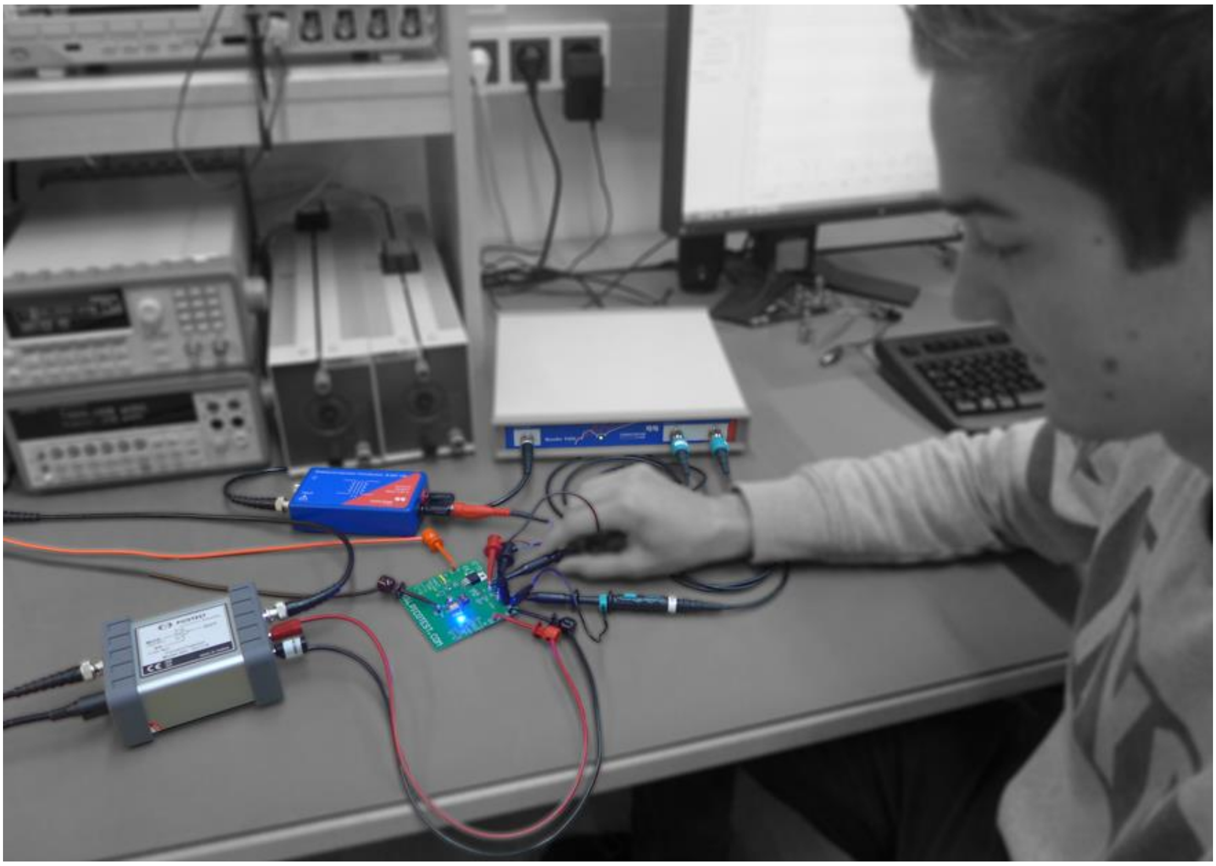
Bode 100 - Application Note

Traditional and Non-Invasive Stability Measurements

Using the Bode 100 and the Picotest J2111A Current Injector



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Note: Basic procedures such as setting-up, adjusting and calibrating the Bode 100 are described in the Bode 100 user manual. You can download the Bode 100 user manual at https://www.omicron-lab.com/bode-100/downloads.html#3

The J2111A does not require calibration. The J2111A comes with and uses the J2170 High PSRR power supply.

Note: All measurements in this application note have been performed with the Bode Analyzer Suite V3.0. Use this version or a higher version to perform the measurements shown in this document. You can download the latest version at www.omicron-lab.com/bode-100/downloads

You can download the latest Picotest Injector manual at http://www.picotest.com/products_injectors.html

1 Executive Summary

This application note shows how the phase margin of a linear voltage regulator can be measured using the Bode 100 and additional accessories.
The same techniques can be used to measure switching regulators as well.

The measurements are performed on the Picotest Voltage Regulator Test Standard (VRTS 1.5) test board[1] using the OMICRON Lab B-WIT injection transformer and the Picotest J2111A Current Injector.

The current injector in combination with the Bode 100, allows direct measurement of the output impedance, group delay and Q(Tg) of the system. Using this information the phase margin of the system can be calculated without breaking the feedback loop of the controller. This method is, therefore, "non-invasive.” The algorithm for this technique is called **N**on-**I**nvasive **S**tability **M**easurement (NISM) and was introduced by Mr. Steve Sandler.

In this application note the results of the non-invasive stability measurement are verified by comparing them with the "classical" Bode plot loop gain measurements.

Additionally, the influence of the output capacitor ESR[2] on the phase margin is investigated. Two different output capacitors are used for the phase margin measurements and the results are compared in the frequency domain as well as in the time domain by performing a small signal step load response.

Additional information on stability measurement with the Bode 100 can be found in the application note: "Measurement of DC/DC Converters with Bode 100" https://www.omicron-lab.com/bode-100/application-notes-know-how/application-notes/dcdc-converter-stability-measurement.html

[1] You can request this demo board by sending an e-mail to support@omicron-lab.com
[2] Equivalent Series Resistance

2 Measurement Task

The phase margin of the voltage regulator is evaluated using two different methods:

1. Traditional stability measurement via the Loop Gain-Phase (Bode plot)
2. Non Invasive Stability Measurement over an output impedance measurement

The two measurements are then compared.

The Picotest VRTS 1.5 board is used as the device under test. The VRTS 1.5 board can be used to perform many voltage regulator measurements using the Bode 100 in conjunction with the Picotest Signal Injectors. The PCB features a linear voltage regulator and two different output caps and load states.

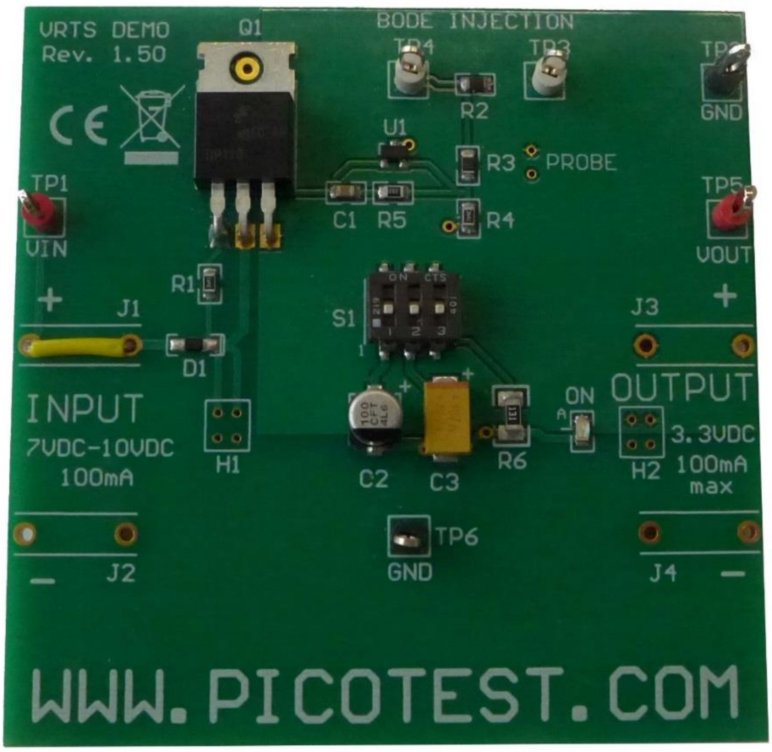

Figure 1: Voltage Regulator Test Standard board

To highlight the influence of the output capacitance on the phase margin of the regulator, two different capacitors are used for the measurements. The two capacitors are a 100 µF aluminum electrolytic capacitor (C2 on the PCB) and a 100 µF tantalum capacitor (C3 on the PCB).

3 Measurement Setup & Results

3.1 Traditional Stability Measurement (Control Loop Response)

We can measure the loop gain $T(s)$, of the voltage regulator feedback system by breaking the control loop and injecting a small-signal voltage across an injection resistor using the B-WIT 100 injection transformer.
The loop gain is then evaluated by comparing the two voltages on either side of the injection resistor. One side is the signal that goes into the feedback system whereas the other side shows the reaction of the regulator. The voltages are picked up by using two passive 1:1 voltage probes.
Details on the loop gain measurement method can be found in [1], [2] and [3]

A constant load current of 25 mA is achieved by either switching on the positive bias current of the J2111A Picotest Current Injector or by switching on the output load resistor (R6) which can be seen in Figure 57. The current injector can provide positive, negative or zero bias, so that the J2111A can operate in class A mode for usage with a Network Analyzer. The negative bias is for use with negative voltages, while the positive bias is for positive voltages. The Current Injector is normally in parallel with the normal circuit load current and impedance. In this measurement, the J2111A Current Injector is acting as a 20 mA constant current load only.

