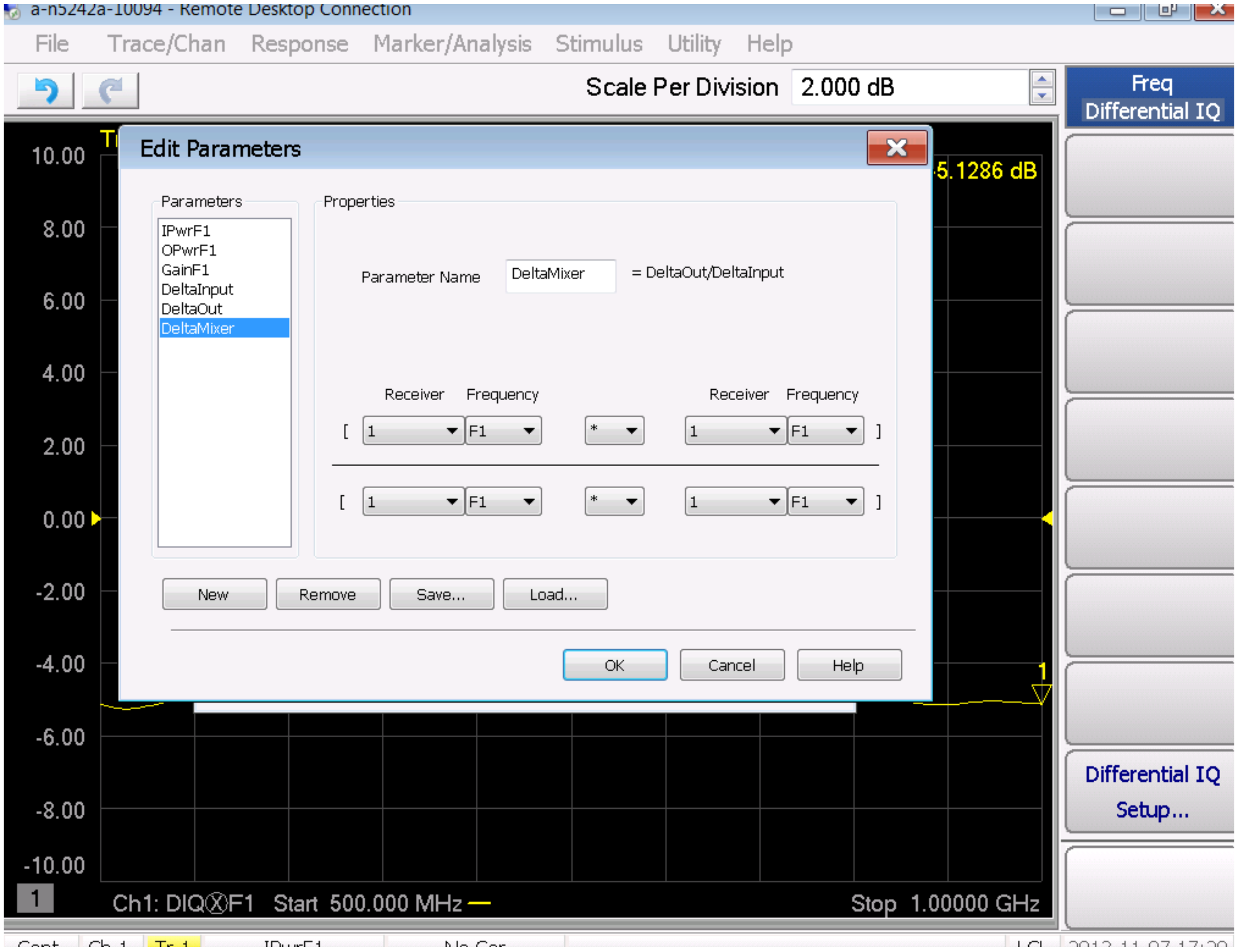
Dual Mixer: setup the mixer Parameters (relative phase input and output, overall relative phase)



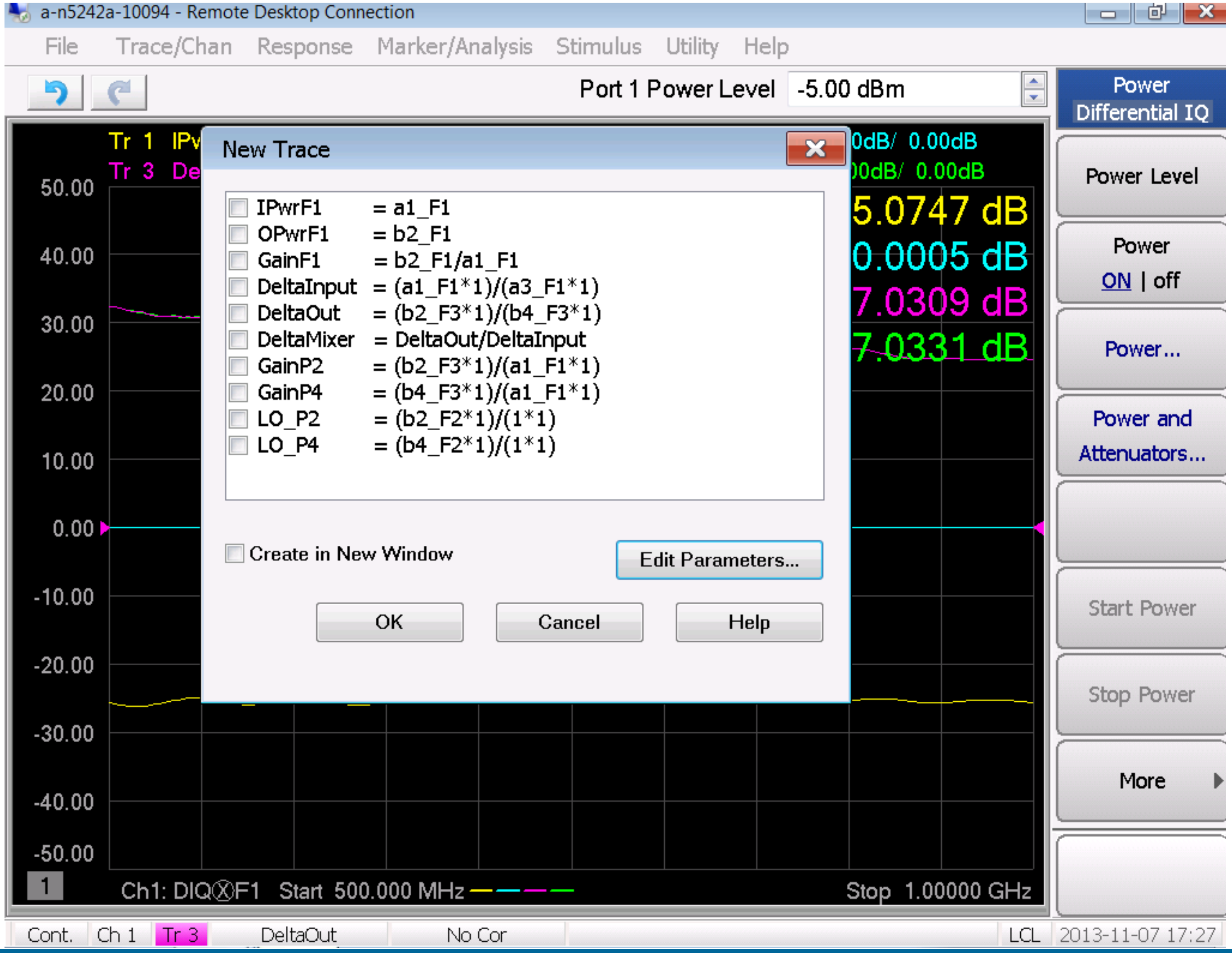
Dual Mixer: Parameter List uses equation editor, so you can ‘hack’ the xml file to create any parameter



Dual Mixer: Now the new parameter shows up.



Dual Mixer: Let's also add gain P2 and gain Port 4, and while were at it, LO leakage to each port.



