Bode and Step Load Tests over Single-Cable Connection to DUT with Rev 2.0 Adapters

Presenter: Christian Kueck

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MPS

Presenter Intro: Christian Kueck

- Senior FAE supporting automotive Tier 1 customers throughout Germany
- Over two decades of experience in PSU challenges
- Deeply involved in the definition and compliance testing of our leading AEC-Q100 power management solutions
- 22 years at Linear Technology, 5 years at MPS
    - Strategic Marketing Manager for Europe – Product definition and product support for PSU and LED circuits
    - Field Application Engineer
- Additional:
    - Design Engineer, Quality Assurance, Materials Engineer
- Microelectronics. Dipl. Ing., Elektrotechnik University of Dortmund

Today’s Agenda

- The Motivation
- Measuring Bode Plots: What Is Required?
- How to Reduce the Hookup Harness
- Examples of Bode Measurement and Interpretation
- Step Load Response with the Same Hookup
- Examples to Step Load Response and Interpretation
- Open Q&A

Motivation

For switch-mode PSU stability and characterization over production parameter spread, stability analysis is essential.

For small-signal stability analysis, Bode measurements of the loop gain and phase provides answers.

For large-signal analysis, the step load analysis provides answers.

Can the Results of Bode and Step Load Be Different?

For an ideal LTI (linear time invariant) system, large-signal and small-signal responses behave the same. Therefore, you can calculate the expected results from Bode to step load, and vice versa.

In the real world, the gain and slew rate of PSU stages are amplitude dependent, so they are often nonlinear across large amplitudes/excitations. In addition to slew rate limitations, the gain is dependent on the device's operation point.

In reality, you can see large-signal step load responses suggesting high stability margins (e.g. asymptotic step loads without any ringing). Conversely, Bode small-signal analysis shows low phase margins.

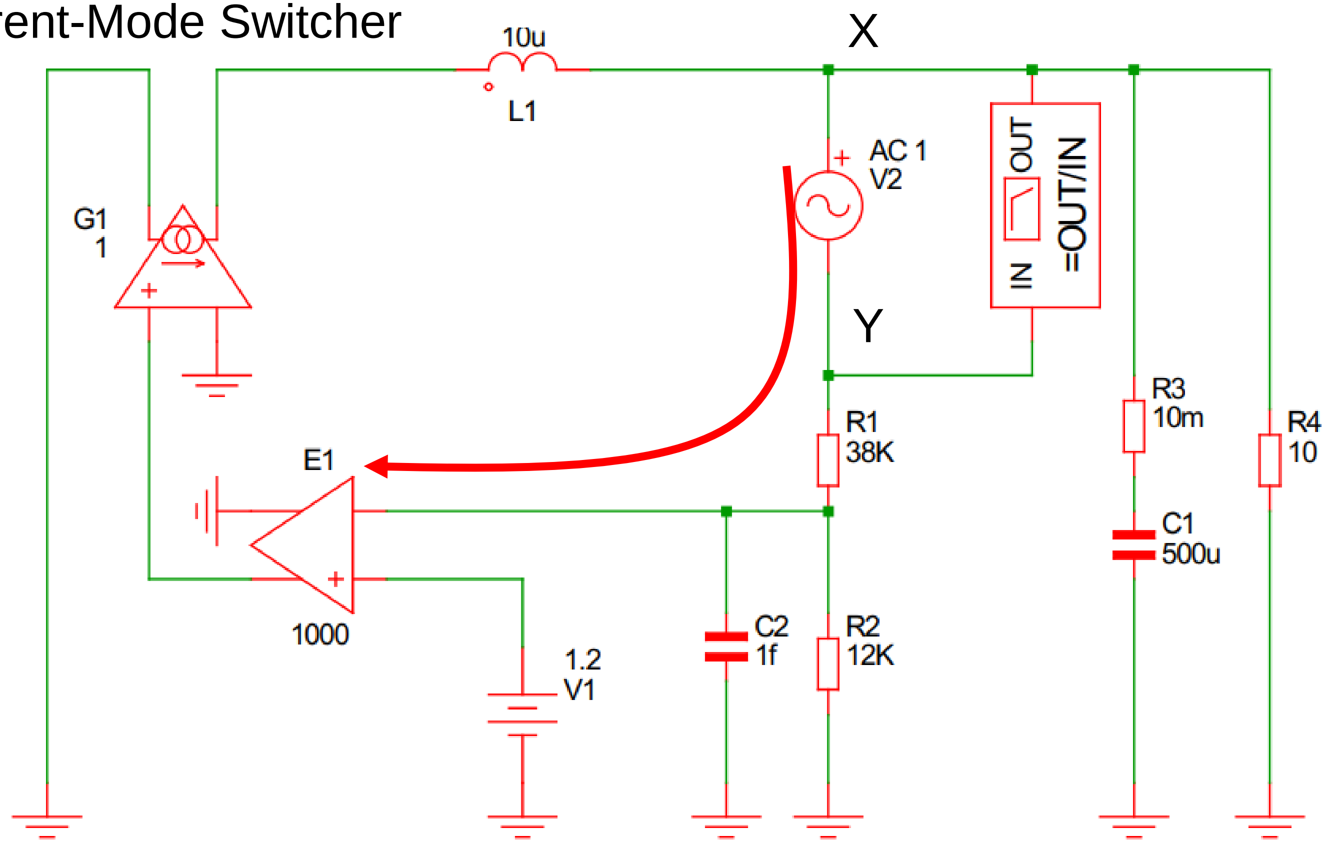
Often, the regulation loop shows less gain for a step load situation because the devices operate at a different point compared to a small-signal excitation within their linear range, as measured by a Bode plot.

This is why it is important to examine both Bode and step load.

How Is a Bode Measurement Made?

You could measure the loop anywhere along this red path.

Current-Mode Switcher



Inject a small signal anywhere into the regulation loop, then measure the vector quotient of V(X) / V(Y).

For the AC excitation source, an injection transformer can be used to get a floating AC source, and there are three wires attached to the DUT board.

Those three wires cannot usually be long, since they are attached to the feedback loop.