3.1.1 Loop Gain Measurement Setup

The VRTS 1.5 board is powered using a 9 VDC supply. The J2111A is powered by the J2170 High PSRR power supply. The TIP120 on the VRTS board is configured with a 787 Ω to 2.49 kΩ voltage divider to deliver a 3.3 V output voltage. The injection resistor has a value of ≈ 5 Ω. We recommended measuring the 3.3 V output voltage before continuing.

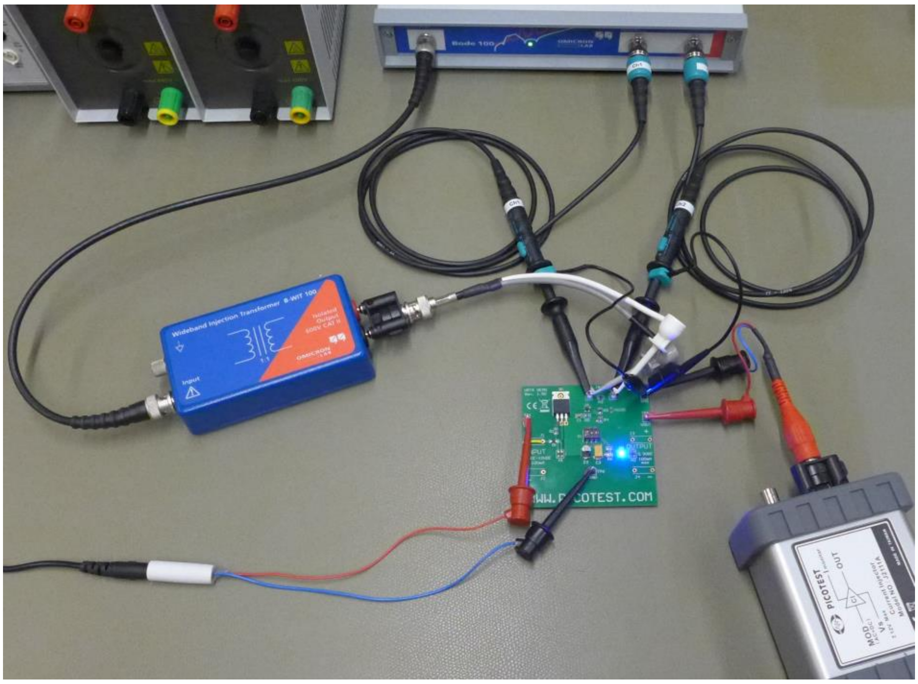

Figure 2: Loop Gain measurement setup with Bode and B-WIT

The B-WIT 100 injection transformer is connected to the test board's *BODE INJECTION* connectors as shown in the picture below. Two oscilloscope probes are connected to the same points as the injection transformer.

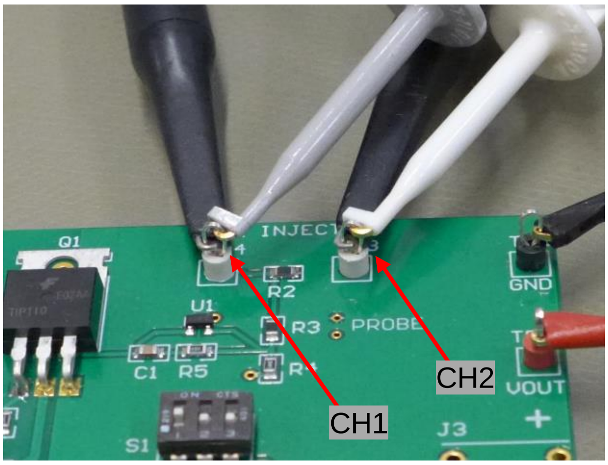

Figure 3: Connection setup of the 1:1 probes

The following picture shows the schematics of the linear regulator and the injection setup for the loop gain measurement.

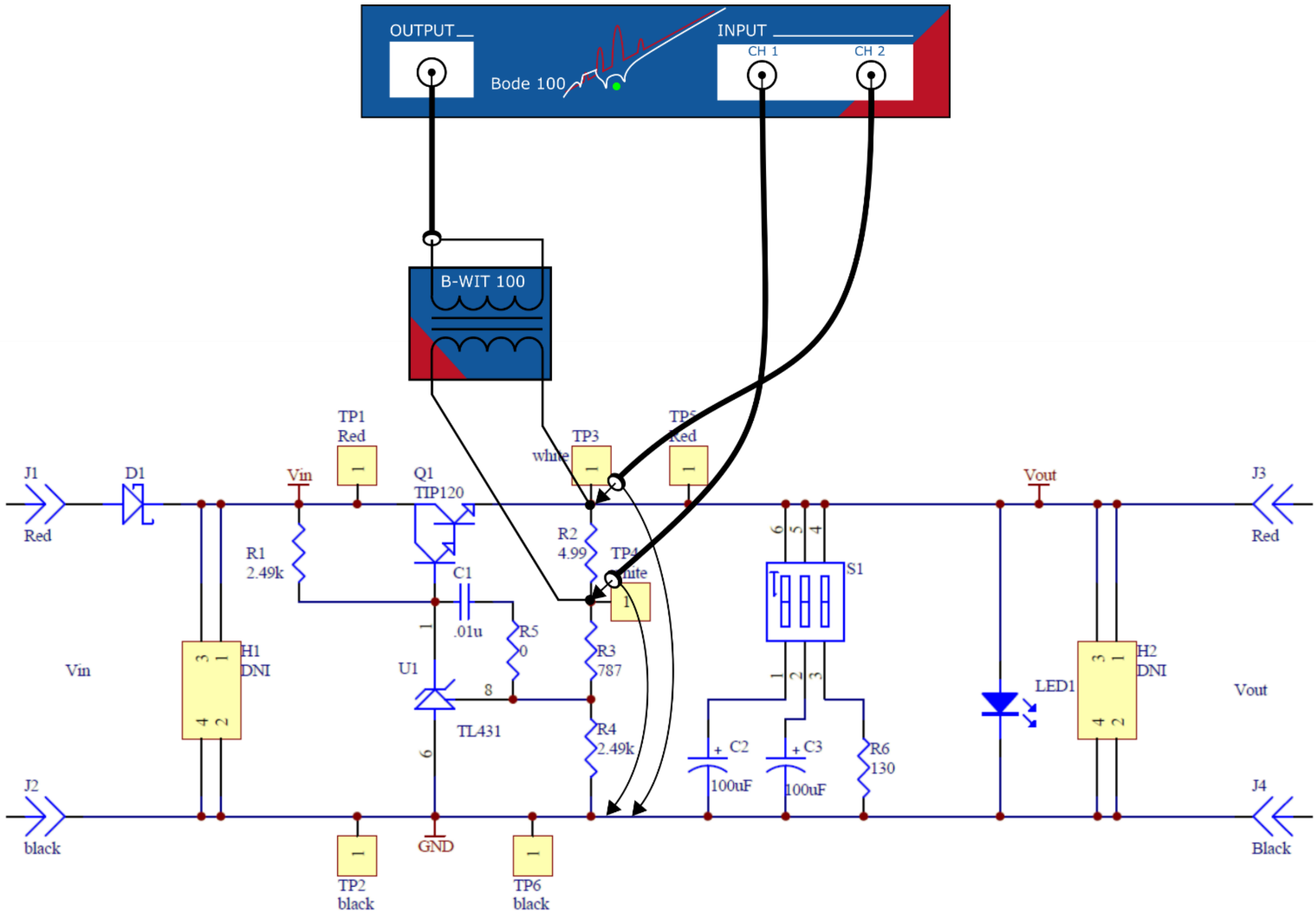

Figure 4: Schematic of the connection setup and the linear regulator

Capacitor C2 is an aluminum capacitor and capacitor C3 a tantalum capacitor. Both have a nominal capacitance value of 100 µF. The resistor R6 is the load resistor to achieve a constant 25 mA load current. The dip switch S1 connects the selected capacitor or load resistor to the output of the VRTS 1.5 board.

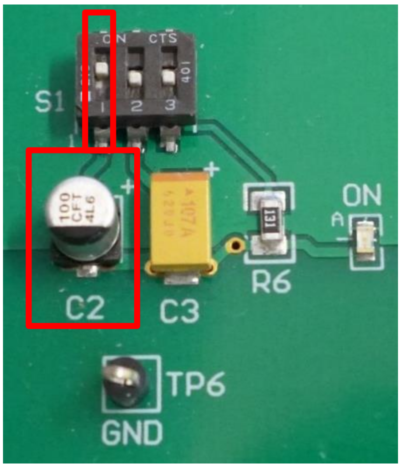

Figure 5: Capacitor C2 (aluminum)

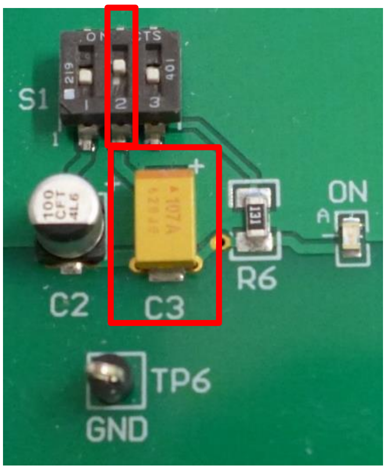

Figure 6: Capacitor C3 (tantalum)

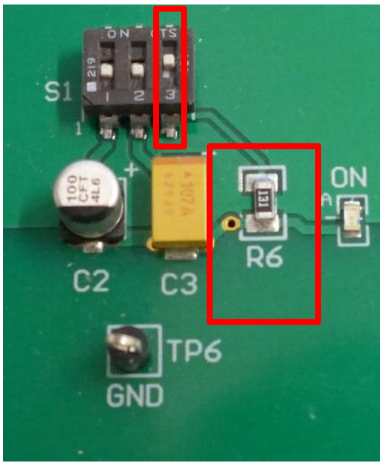

Figure 7: Resistor R6 (load)

With this setup we can measure the loop gain and determine the phase margin of the system depending on the output capacitor and different loads. For the stability measurement the Bode 100 needs to be configured correctly.