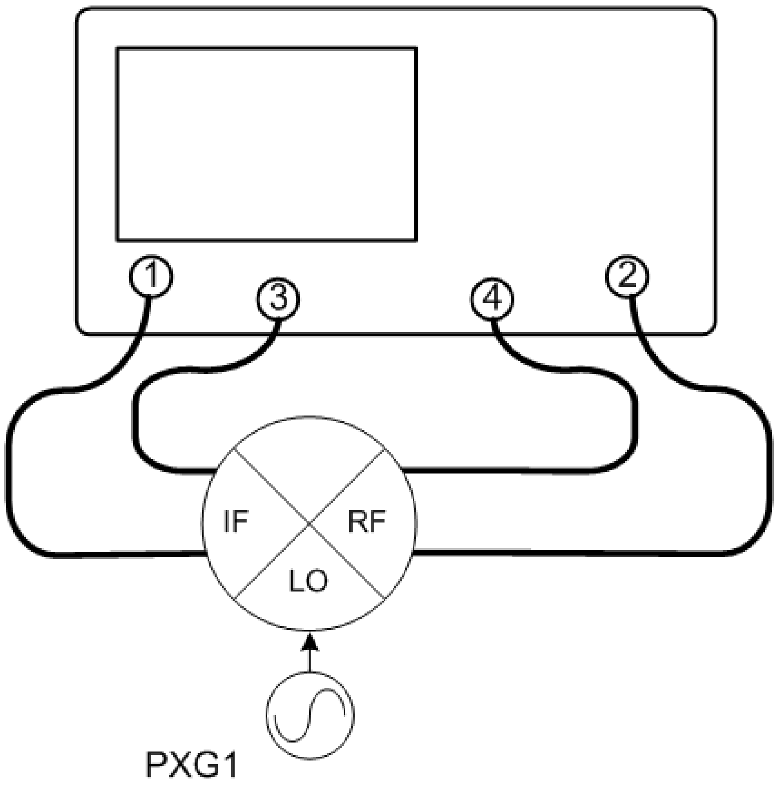
Use Case 4 – Balanced Mixer

Test Requirements:

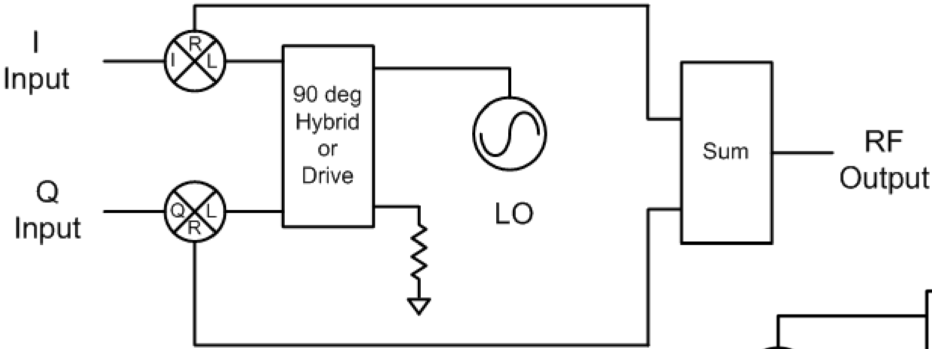
- Stimulate the input with balanced signal
- Measure the input differential power
- Measure the output differential power
- Measure output at both LO+Input (main signal) and LO-Input (Image signal)
  - As of function of frequency
  - As a function of input phase
- LO may be embedded.
- Provide match corrected measurements of power, provide leveled input power.

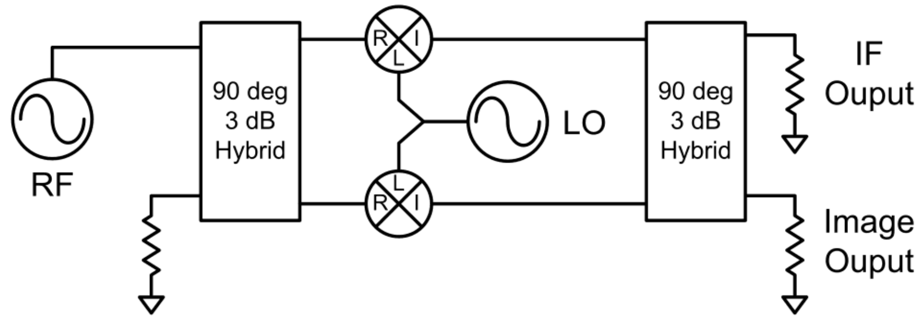
Wants

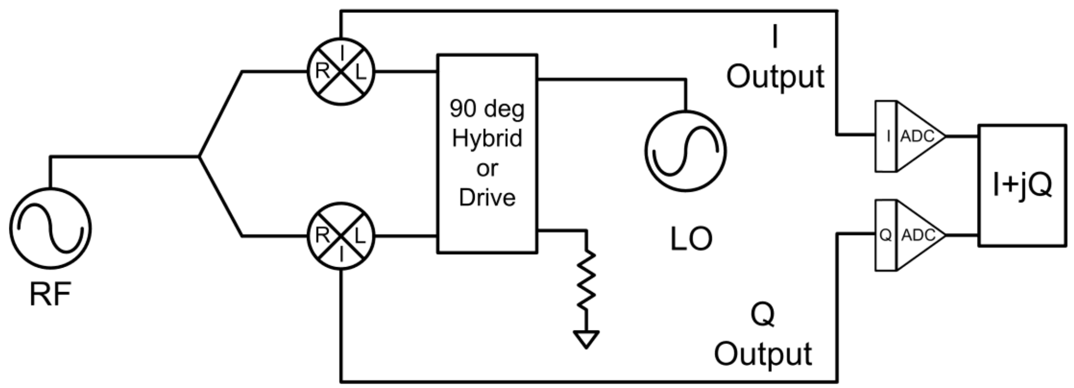
- Measure higher order products of m*LO+-n*Input



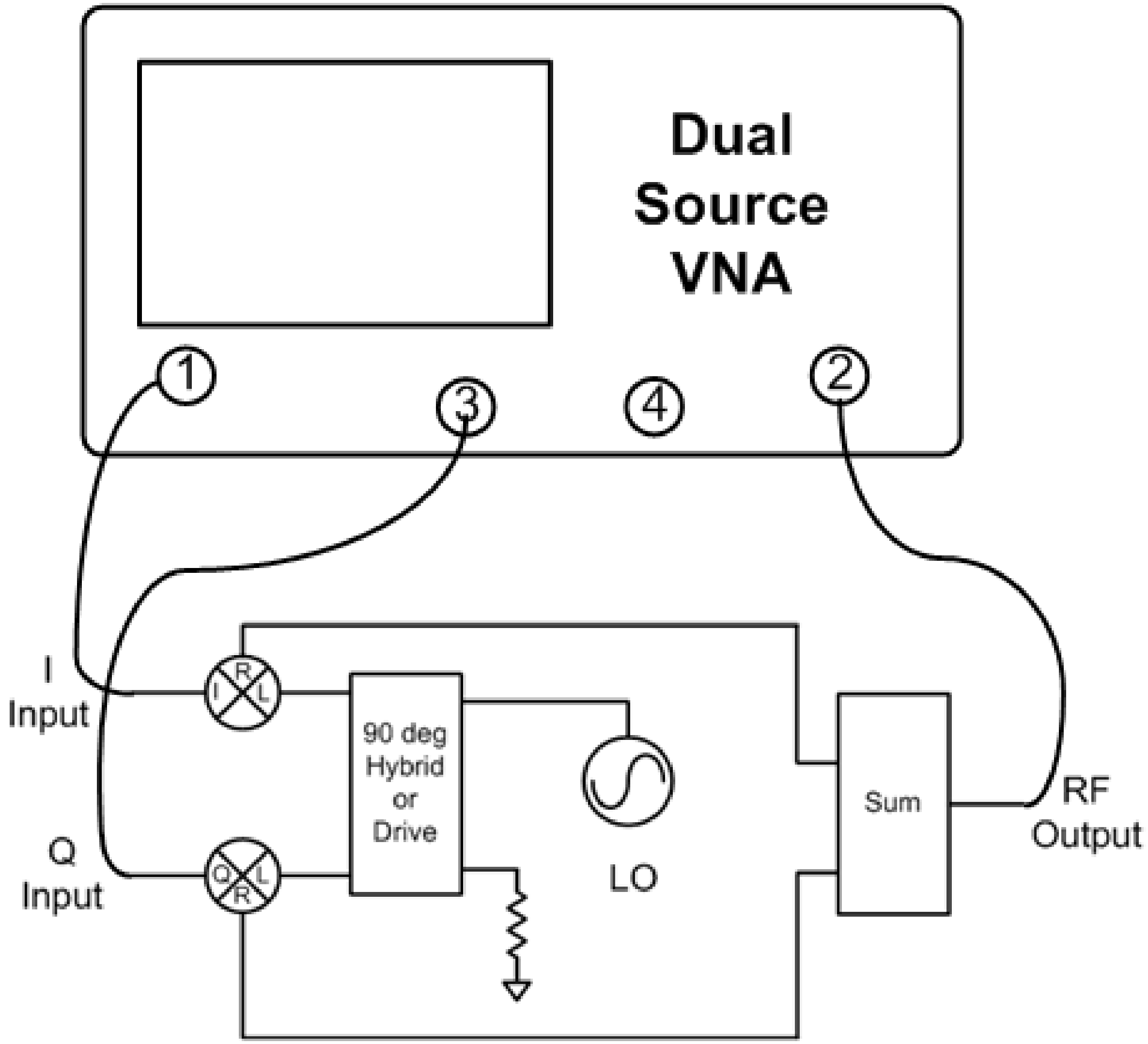
IQ Mixers and Modulators and Down Converters