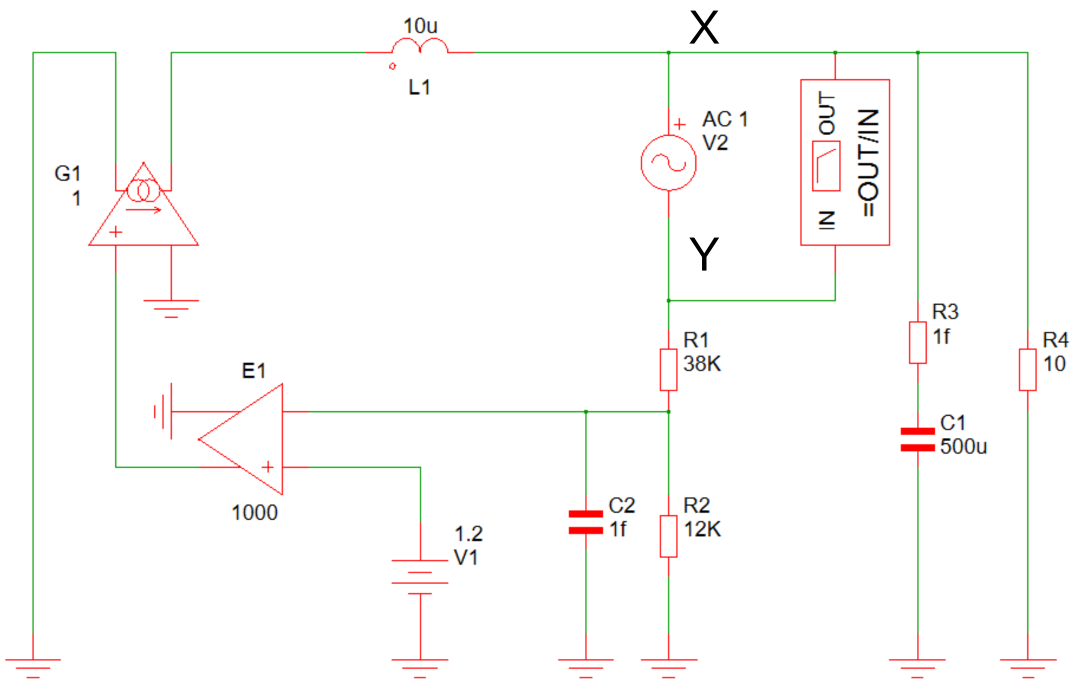
Motivation

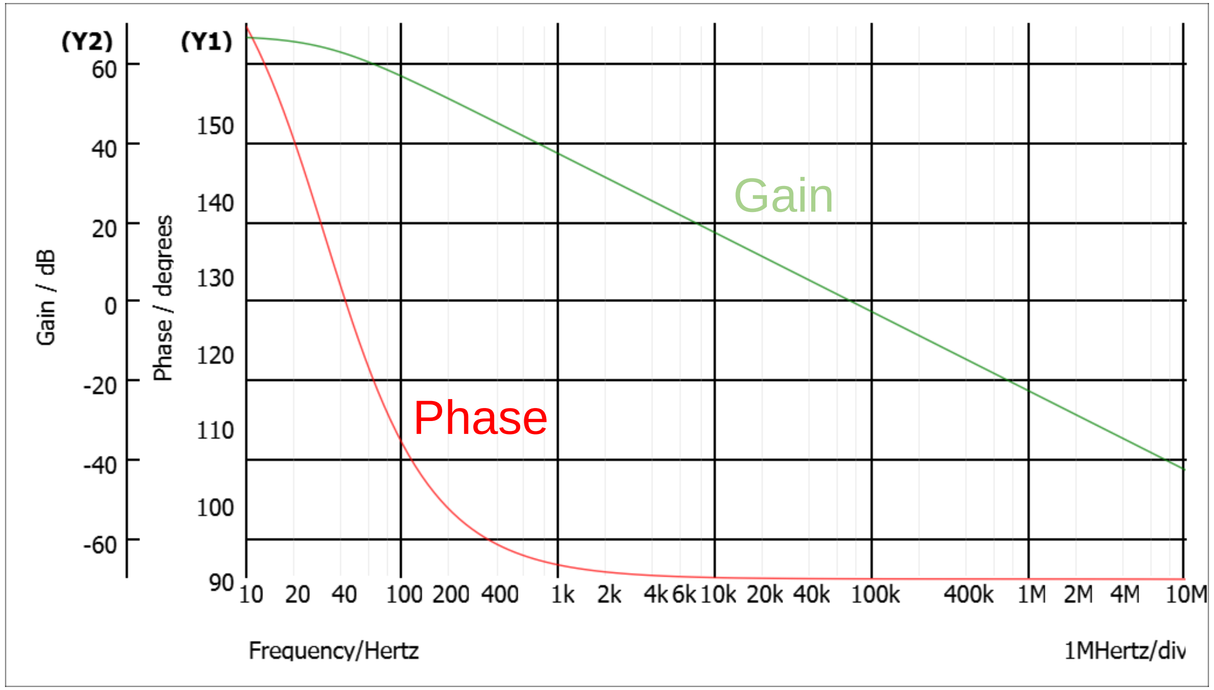
A Bode measurement on a final production board is as much a mechanical probing problem as it is an electrical one.

Two scope probes and a banana cable or yellow wire hooked up to the transformer are not a mechanically stable system to use in a climate chamber or similar environment.