3.1.2 Device Setup for Loop Gain Measurement

To measure the frequency response of the control loop (loop gain), two voltages at the injection point must be measured. The loop gain transfer function is then given by:

$$T(s) = \frac{V_{CH2}(s)}{V_{CH1}(s)}$$

This measurement can be performed directly with the Bode 100 using the *Gain / Phase* measurement type.

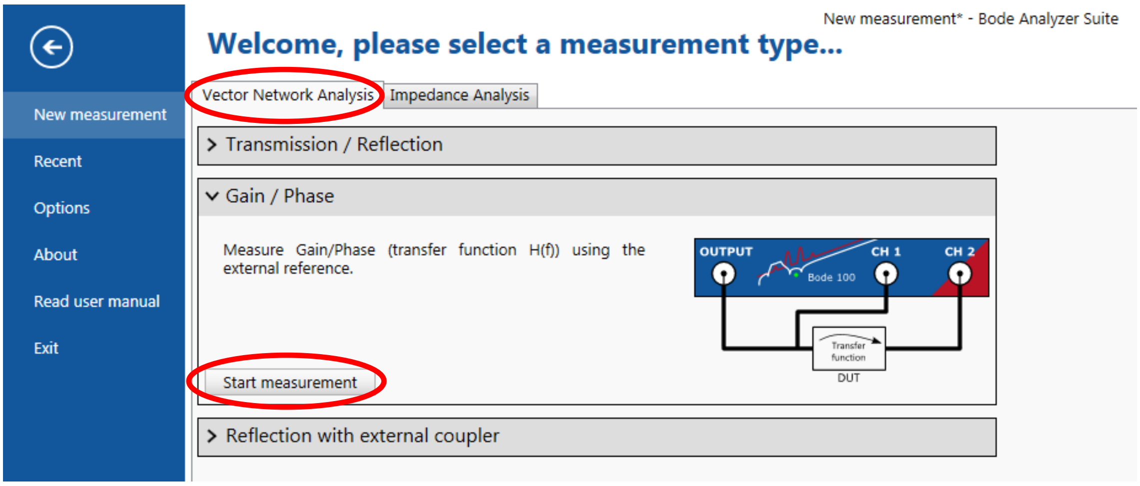

Figure 8: Start menu

The Bode 100 is set up as follows:

Start Frequency:	100 Hz
Stop Frequency:	10 MHz
Sweep Mode:	Logarithmic
Number of Points:	201 or more
Level:	0 dBm
Attenuator 1 & 2:	0 dB
Receiver Bandwidth:	100 Hz

To directly measure the Bode plot we want to display the magnitude in dB and the phase of the loop gain in degree.

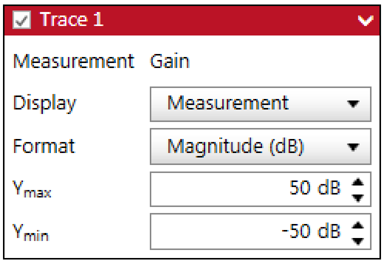

Figure 9: Trace 1 settings

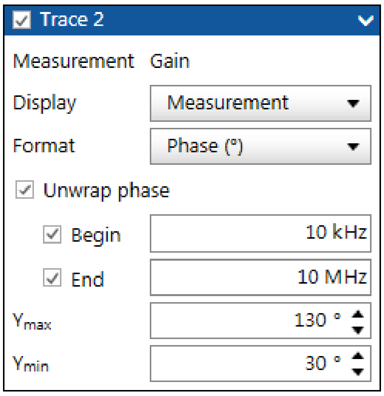

Figure 10: Trace 2 settings

By choosing “One trace per chart”, the phase can be displayed in a separate diagram.

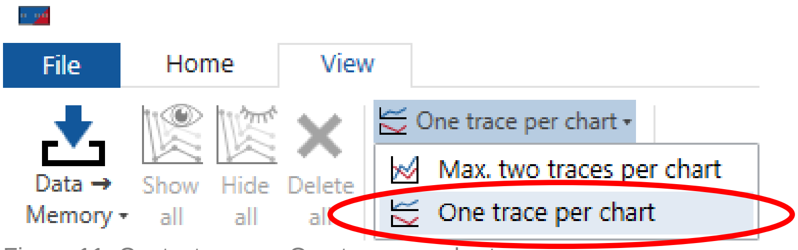

Figure 11: Context menu - One trace per chart

3.1.3 Calibrating the Probes

Note: Calibration is optional and only necessary of the two probes at CH1 and CH2 are not identical. Therefore it is recommended to first check if a calibration is necessary:

Check if calibration is necessary:

1. Connect both probes to the same point in the circuit as shown in Figure 12.
2. Perform a sweep and check if the Gain and Phase diagram shows 0 dB and 0°.
3. Calibration is necessary if the Gain and Phase curve is not 0 over the entire frequency range.

Performing the calibration:
If the two voltage probes are not identical THRU calibration can be used to compensate for the Gain and Phase difference between the probes. To do so both probes are connected to the same injection point as shown in the left picture below and the THRU calibration is started.

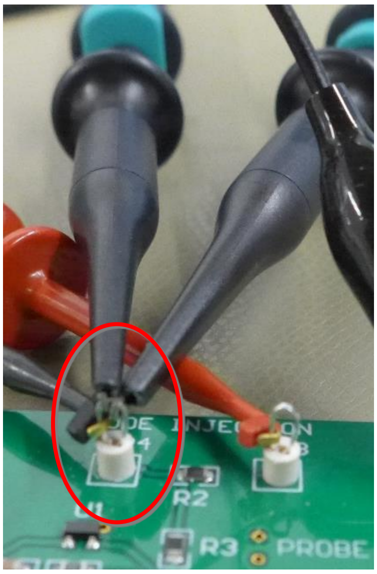

Figure 12: THRU Calibration

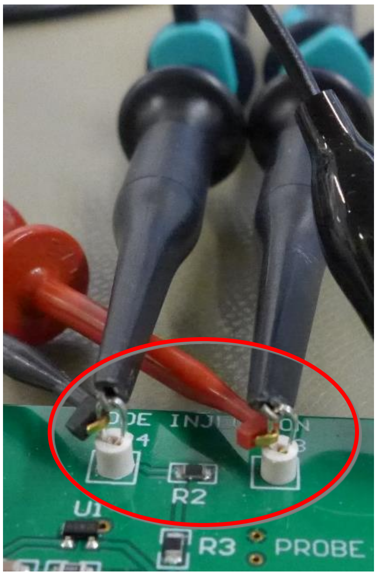

Figure 13: Measurement

The calibration removes differences between the two probes. The calibration can be switched off manually to e.g. check the influence of the calibration:

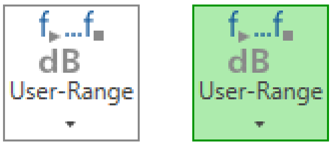

Figure 14: Calibration icon – Off & On

The calibration can be switched ON and OFF by clicking on the calibration indicator. If the indicator is green, calibration is active!

3.1.4 Loop Gain Measurement

Note: The upcoming measurements were performed without the J2111A, but an always activated R6 as load on the VRTS 1.5 board.

We will first measure the Bode plot with the tantalum capacitor placed at the regulator output. Starting a single sweep leads to the following Bode plot:

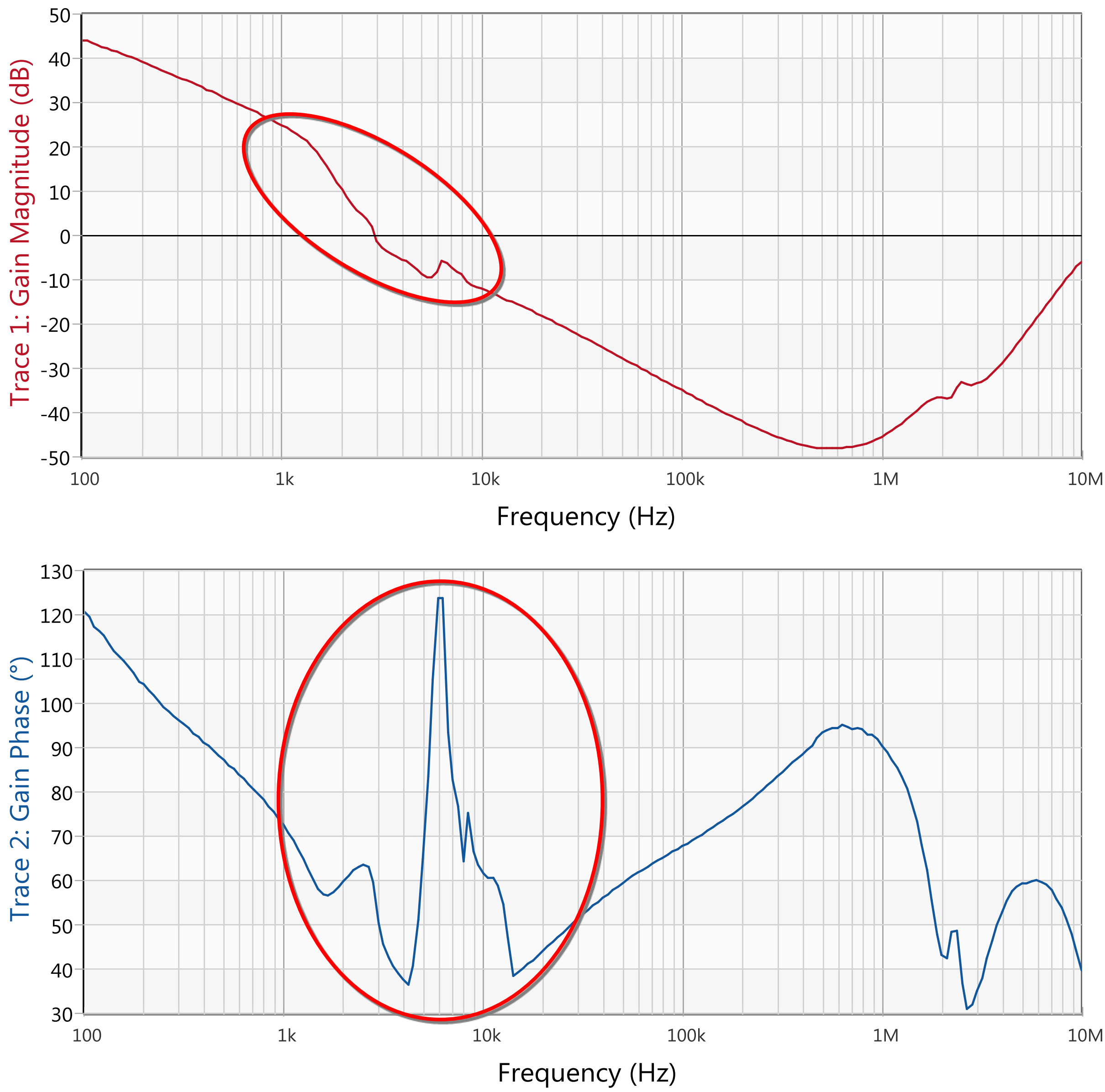

Figure 15: Bode plot with tantalum capacitor and 0 dBm output power level

The marked area shows an unexpected result and indicates that the measurement is not correct. The distortions in the curve are caused by excessive injection signal level which causes nonlinearities of the system to be measured. This is not a result of the analyzer, but is due to large signal effects within the regulator [4]. Since loop gain is a “small signal” quantity, the injection signal needs to be reduced until the level of the injection signal has no influence on the result anymore. This is the condition for a linear measurement.

The injection signal level needs to be decreased. Reducing the Bode 100 source level to a value of −27 dBm leads to the following Bode plot:

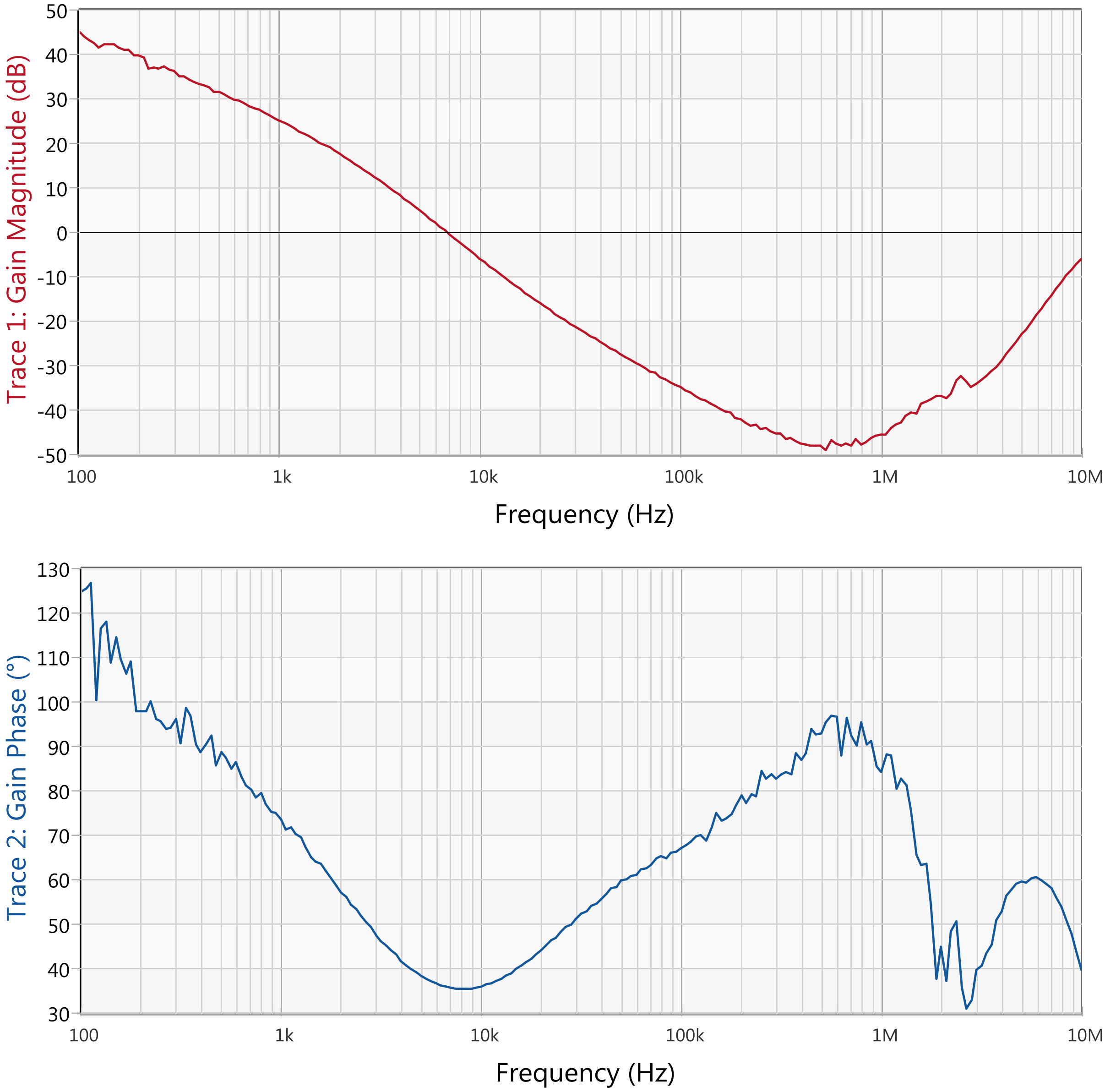

Figure 16: Bode plot with tantalum capacitor and -27 dBm output level

The nonlinearities in the curves disappear. To check if the output level is small enough it should be possible to increase the output level by ≈ 6 dB without nonlinear effects appearing on the measurement and without shifting the crossover frequency.

Reduction of the injection level is necessary to overcome nonlinearities but the noise on the measurement result can increase when the injection level is very low.
To accomplish both, correct small signal results and reduced measurement noise the shaped level function of the Bode 100 can be used. With the shaped level, the output level of the Bode 100 can be chosen to be variable with frequency. E.g. high injection signal at low frequencies but low injection signal around crossover.
The Bode 100 also allows averaging and reducing Receiver Bandwidth for noise reduction.

Activate the Shaped Level feature as shown in the following picture:

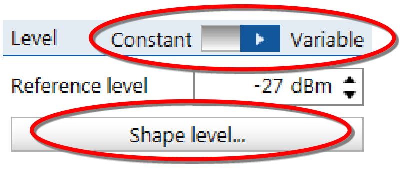

Figure 17: Shaped level settings

In the Shaped Level window frequency and the associated level can be entered. This enables the Bode 100 to reduce the level only at the points where a reduction is necessary and to increase the level in regions were the measurement shows too much noise. For sure you can also click on the curve to add and move points of the level curve with the mouse.

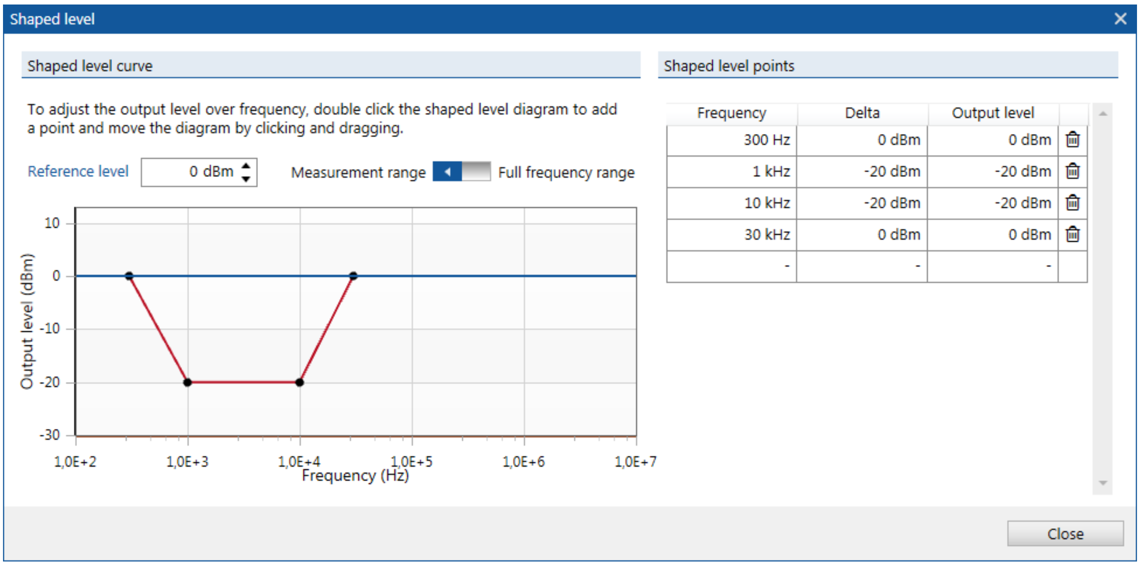

Figure 18: Shaped level window

It is possible to use an optimal measurement level for every frequency range using a shaped level as shown in the picture above.