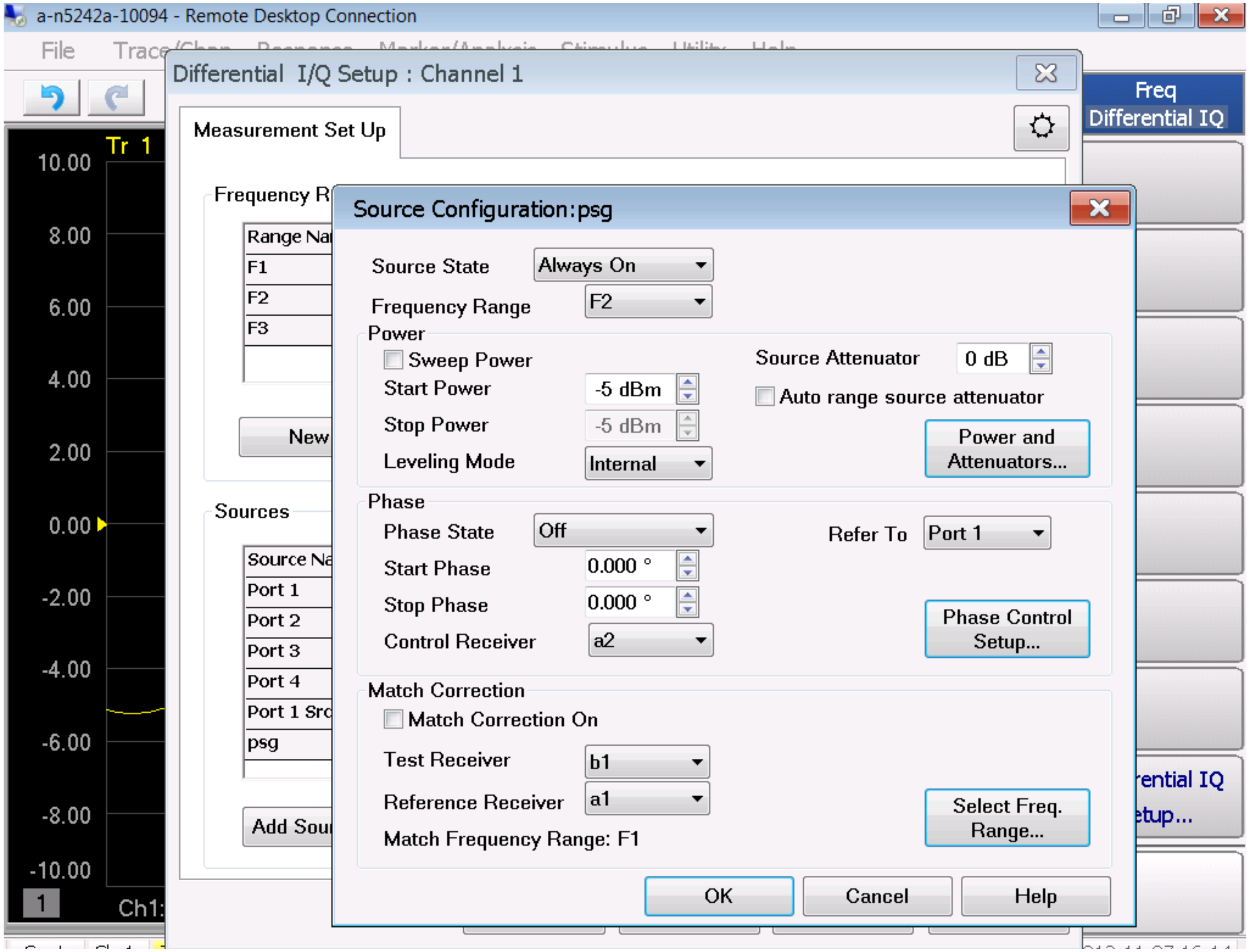
IQ Mixers and Modulators and Down Converters



Making IQ Mixer Measurements

- Special Characteristics of IQ mixer and modulators
  - Image Signal is suppressed
  - Output signal can be on either side of the LO, depending upon the phase of the Q single
  - Provides direct modulation without the need for image filters
  - Key performance criteria:
    - LO Suppression
    - Image Suppression
  - Often requires determining LO, I and Q offsets for optimum performance
    - Very slow and difficult to determine over a wide frequency range.