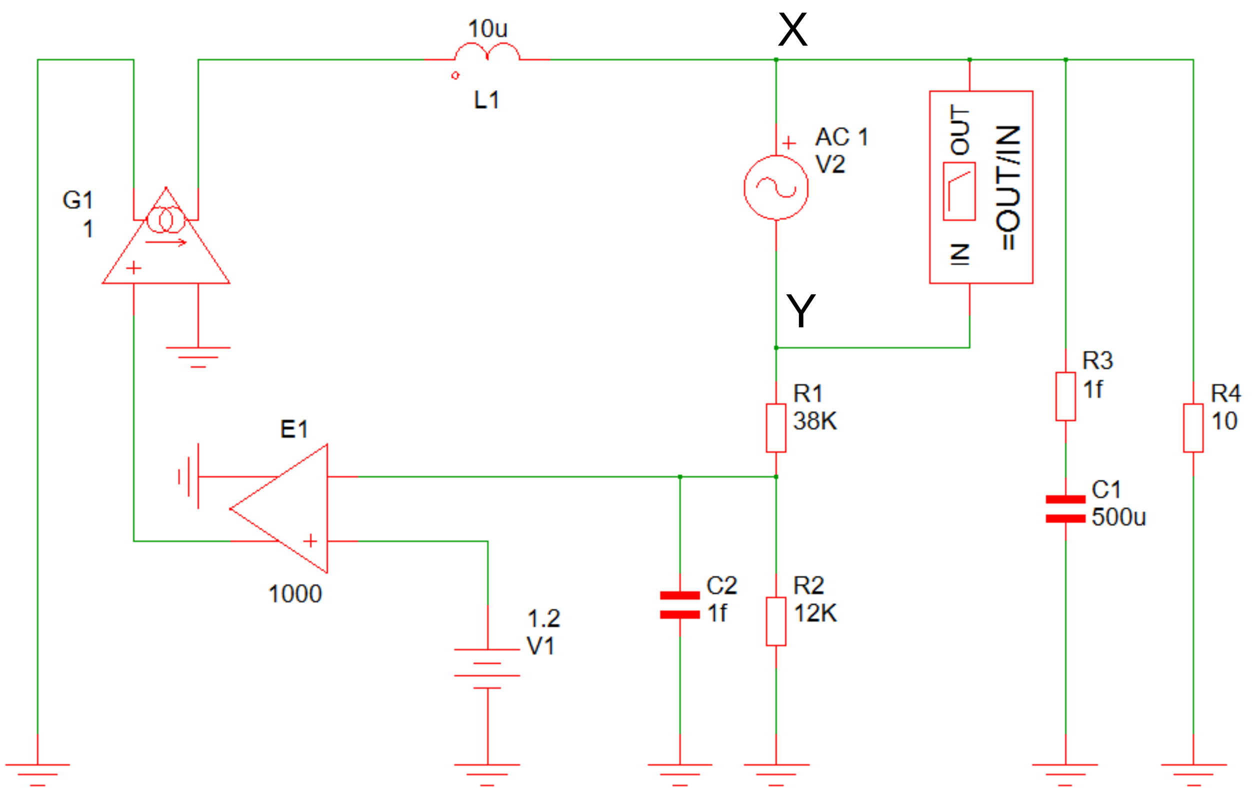
How Is a Bode Measurement Made?

Bode plot made with an MPSmart simulation of a nearly ideal current-mode PSU.





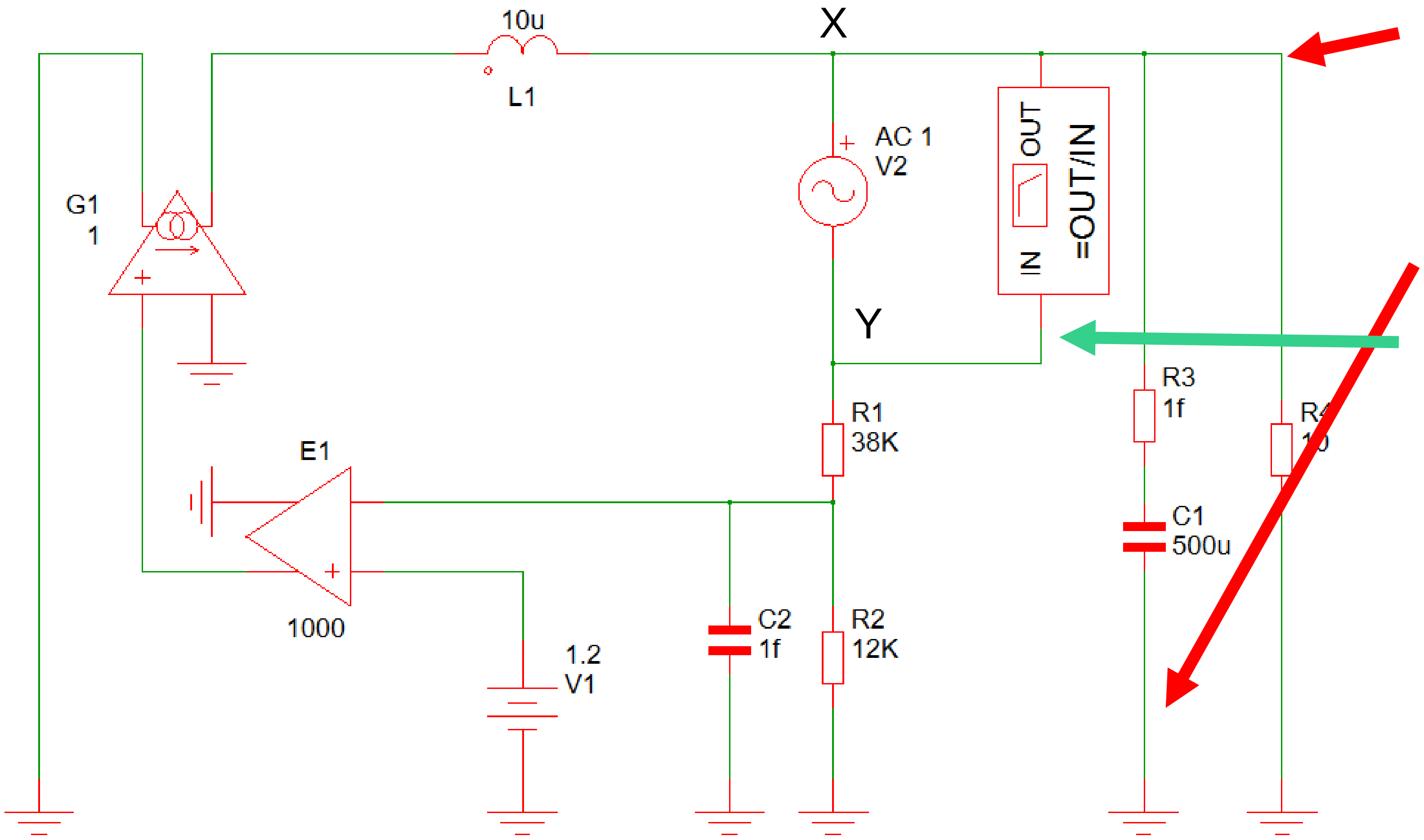
Conventional Bode Measurement



On an auxiliary board with an injection transformer and hooks for the probes, there are three wires attached to the DUT board. Those three wires cannot usually be long, since they are attached to the feedback loop.

For the AC source, an injection transformer is required to get a floating AC source.