3.1.5 Measurement Result

Measurements using the 100 µF **tantalum** capacitor:

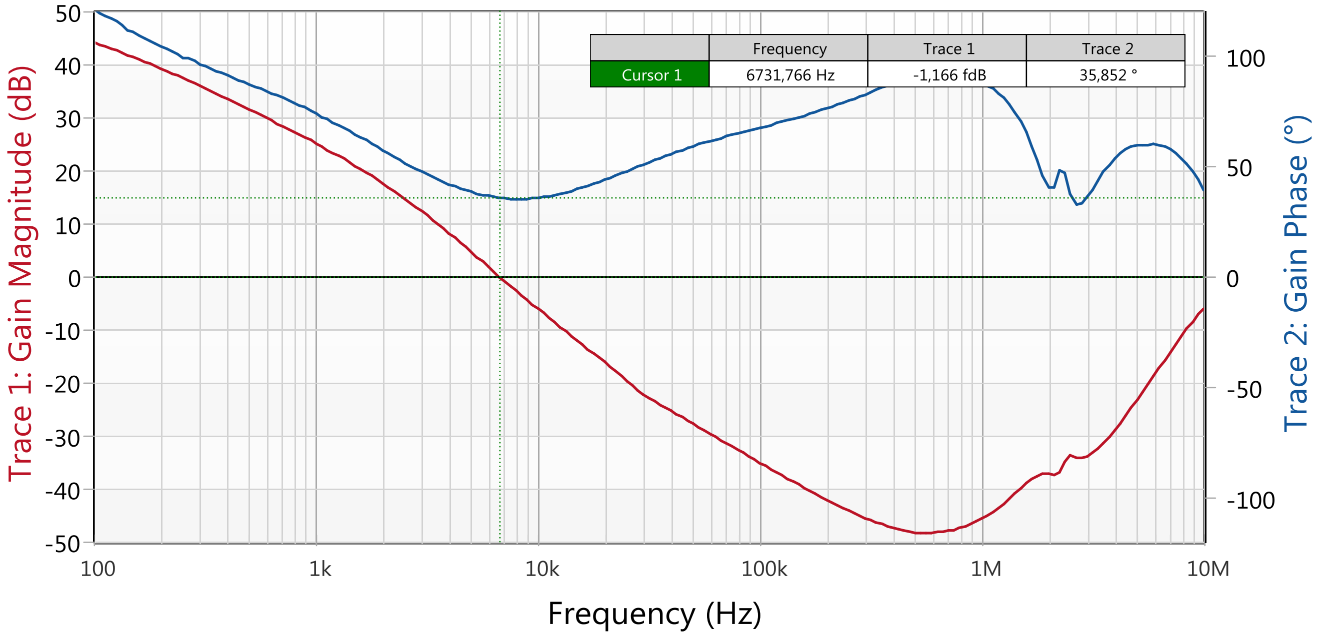

Figure 19: Bode plot with tantalum capacitor and shaped level

The loop gain Bode-plot with a 100 µF tantalum capacitor shows a phase margin of $\varphi_m \approx 35.9°$ at the crossover frequency of $f_c \approx 6.7\ \mathrm{kHz}$. In the higher frequency range additional crossover frequencies might exist. The Bode 100 performs measurements up to 50 MHz allowing investigation of these high frequency effects, which are often related to capacitor, PCB or connection parasitics.

Measurements using the 100 µF **aluminum electrolytic** capacitor:

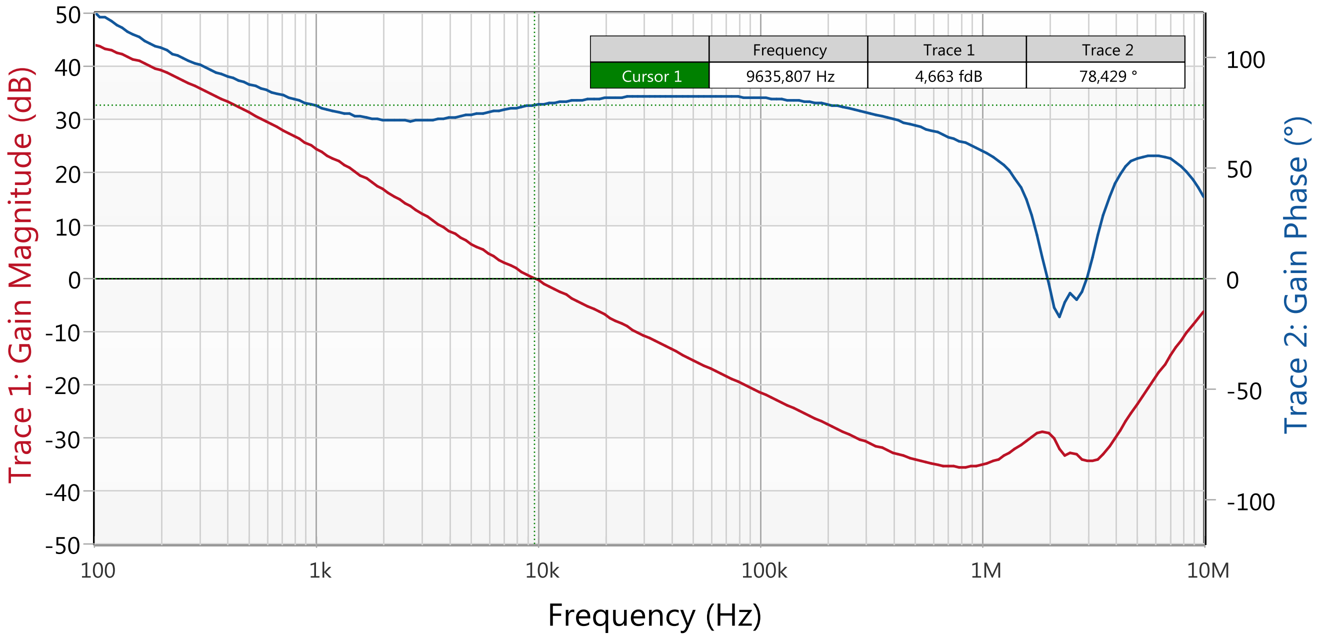

Figure 20: Bode plot with aluminum capacitor and shaped level

The loop gain Bode-plot with a 100 µF aluminum capacitor shows a phase margin of $\varphi_m \approx 78.4$ at the crossover frequency of $f_c \approx 9.6\ \mathrm{kHz}$.

Note that the aluminum capacitor did cause the system to be very stable (highly damped) and even faster than with the tantalum capacitor. The main reason for this change is that the two capacitors have different ESR. We will measure the capacitor ESR in section 0.

3.2 Output Impedance Measurement

Together with the Picotest J2111A Current Injector the Bode 100 offers a simple and non-invasive method to measure the output impedance of a regulating system. The output impedance data provides a measurement of the phase margin without the need to inject a signal into the control loop. This is the only way to measure the phase margin of a fixed voltage regulator, where the control loop is not available for a traditional loop gain (bode plot) measurement.