IQ Mixer Mixer: Setup the sources, make the phase 90 degrees

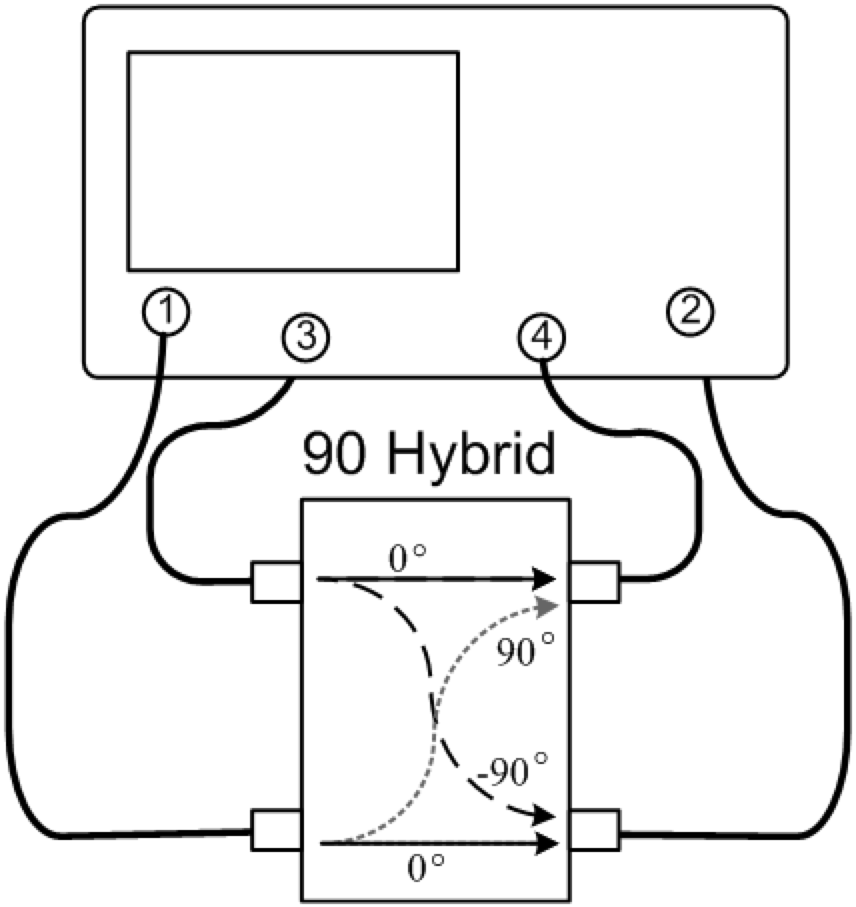


IQ mixer theory

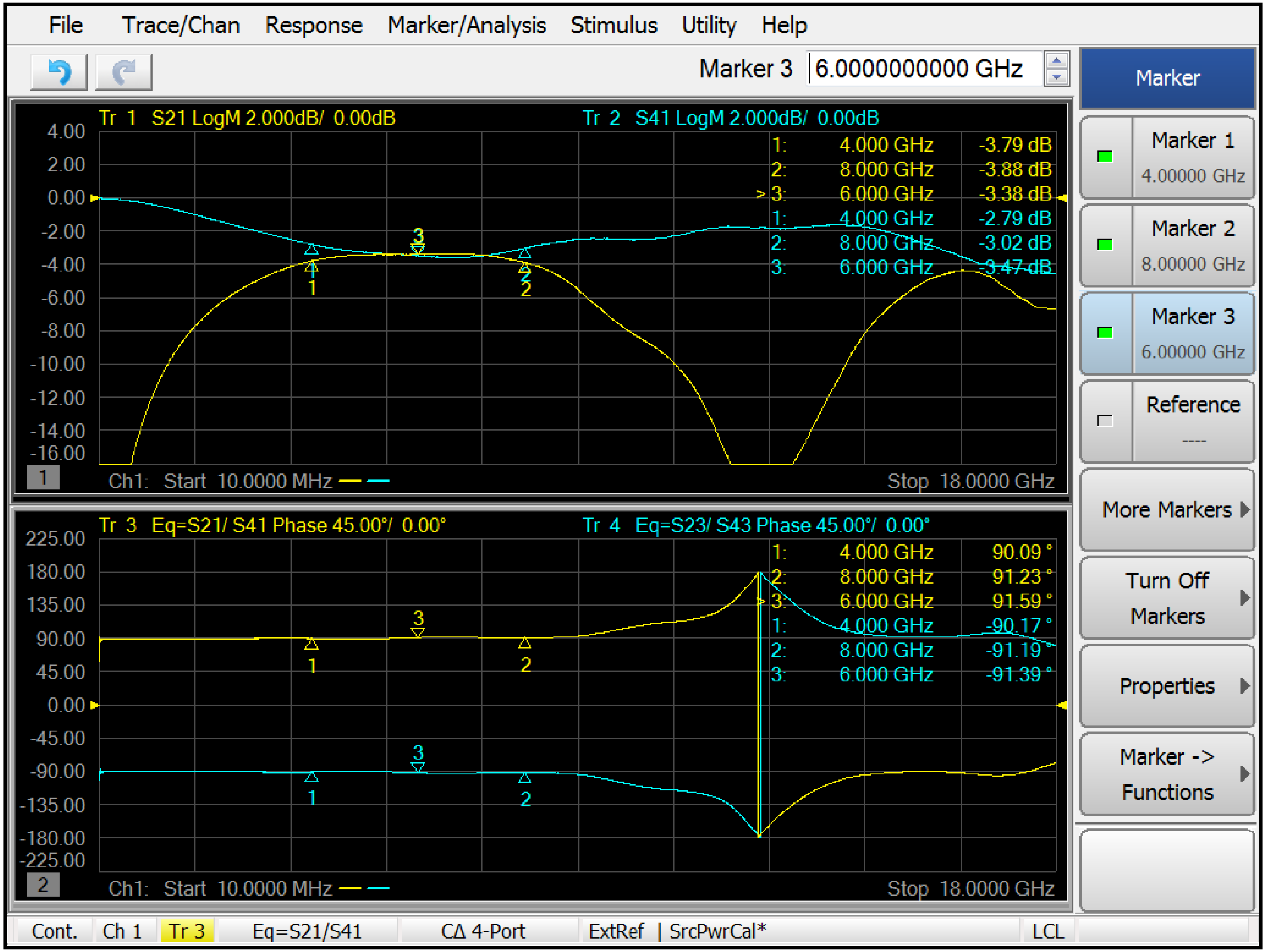
$$a_I = \frac{V_I^F}{\sqrt{Z_0}}, \quad a_Q = \frac{V_Q^F}{\sqrt{Z_0}}, \quad IQ\_power = a_I + j \cdot a_Q$$

User defined parameters can make use of the equation editor to determine the overall input power