Where to Hook for Bode

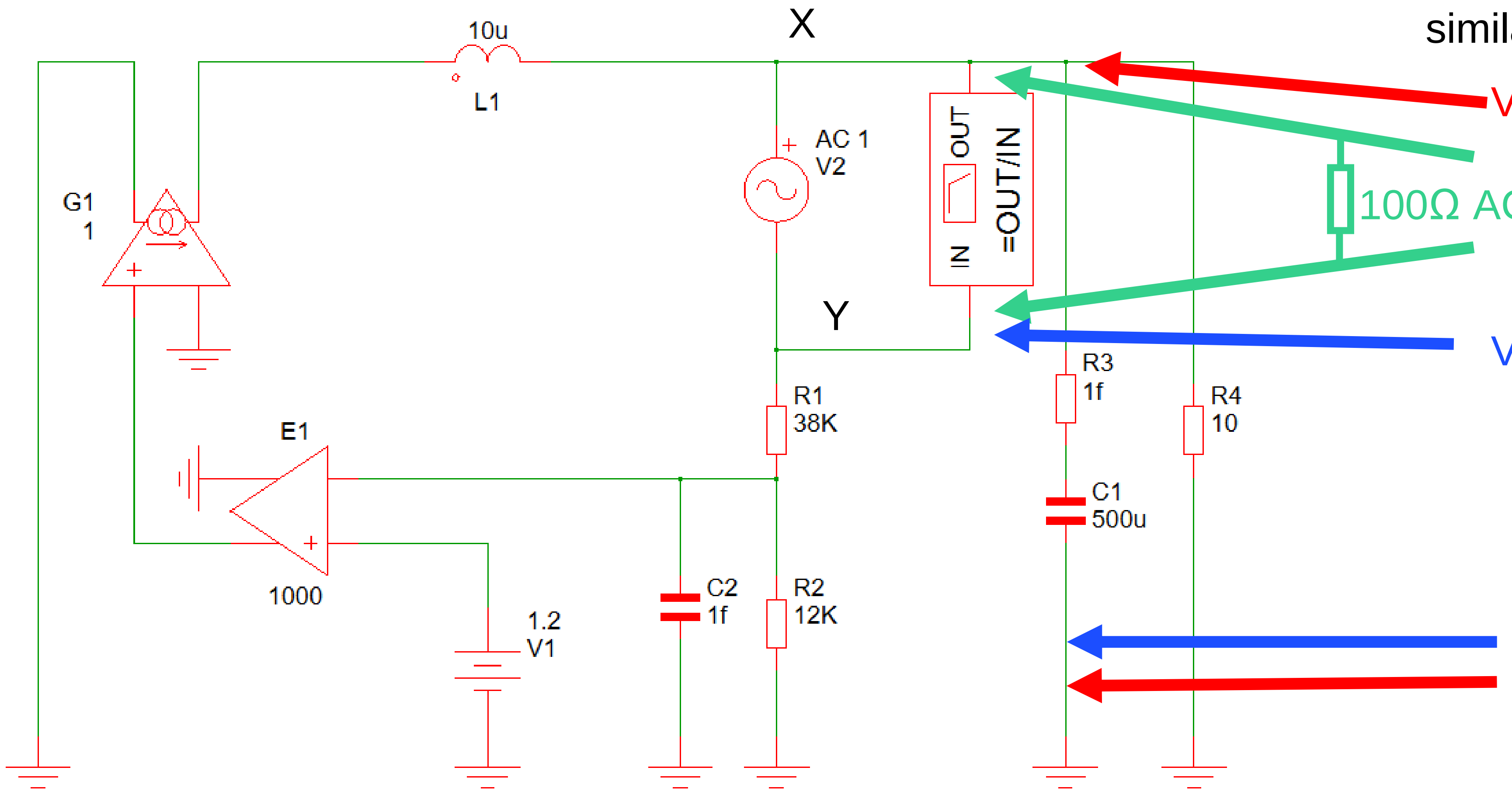


Low-impedance hooks. V_{OUT} and GND are found at the output capacitors, which are easy-to-probe, low-impedance points and are mechanically robust.

The Y-node is higher impedance. Typically, it is recommended to use a 50Ω or 100Ω resistor here on the board between the X-node and Y-node to keep impedance low.

Idea: Hook on the Output Capacitor and Leave the AC Source Isolation at the Analyzer

This requires three cable pairs with similar defined RF characteristics.

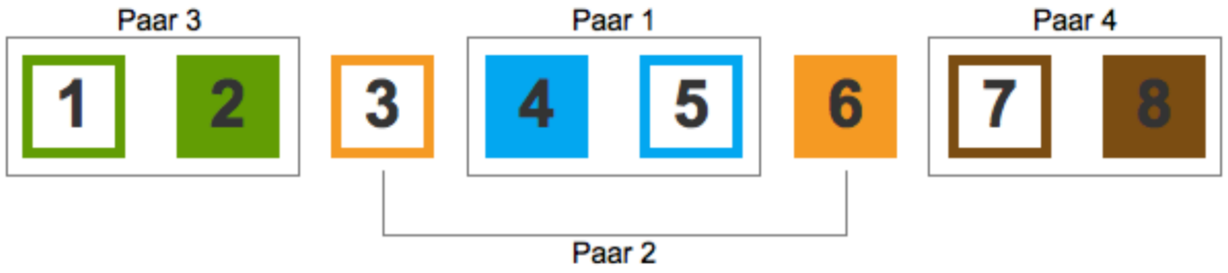


Terminating the AC injection signal with 100Ω at the DUT also, to some degree, terminates the V(Y) signal. The V(X) signal is low-impedance, and is not terminated at the DUT.

If Searching for a Single Cable that Does the Job, LAN/Ethernet Patch Cables Are an Ideal Solution

They combine:

- Four pairs for four channels available (a minimum of three are required)
- They come with a specified impedance: 100Ω ±10%
- Good RF isolation between one pair and the other
- Inexpensive
- Available in all lengths and colors with a standard RJ45 connector
- RJ45 connectors are inexpensive and available in surface-mount packaging
- High-reliability gold contacts
- Rated for 60V and small-signal use (about 1A, but beware of resistance)