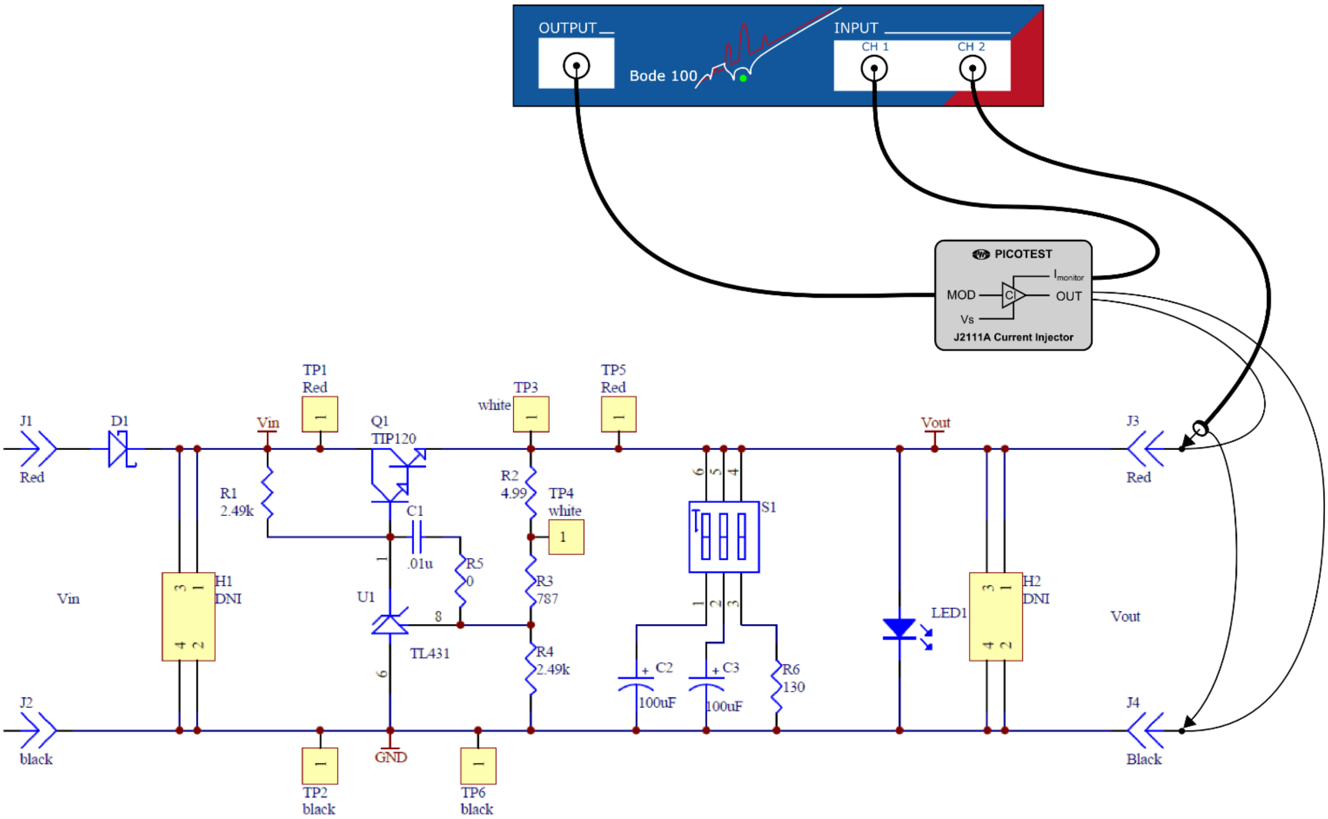

Figure 21: Output impedance measurement using Bode 100 and Picotest J2111A

3.2.1 Measurement Setup

The figure above shows the basic measurement setup used to measure the output impedance of a regulator system with the Bode 100 and the Picotest J2111A Current Injector. The output of the Bode 100 is connected to the modulation input of the J2111A (MOD). A signal at the MOD input of the injector leads to a change in load current according to the input signal at a gain of $10\ \mathrm{mA/V}$.

The monitor output of the injector ($I_{monitor}$) delivers a voltage signal that is proportional to the current flowing through the injector output. The current monitor output is $1\ \mathrm{V/A}$ when terminated with 50 Ω.

This signal is measured at channel 1 of the Bode 100. The output voltage is measured using a 1:1 probe at channel 2. Performing a gain measurement with an external reference leads to the output impedance:

$$\frac{V_{CH2}}{V_{CH1}} \triangleq \frac{V_{out}}{I_{out}} \triangleq Z_{out}$$

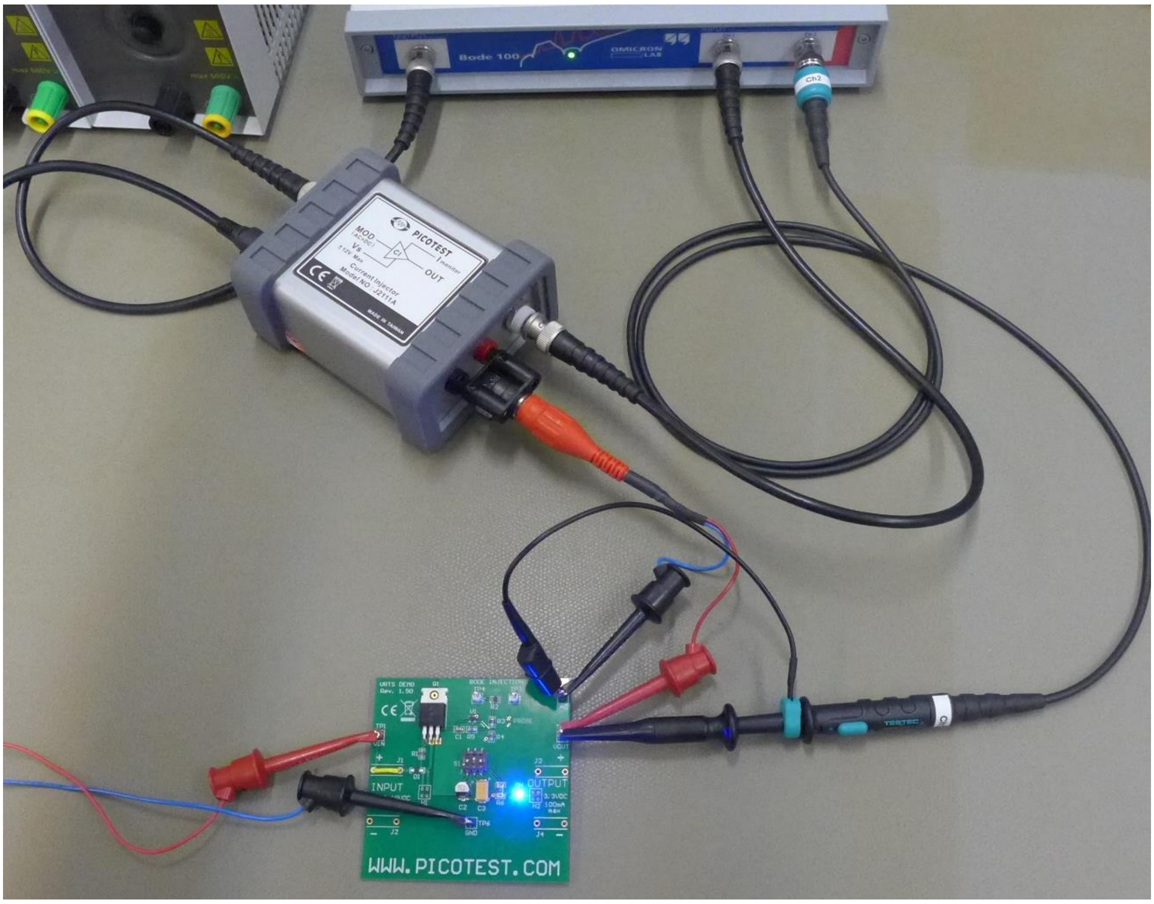

Figure 22: Output impedance measurement example

3.2.2 Device Setup

Current Injector J2111A:
The positive bias of the current injector has to be switched on (+bias) as the Bode output voltage does not have a DC offset and the TIP120 delivers a positive output voltage. The positive bias will provide a 25 mA offset current, allowing the current injector to operate in class “A” mode. For best performance, the output wires from the J2111A should be twisted or a coax.

VRTS 1.5:
The resistive load on the VRTS 1.5 board is switched off in this measurement since the current injector draws a 25 mA load current as well as the resistive load on the VRTS 1.5 board. That would result in a 50 mA load current and the result would not be comparable with the loop gain measurement where we used 25 mA load current.

Select the measurement type *Voltage / Current* since the output impedance is measured and open the hardware setup to set CH1 to 50 Ω.

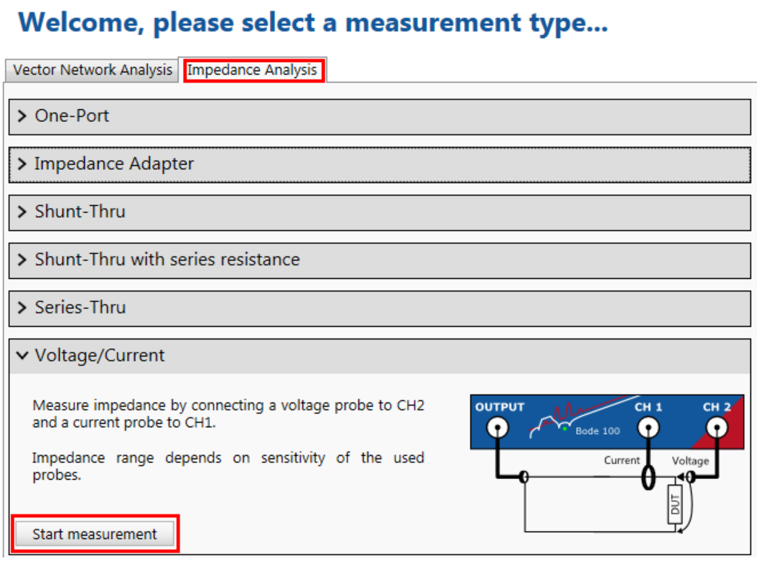

Figure 23: NISM - measurement type selection

Figure 24: NISM - hardware setup button

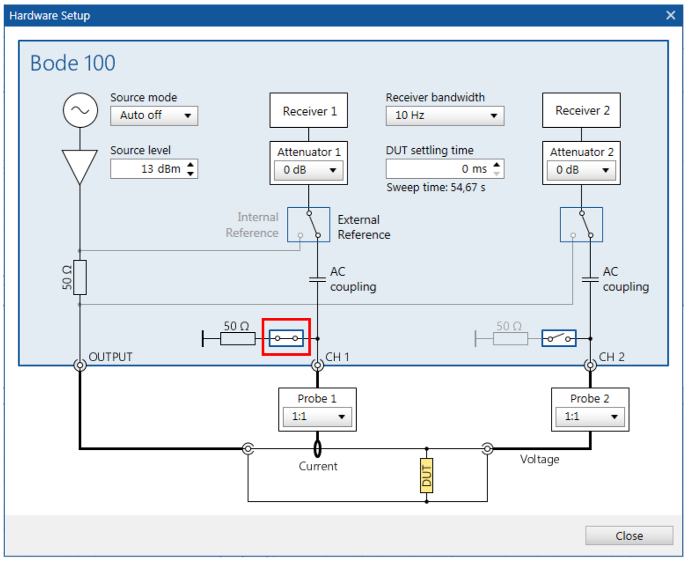

Figure 25: NISM - set CH1 to 50 Ω

Trace 1 & 2 are set to *Magnitude* and *Q(Tg)* so that the basic phase margin calculation can be used to calculate the phase margin. In addition, the measurement settings are as follows:

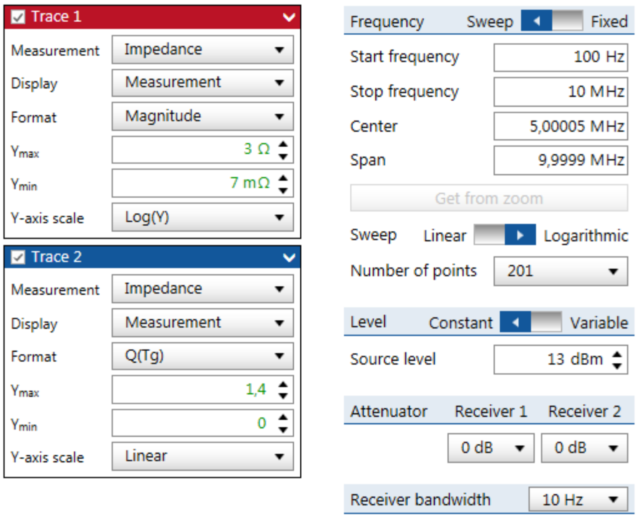

Figure 26: NISM - Trace and measurement settings

3.2.3 Non-Invasive Phase Margin Calculation:

According to [3] the phase margin φ_m is related to the quality factor Q by:

$$Q = \frac{\sqrt{\cos \varphi_m}}{\sin \varphi_m}$$

The quality factor at the crossover frequency can be calculated from the measured group delay by $Q(T_g) = \pi \cdot f \cdot T_g$. Therefore the phase margin at crossover frequency can be calculated from an output impedance measurement using the relations from above.

The Bode Analyzer Suite directly supports the phase margin calculation from the output impedance measurement. There are two different algorithms to calculate the phase margin:

1. Basic PM Calculation (single cursor)
2. Advanced PM Calculation (two cursors)

The basic PM calculation uses one cursor value to determine the phase margin value from the $Q(T_g)$ peak by evaluating the previously mentioned relations. This method is very accurate for low phase margin values below ≈40°.
For higher phase margin systems the output impedance peak will not exactly occur at the same frequency as the $Q(T_g)$ peak. The advanced PM calculation accounts for this difference in frequency by using two cursor values to calculate the phase margin (see [5]). One cursor must be placed at the peak of the output impedance magnitude and the other cursor must be placed at the peak of $Q(T_g)$.

Note: Details about the Non-Invasive stability measurement method developed by Steven Sandler and implemented in the Bode Analyzer Suite can be found in [6] and [5].

In the following we use the *Basic PM Calculation (single cursor)*. As you will see later, this method is sufficient in this case since the peak in impedance and the peak in $Q(T_g)$ occur at the same frequency.

The basic PM calculation is activated in the *Cursor* tab.

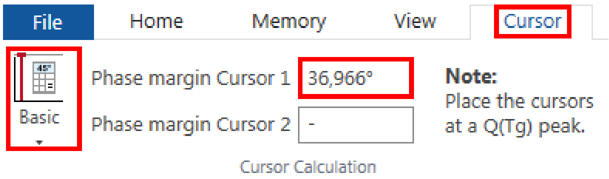

Figure 27: NISM - basic phase margin calculation

Note: $Q(T_g)$ is a function of group delay T_g. T_g is calculated by numerical differentiation. Therefore we recommend not to choose too many points in the sweep. 201 points is the recommended choice. Furthermore logarithmic Y-scale can be of advantage for a better visibility of the meaningful result areas.

3.2.4 Measurement

First we measure the phase margin with the tantalum output capacitor. Starting a single sweep leads to the following measurement result:

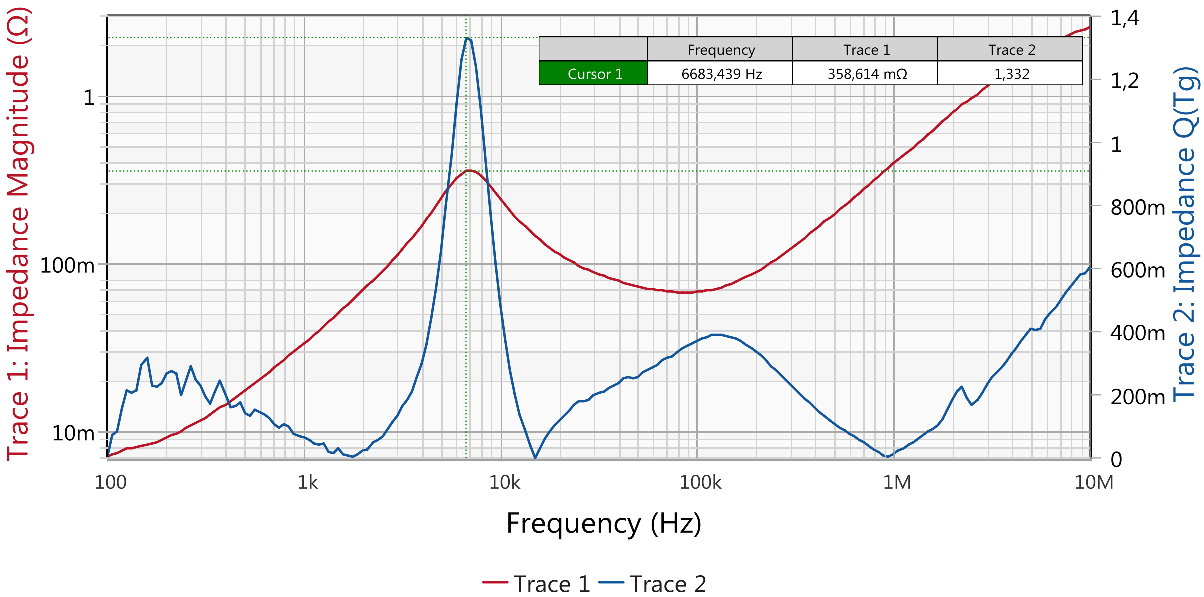

Figure 28: Output impedance with tantalum capacitor

Setting the cursor to the resonance peak in the output impedance leads to the crossover frequency and the calculated phase margin which are displayed in the cursor table. The output impedance measurement with a 100 µF tantalum capacitor shows a phase margin of $\varphi_m \approx 37°$ at the crossover frequency of $f_c \approx 6.7\ \mathrm{kHz}$. These results are in close agreement with the results from the loop gain measurement ($\varphi_m \approx 35.8°$ and $f_c \approx 6.9\ \mathrm{kHz}$).

Next, we connect the aluminum electrolytic capacitor to the output and restart the measurement.

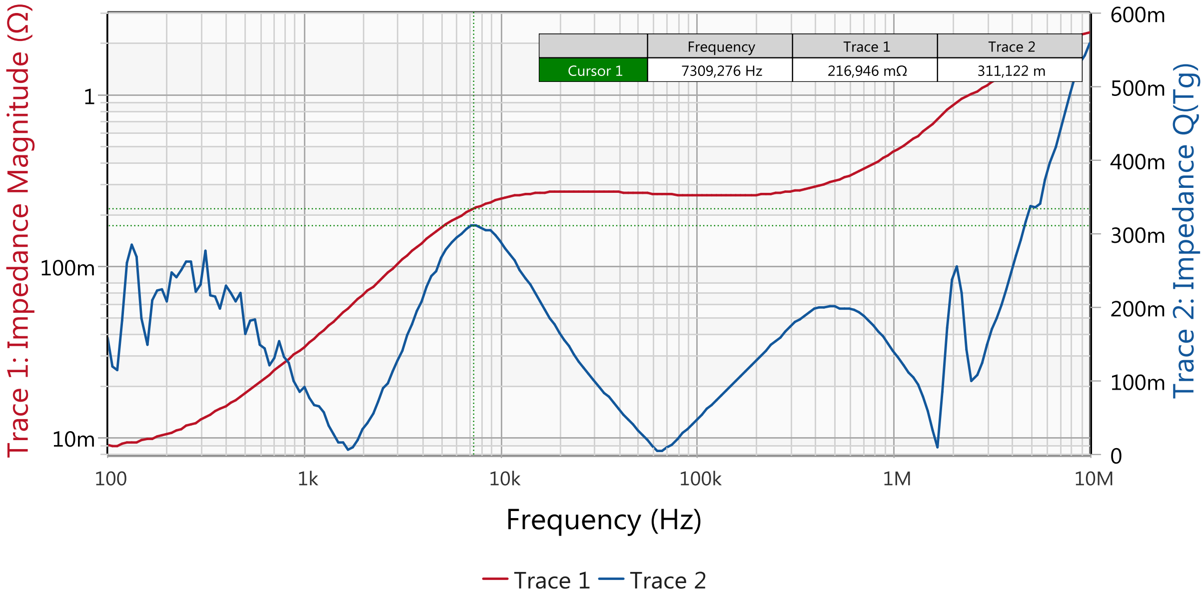

Figure 29: Output impedance with aluminum capacitor

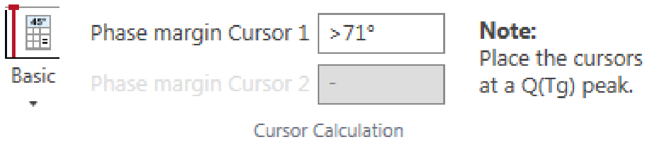

Figure 30: NISM - phase margin calculation electrolytic capacitor

The aluminum capacitor has a very high ESR in comparison to the tantalum cap which results in high damping. As the phase margin is >71° damping is very high and no resonance peak appears in the output impedance. This output impedance curve therefore shows a very stable system with high damping and the display indicates a phase margin of $\varphi_m > 71°$.