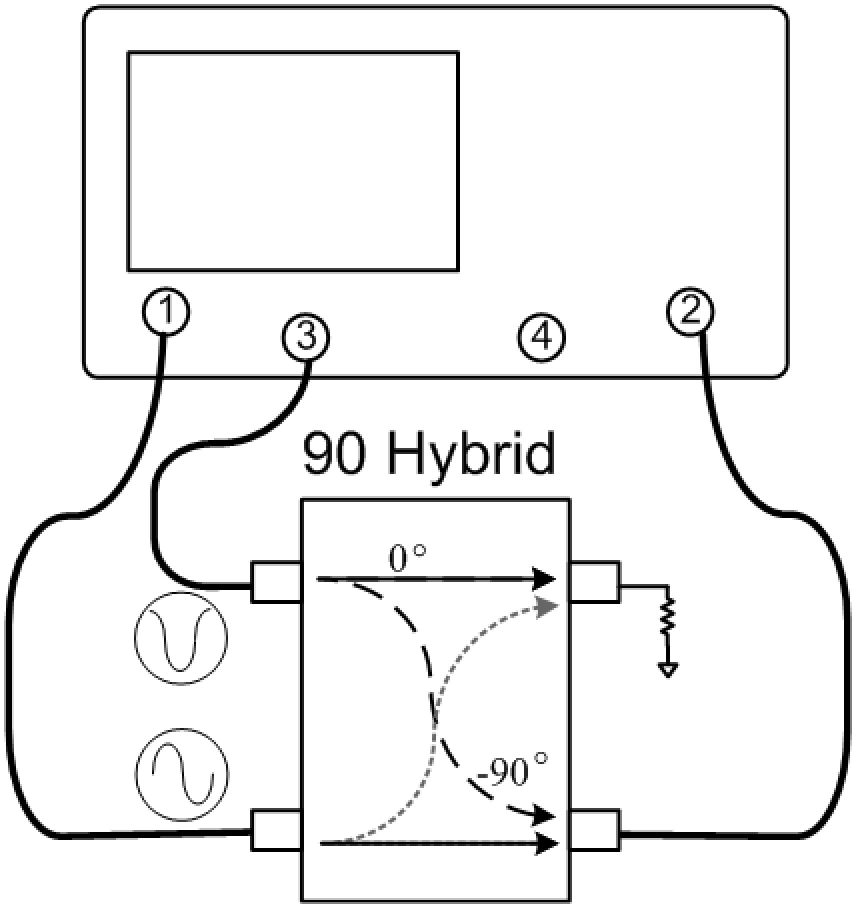
Lets look at a 90 degree Hybrid



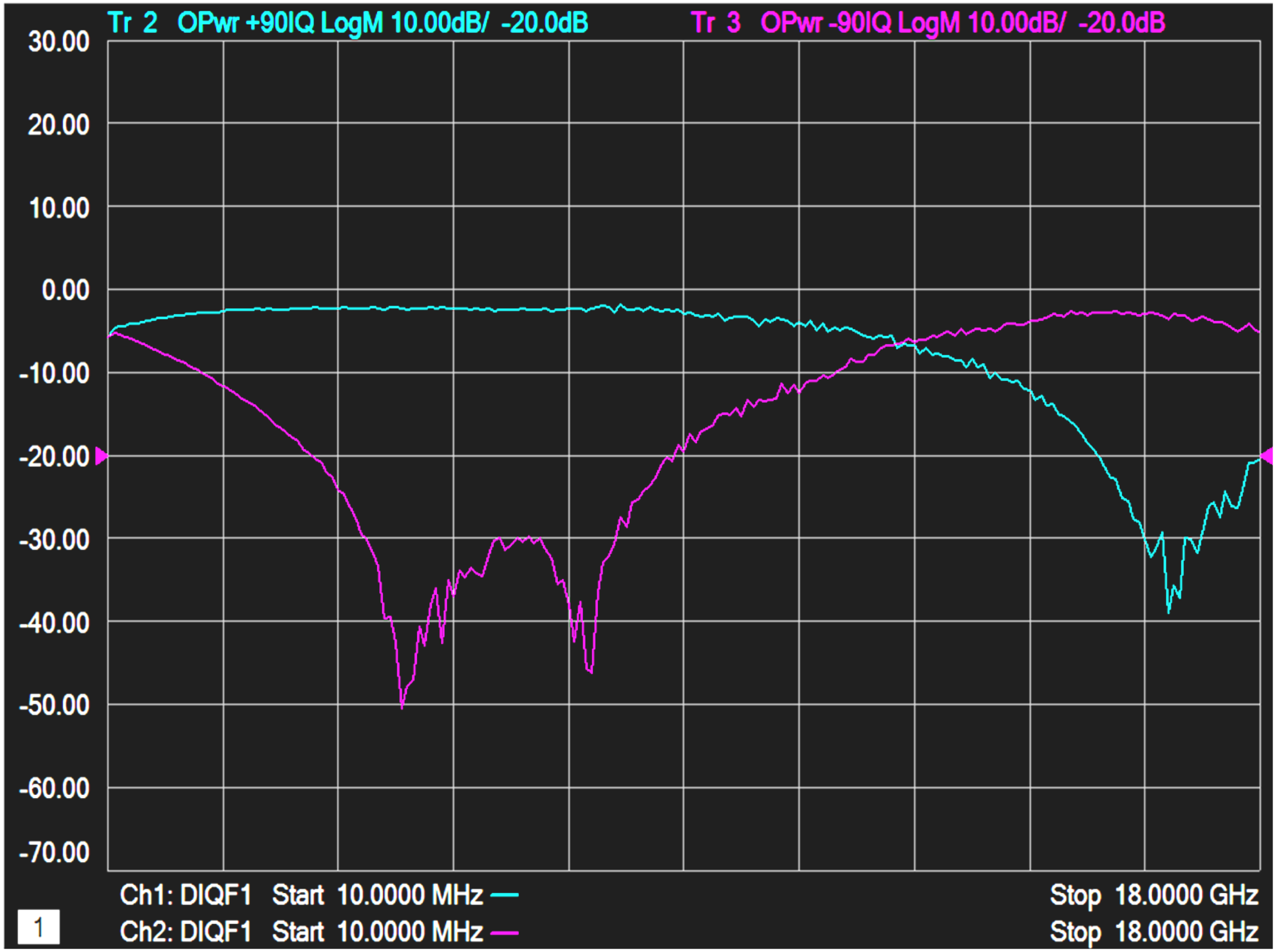
Lets look at a 90 degree Hybrid



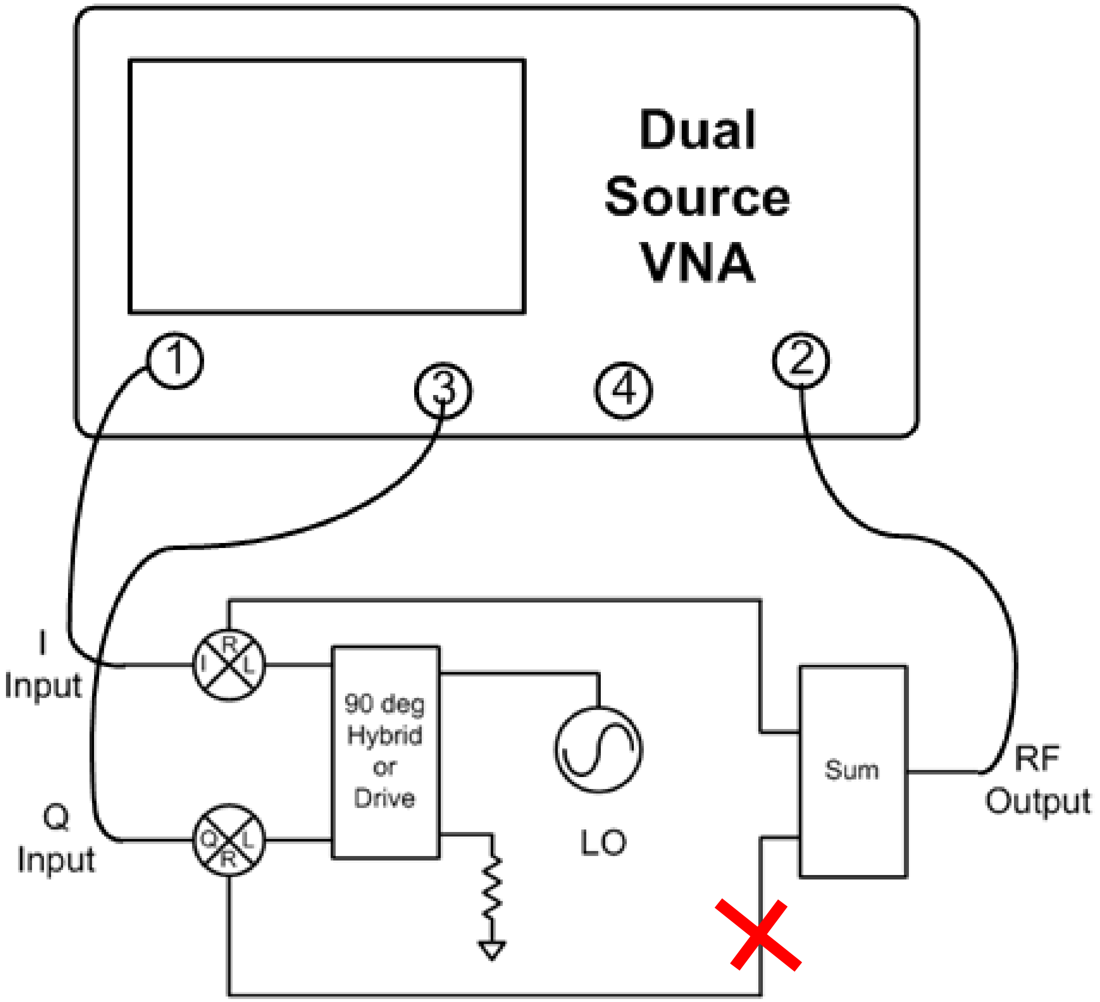
Now Measure it with 0 and 90 degree true-mode drive on the input ports, and sweep frequency