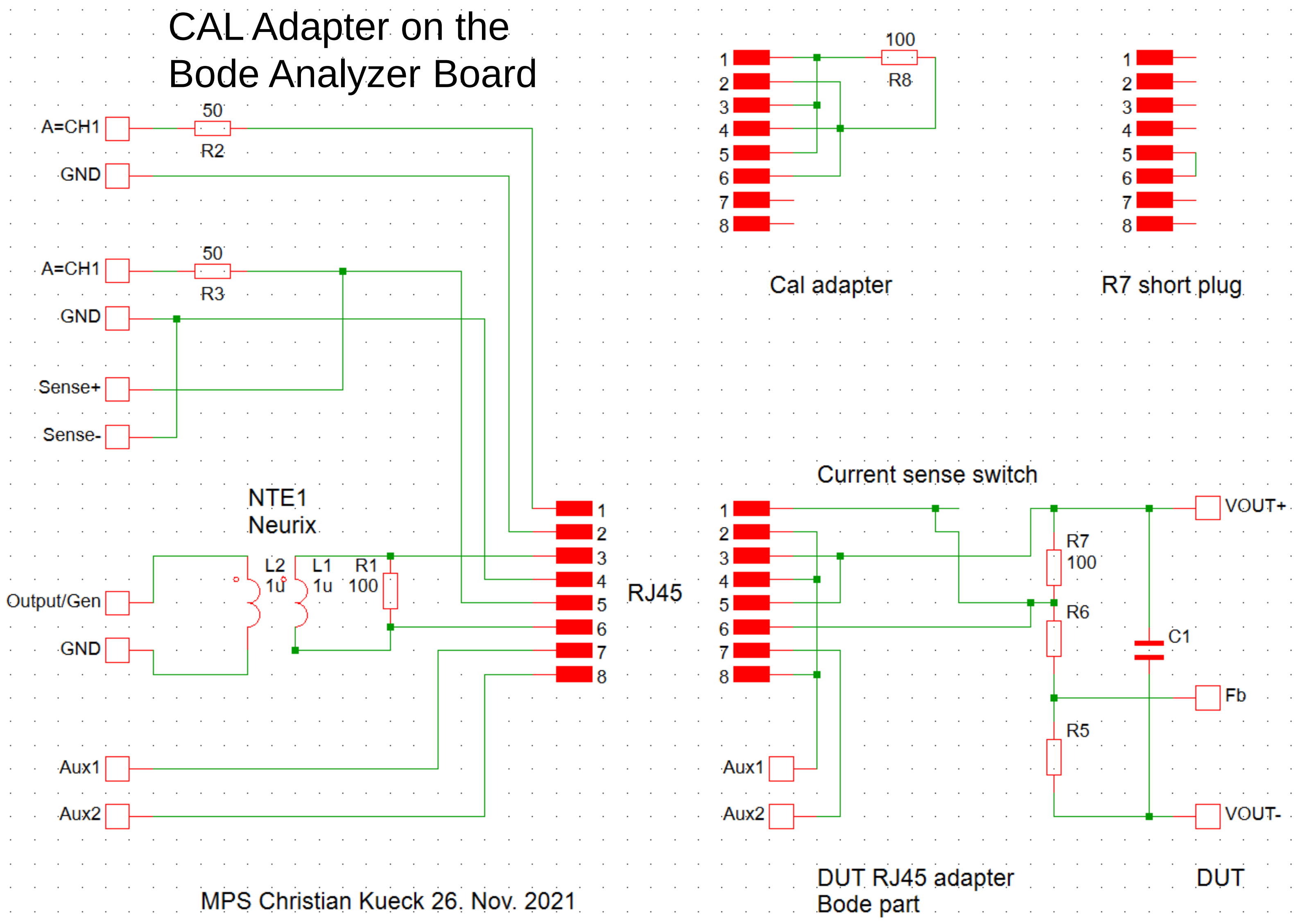
Attention:

Pair 2 is on pins 3 and 6

Through-hole RJ45 connectors often have non-standard, non-sequencing pin out. Use only SMT RJ45 connectors if possible.

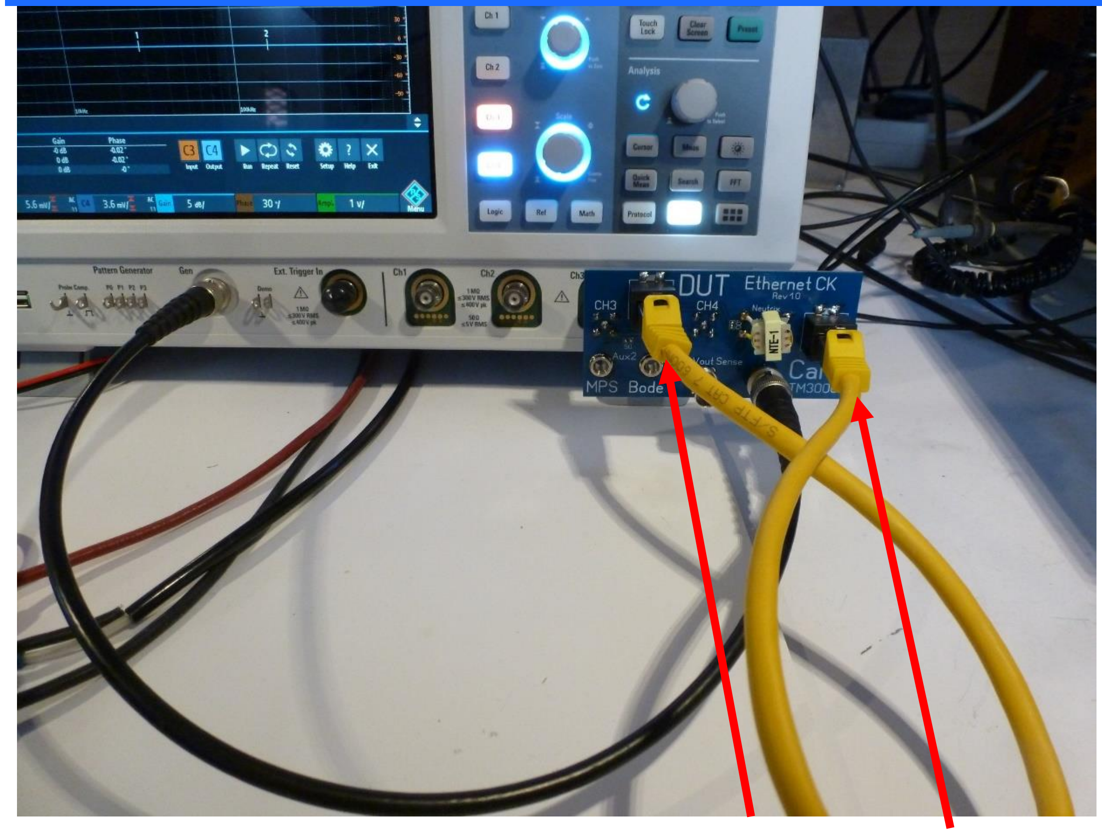
Find out why….