3.3 Equivalent Series Resistance Measurement

The great difference in stability of the system depending on the output capacitor is caused by the different ESR of the capacitors. The ESR of the two capacitors is shown in the figure below. The measurements were performed using the Bode 100 with the B-SMC impedance adapter (Details on this measurement can be found in [7]). The tantalum capacitor has a very low series resistance of about 50 mΩ in the vicinity of the crossover frequency. The aluminum electrolytic capacitor on the other hand has a much higher series resistance of about 0.4 Ω.

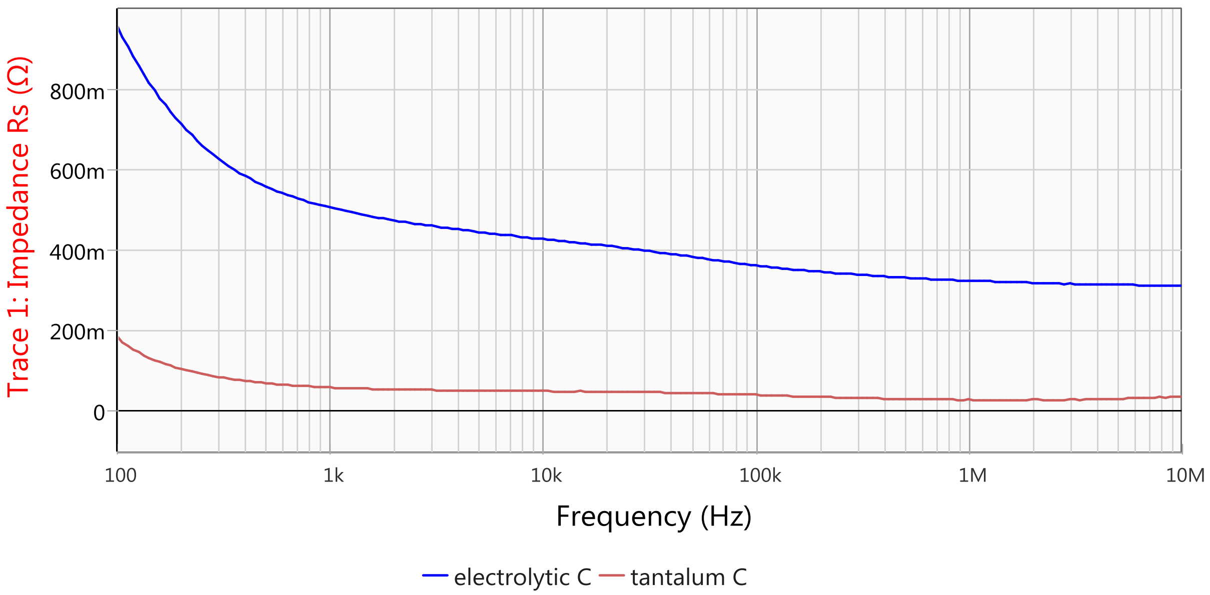

Figure 31: ESR measurement of C2 and C3

3.4 Step Load Response

The measurement setup we used for the output impedance measurement can also be used to measure small signal step load response. An arbitrary waveform generator is used to provide a rectangle signal and is fed into the J2111A modulation input. Current and voltage are now measured with an oscilloscope. The chosen step size is 10 mA around the 25 mA DC operating point.

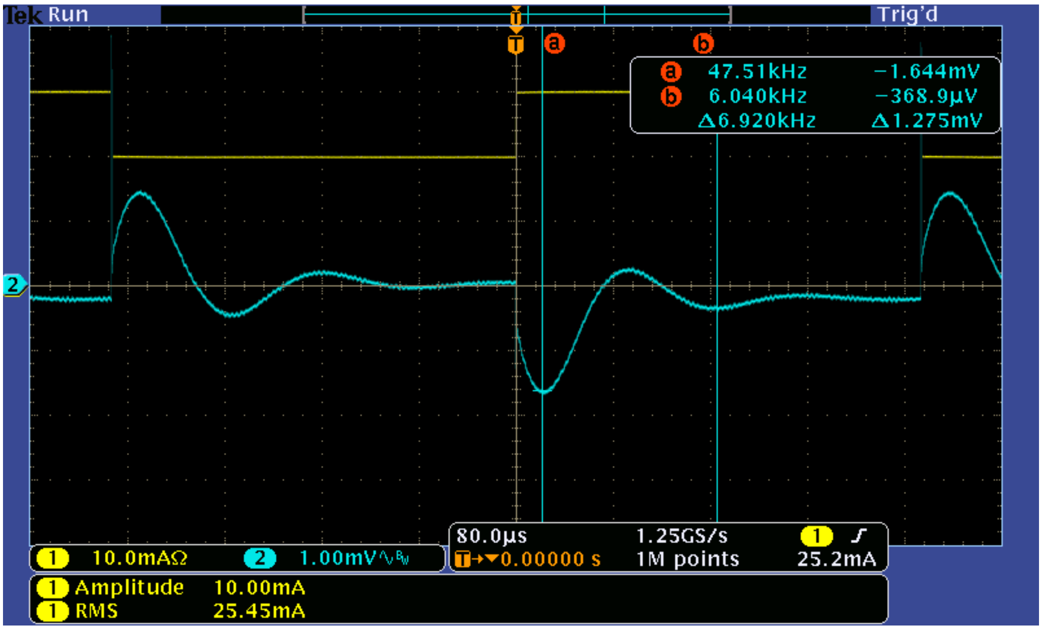

Figure 32: Step load response with tantalum capacitor

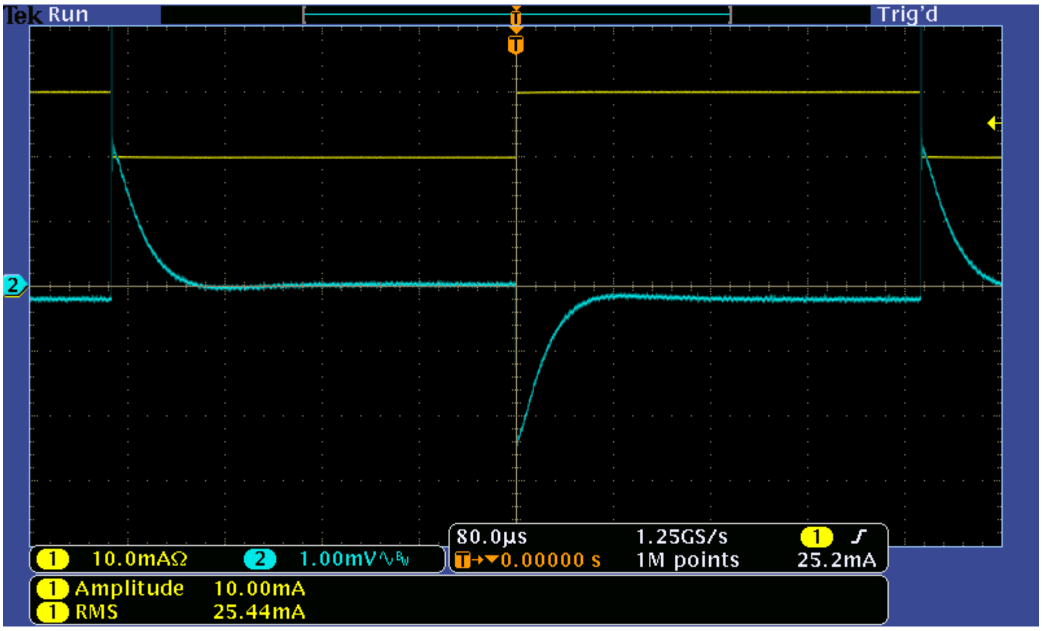

Figure 33: Step load response with aluminum capacitor.

The step load response shows that the aluminum capacitor suppresses any ringing. The tantalum capacitor shows ringing at a frequency of about 6.9 kHz which equals the crossover frequency.

4 Conclusion

With the Bode 100 you can perform a traditional Bode loop response as well as the Non-Invasive Stability Measurement (NISM) when combined with e.g. the Picotest J2111A Current Injector. The Non-Invasive Stability Measurement has been shown to be in excellent agreement with the traditional measurement, offering a simple and reliable method to evaluate the stability of voltage regulators without breaking the feedback loop. The Bode 100 is the first analyzer that offers direct NISM calculation with simple and improved method.

In addition, it can be seen that the equivalent series resistance can have a very high influence on the stability of a voltage regulator. As the ESR is not always specified in the high frequency range it is essential to measure it. The Bode 100 with the impedance adapters offers an easy way of measuring ESR over frequency.

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