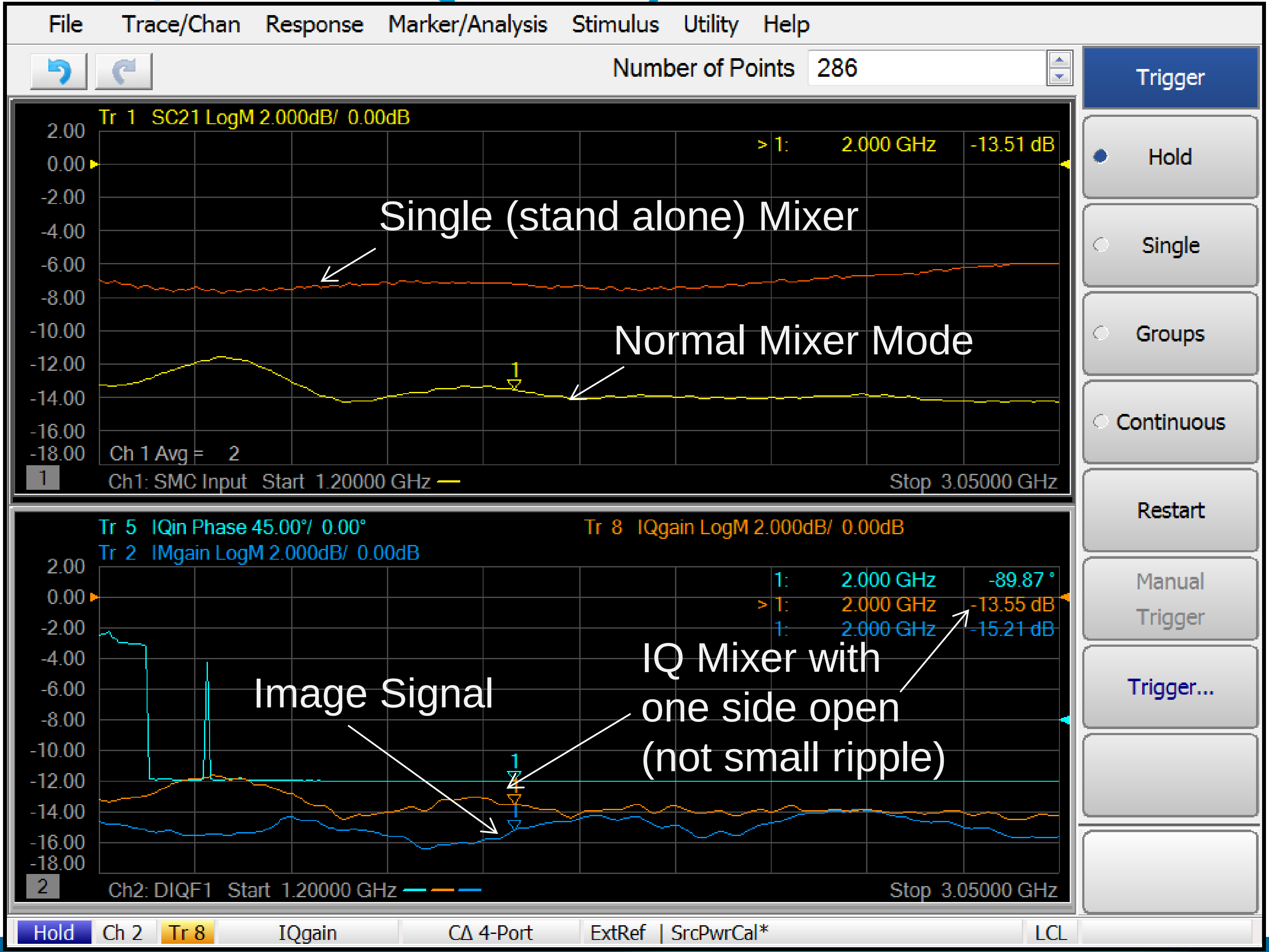
IQ Measurements: Output of Hybrid, across frequency. Phase of IQ set to + or – 90 deg.



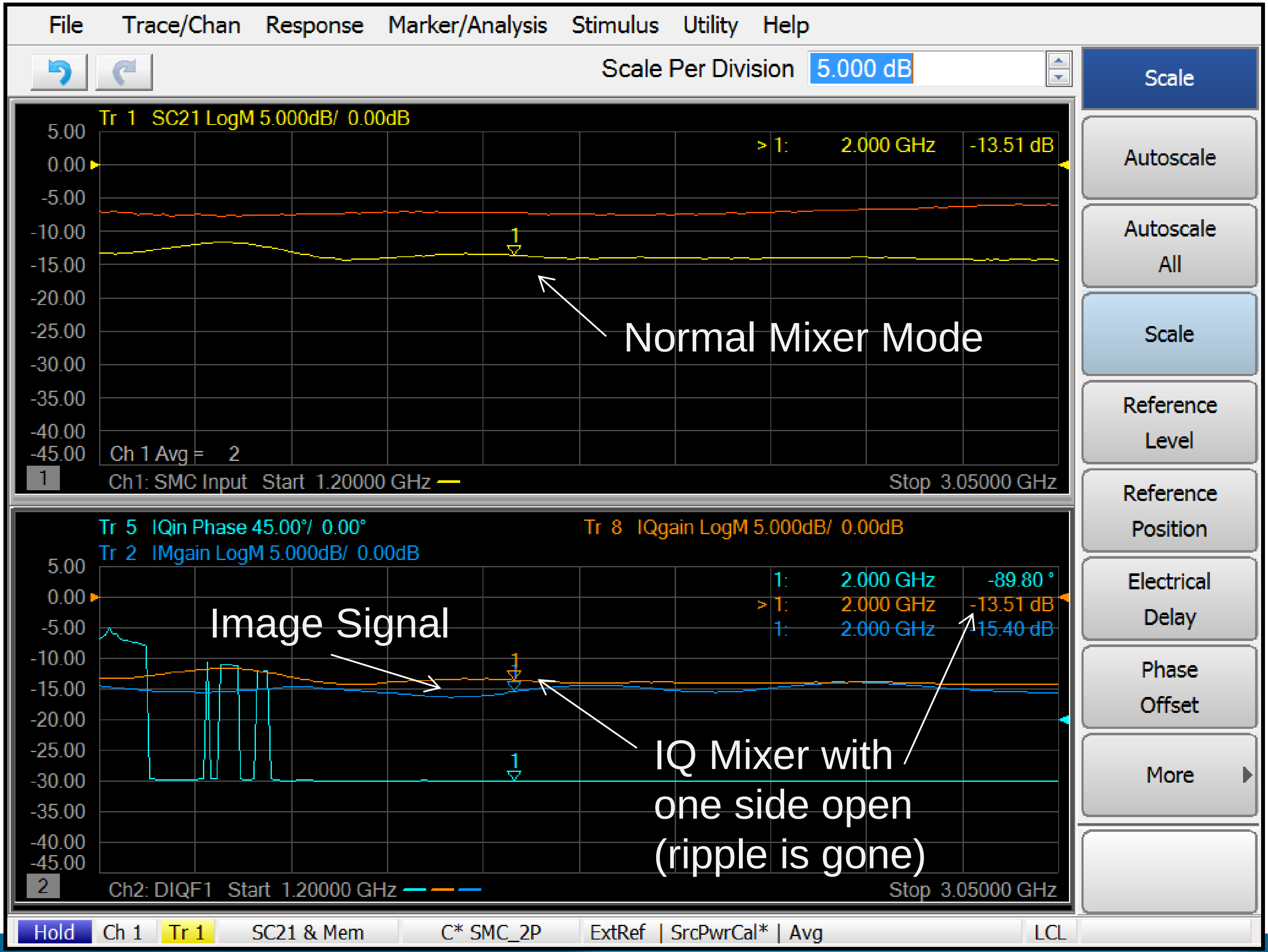
IQ Mixers: Measure just one side (in normal Scalar Mixer Mode, and in IQ Mode)