Bode Connector Schematic

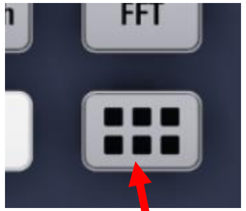


MPS Christian Kueck 26. Nov. 2021

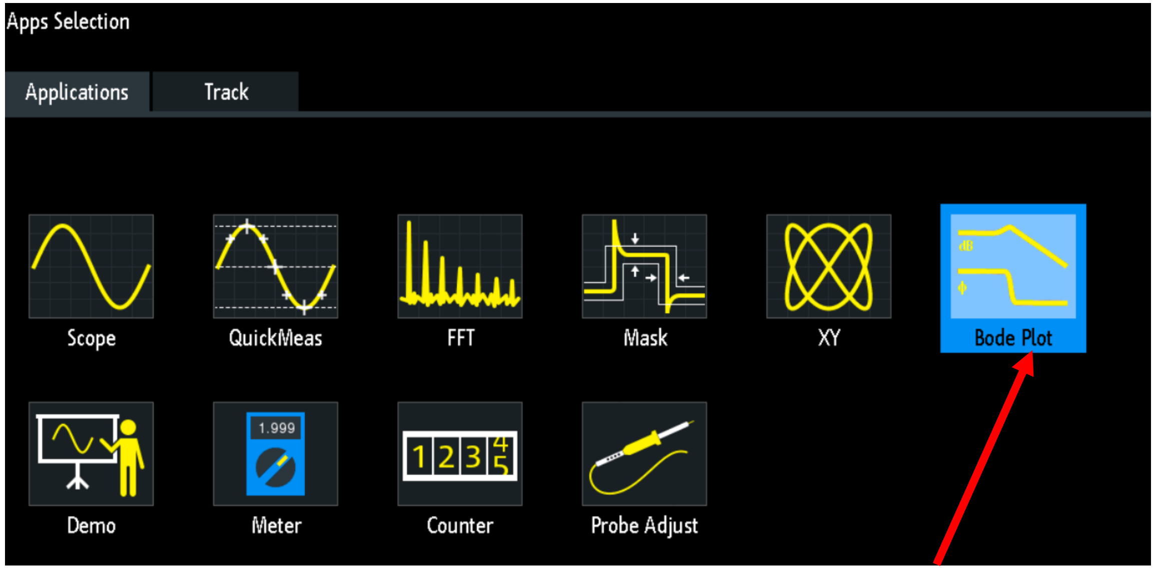
RTM3000 Set-Up for Bode



Connect Patch Cable into Cal Plug



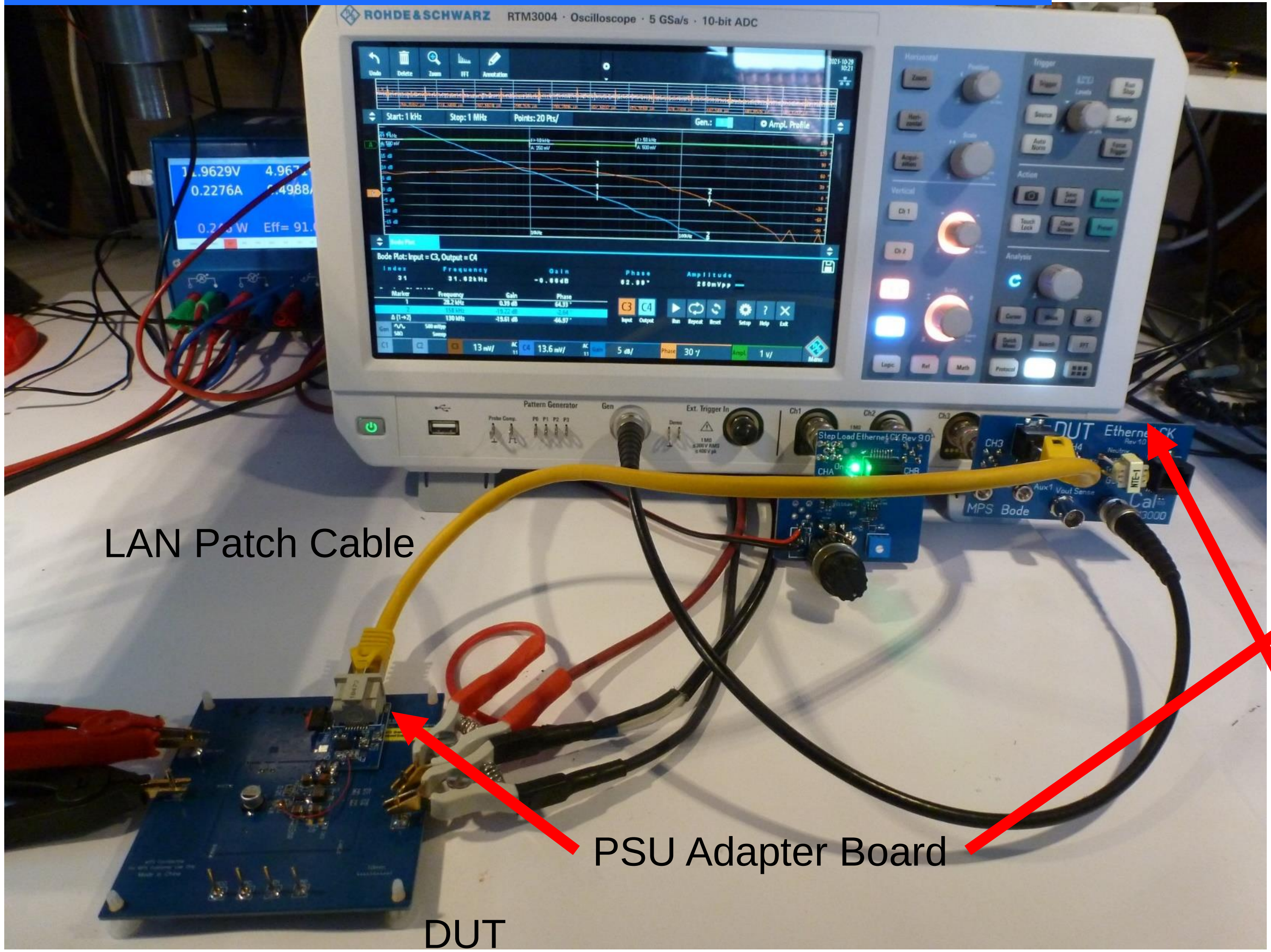
Apps Selection Menu



Activate Bode Plot

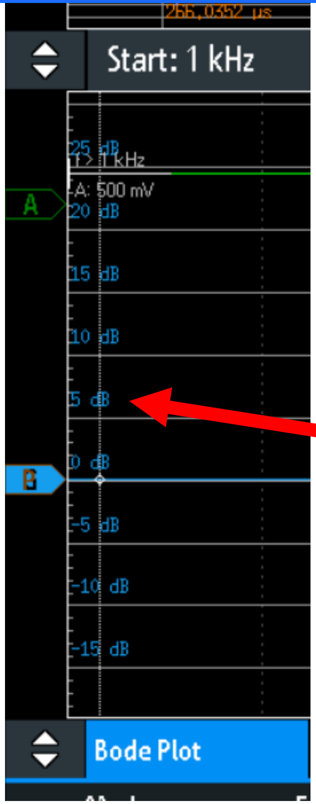
Activate C3 as Input and CH4 as an Output Channel

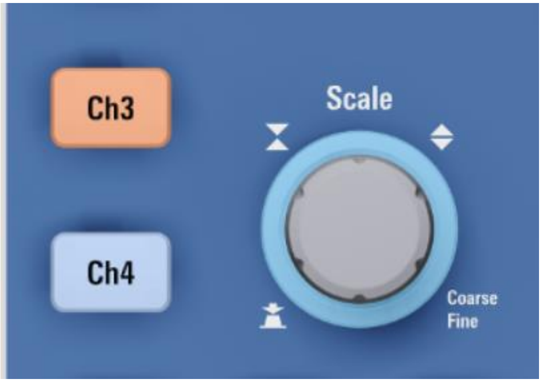
Bode Set-Up



PSU Adapter Board with an Fb Connection

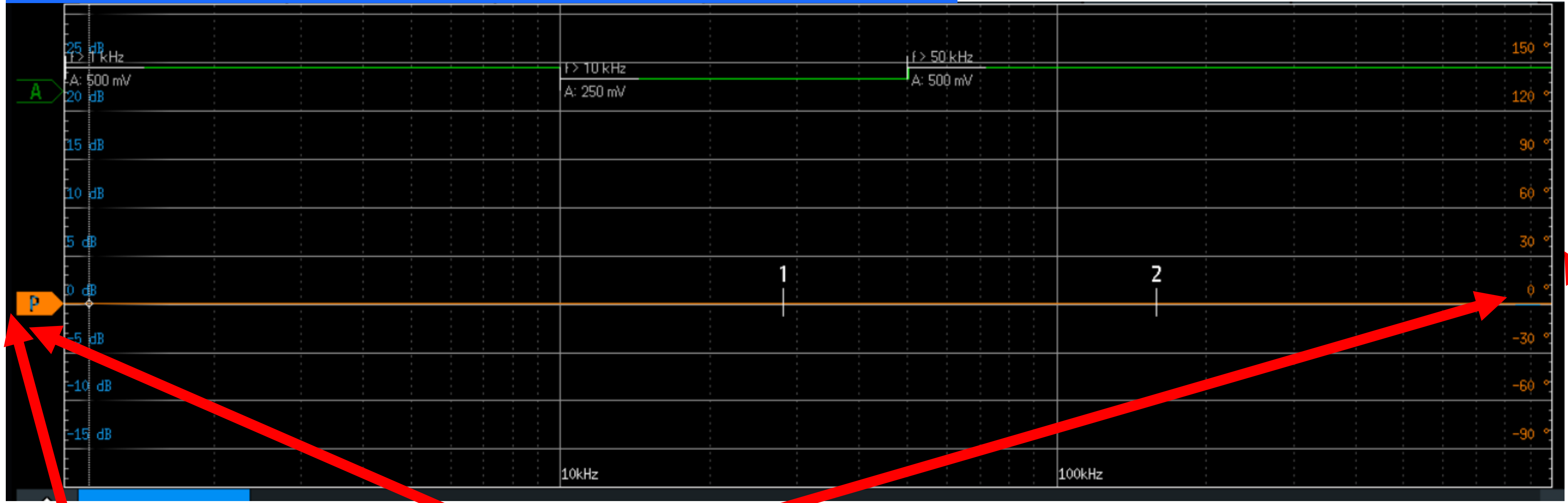
Bode Set-Up Gain





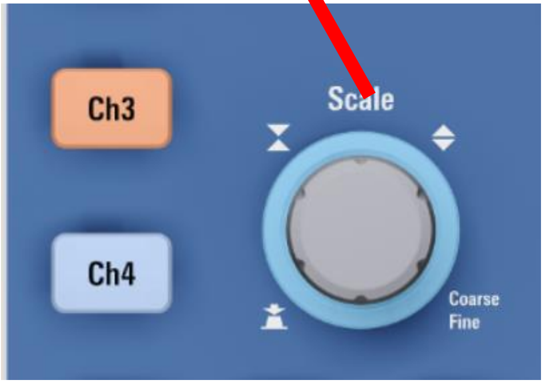
Using the “Scale” knob, set the gain to a decent scale, such as 5dB/div. Auto-scaling or zooming on the touchscreen will provide unusable steps.