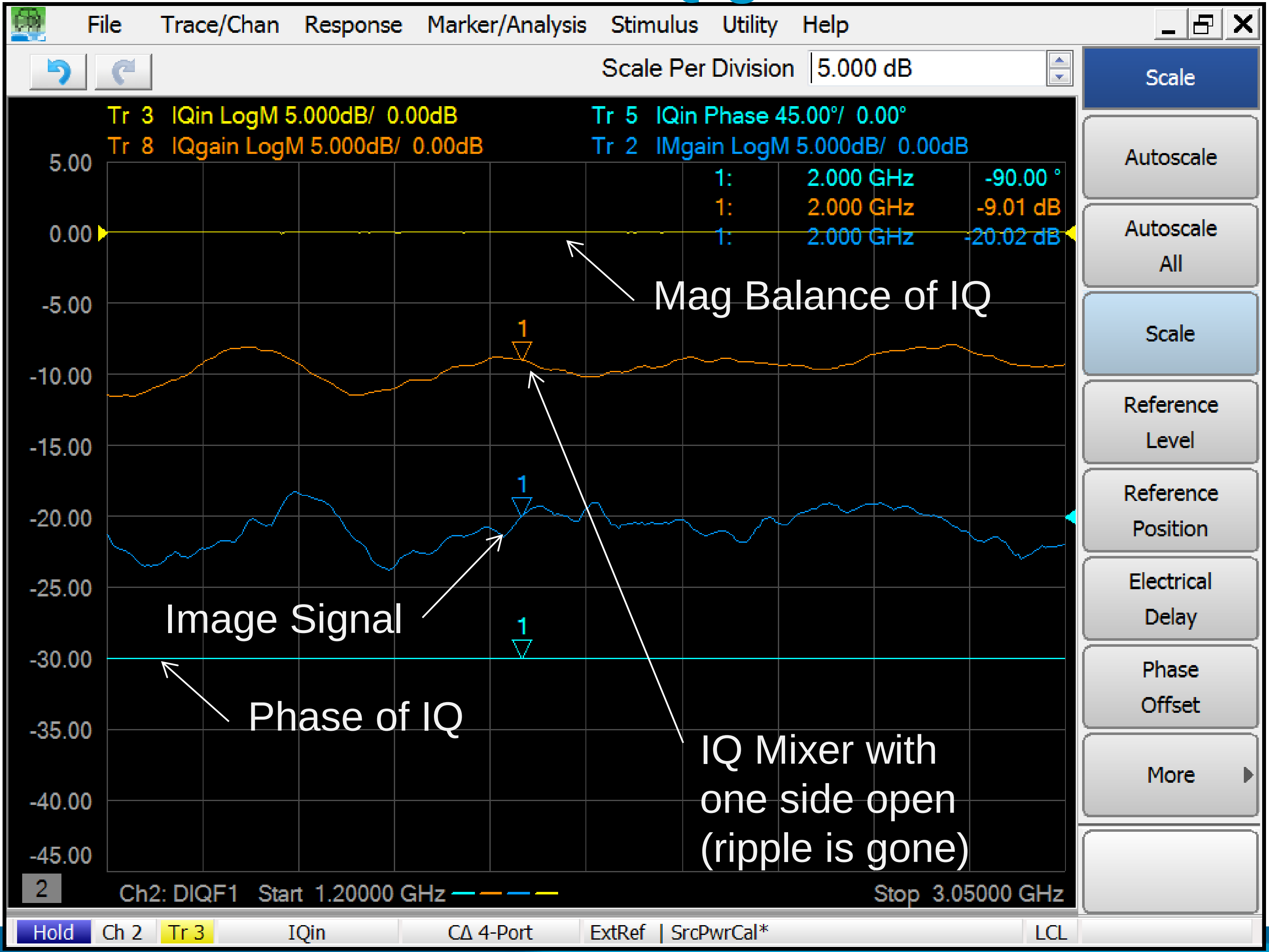
IQ Mixers: Measure just one side (in normal Scalar Mixer Mode, and in IQ Mode)



IQ Mixers: Measure just one side:
Add Match Correction



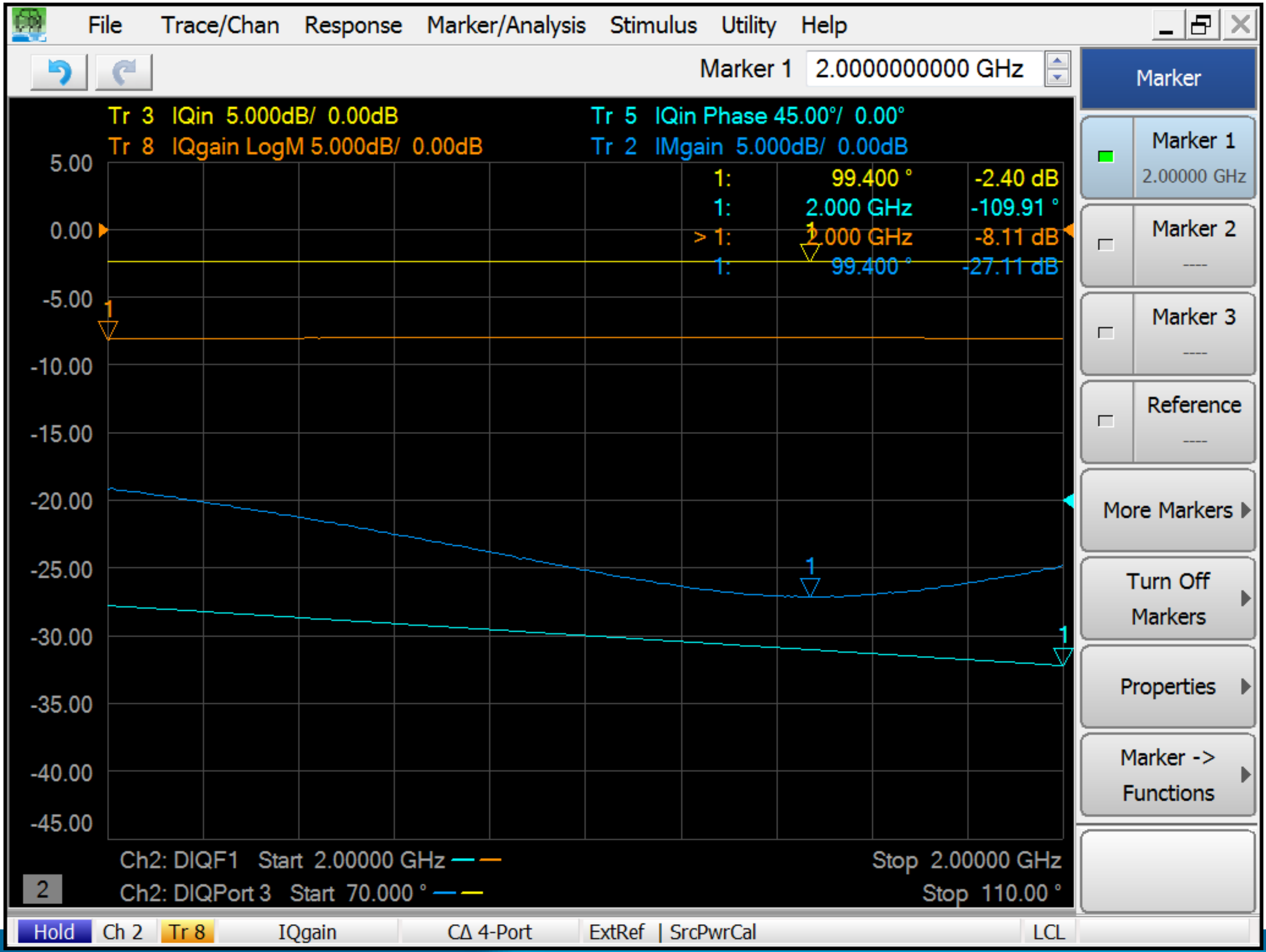
IQ Mixers: Both sides connected now shows image rejection! And increased IQ gain.



Agilent Technologies

IQ Measurements: IQ input power, output power, image power, LO power vs frequency

IQ Measurements: Output Gain, Image Gain, vs IQ Phase Skew: Fix CW and Sweep Phase



IQ Measurements: Output gain, Image Gain vs IQ Amplitude Skew

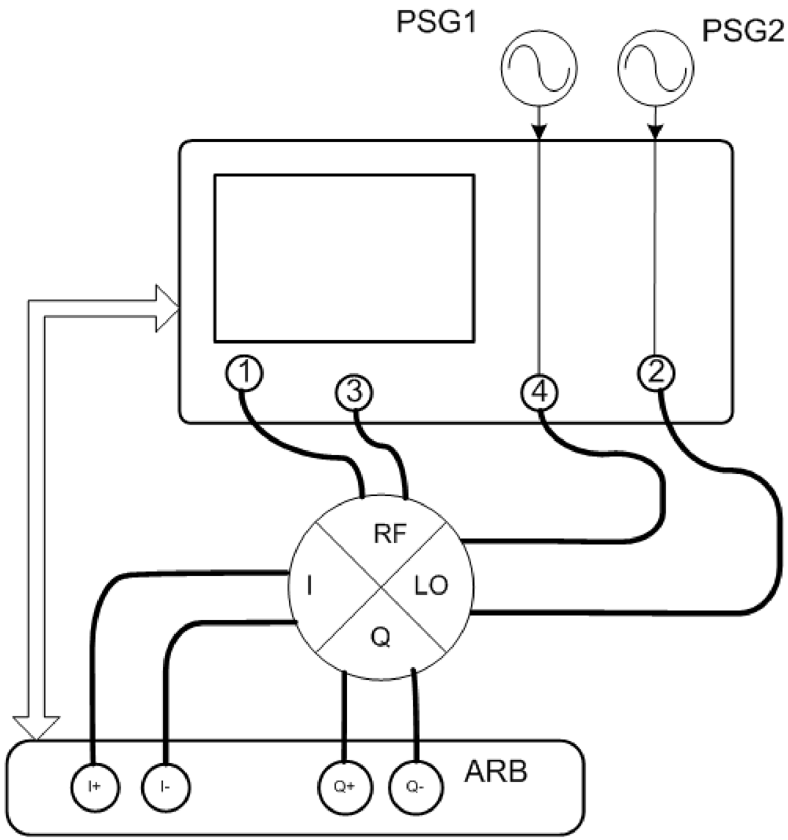
Other Measurement Configurations can make use of External Sources

- Use an arb (currently supported for 81150A and 81160A arbs) to generate IF signal input up to 500 MHz
- User external PSG or MXG to generate I/Q Balanced signal or Balanced LO (utilizing an external test set for switching).
- Use external PSGs and MXG an all 8 receivers (no match correction)

Wideband I/Q Mxr. using ARB Match RF, LO; Balanced Everything, with phase controlled LO, I/Q

Test Requirements:
- Stimulate the input with balanced, I Signal
- Stimulate the input with balanced, Q Signal
- Stimulate the LO with a Balanced Signal
- Set phase of I vs. Q
- Measure the input differential power
- Measure the output differential power
- Measure output at both LO+Input (main signal) and LO-Input (Image signal)
  - As of function of frequency
  - As a function of I/Q phase
- Provide corrected measurements of power, provide leveled input power
  - Open: How to calibrate mag and phase I and Q outputs from the ARB
- Issue: Controlling ARB (generic exe?)
- Cover SE cases for RF, LO (subset of balanced)

Wants
- Measure higher order products of m*LO+-n*Input



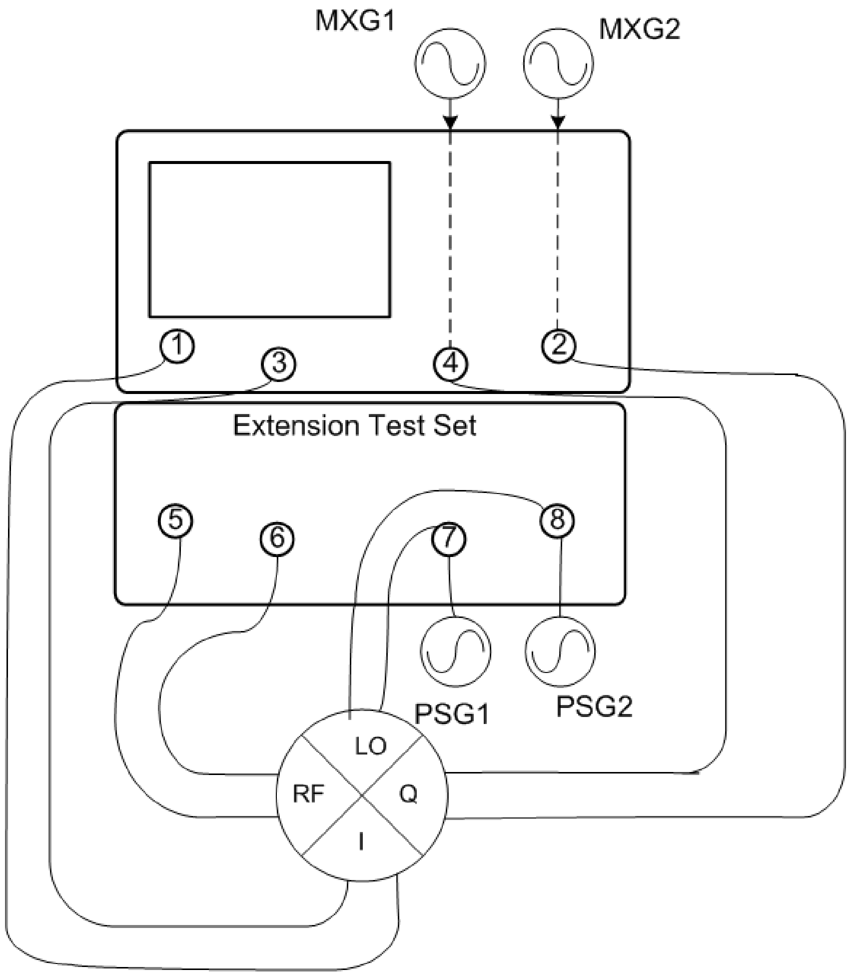
- Wideband I/Q mixer measurement w/extension testset
Match corrected I/Q, RF; Balanced Everything, with phase controlled LO

Test Requirements:

- Stimulate the input with balanced, I Signal
- Stimulate the input with balanced, Q Signal
- Stimulate the LO with a Balanced Signal
- Set phase of I vs. Q
- Measure the input differential power
- Measure the output differential power
- Measure output at both LO+Input (main signal) and LO-Input (Image signal)
    - As of function of frequency
    - As a function of I/Q phase
- Provide corrected measurements of power, provide leveled input power
    - Open: How to calibrate mag and phase of PSG1 and PSG2 paths.
- How to control 6 or 8 port paths (test set control?)

Wants

- Measure higher order products of m*LO+-n*Input



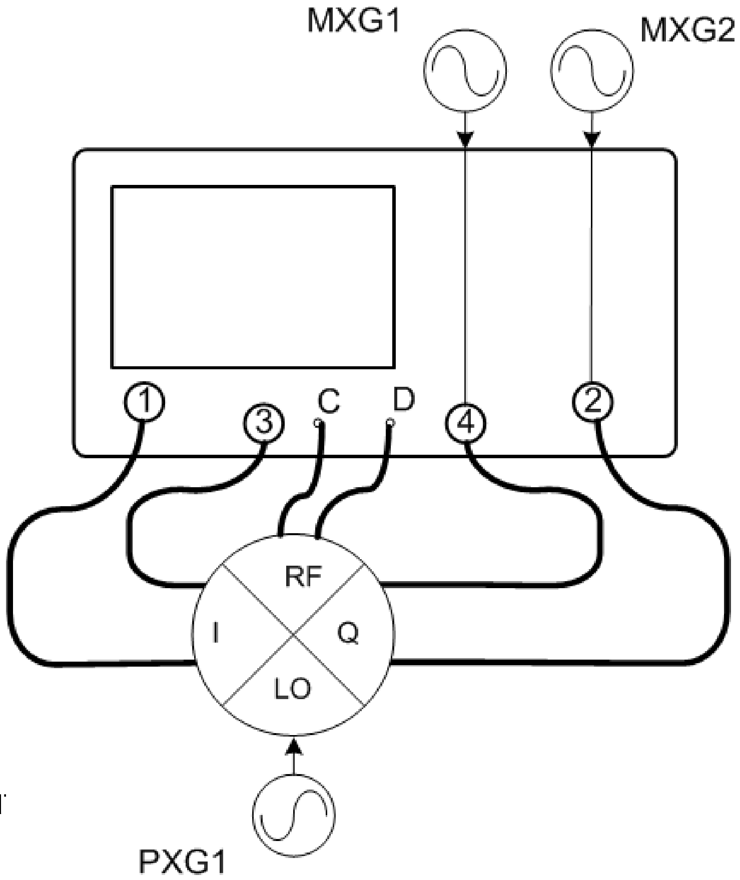
- Wideband I/Q mixer measurement, No match correction on port 3 or 4 (I-, Q-) or on C or D receiver (output),

Test Requirements:

- Stimulate the input with balanced, I Signal
- Stimulate the input with balanced, Q Signal
- Set phase of I vs. Q
- Measure the input differential power
- Measure the output differential power
- Measure output at both LO+Input (main signal) and LO-Input (Image signal)
  - As of function of frequency
  - As a function of I/Q phase
- Provide corrected measurements of power, provide leveled input power
  - Open: How to calibrate C & D receivers.
- Support SE case for RF out (subset)

Wants

- Measure higher order products of m*LO+-n*Inpu



Summary:

- New software control methods allow users to create very sophisticated stimulus conditions at microwave frequencies.
- Match corrected calibration implies that de-embedding is possible, meaning on-wafer and in-fixture applications are now possible
- Flexible receiver control allows a single channel to make multiple phase-related measurements in a single acquisition.
- Full match correction on all receivers improves accuracy.
- Really hard to do all the control…don’t look under the covers.☺

These capabilities were only dreamed of… Dreams Made Real!