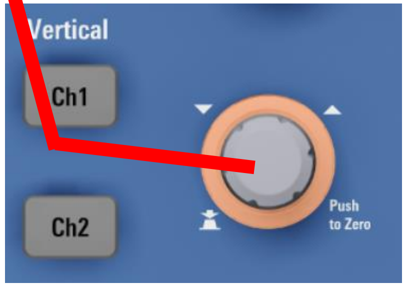
Bode Set-Up Phase



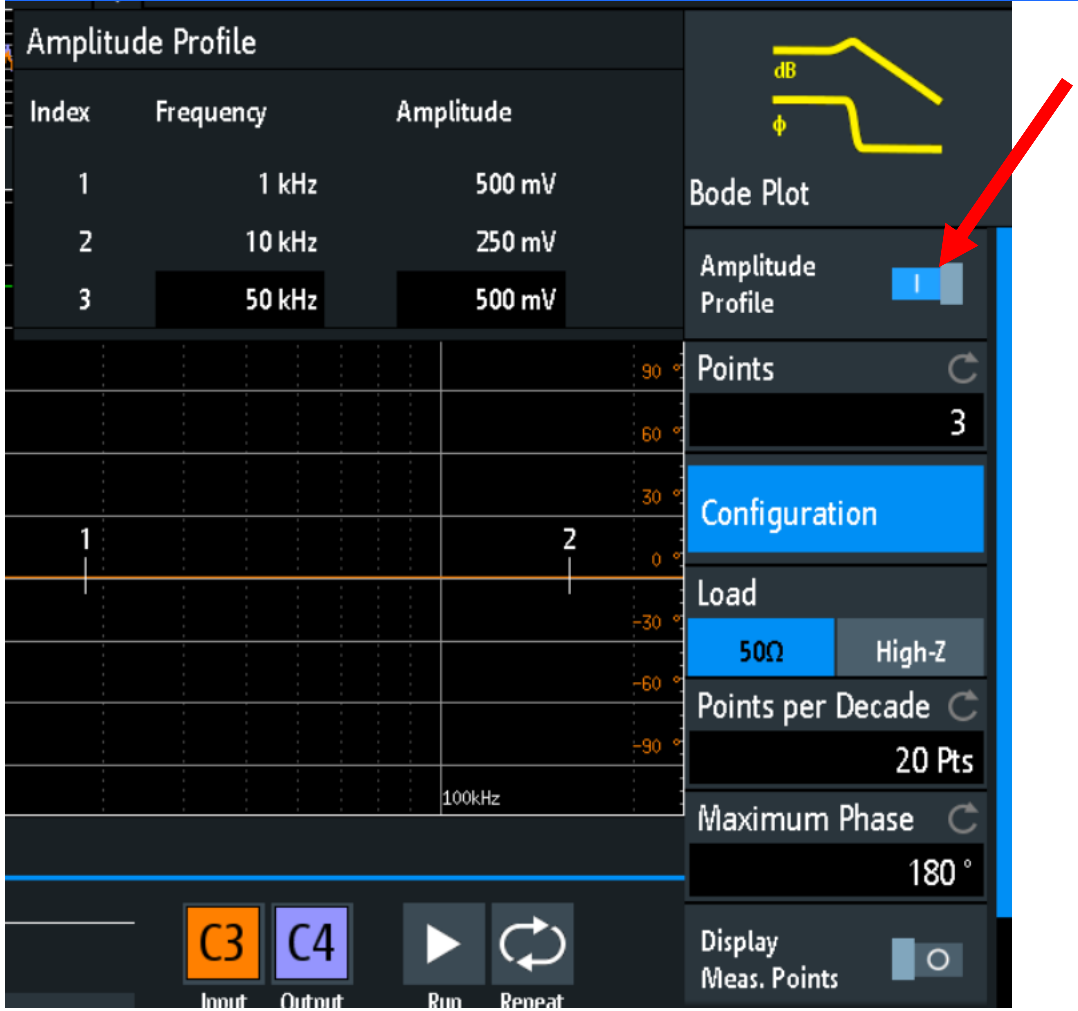
Set the phase scale with the scale knob to a decent scale, like 30°/div.
Auto-scaling or zooming on the touchscreen will provide unusable results.

Set 0° to the same line as the 0dB gain, which eases graph interpretation.



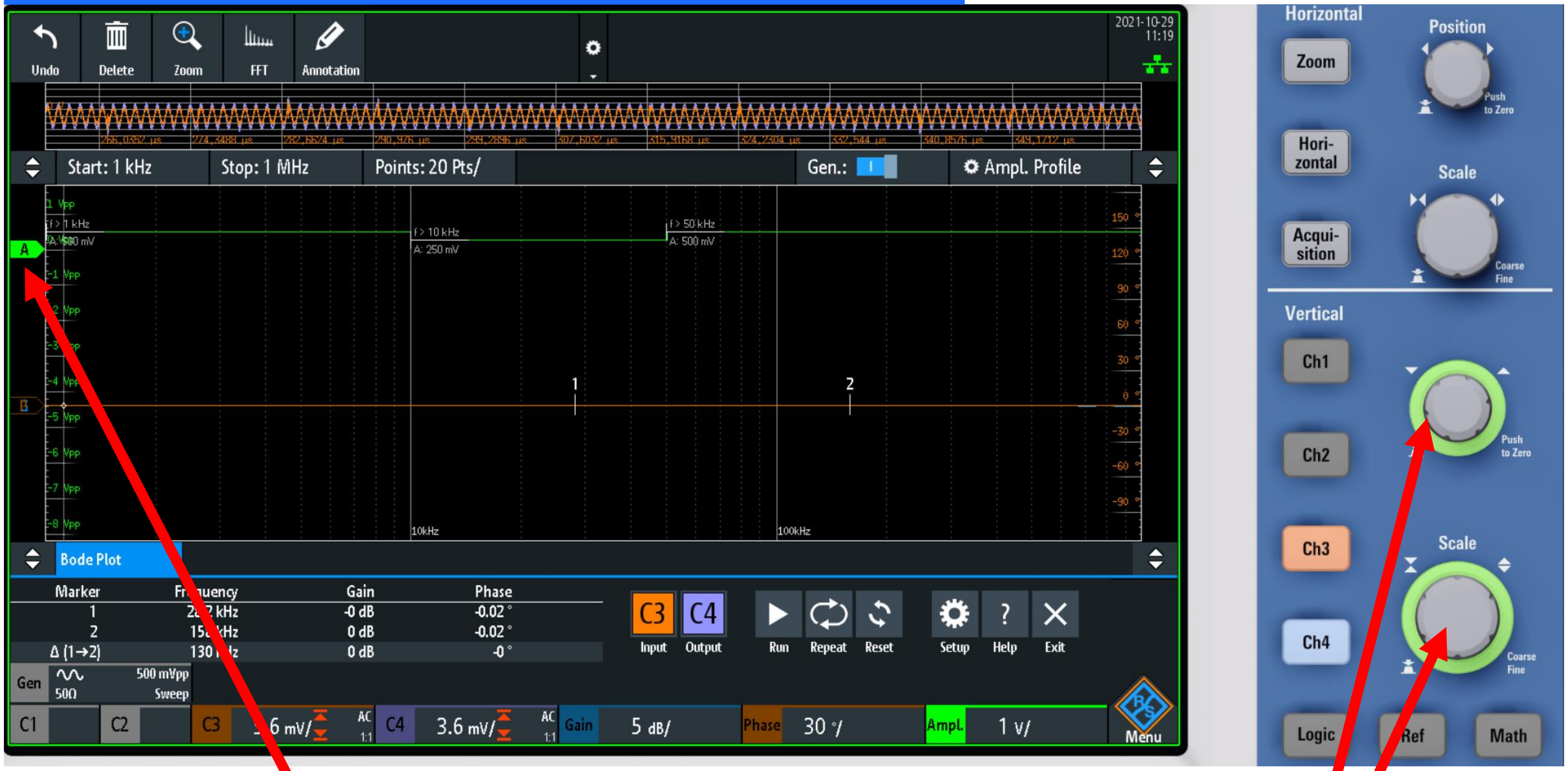


Bode Set-Up Amplitude



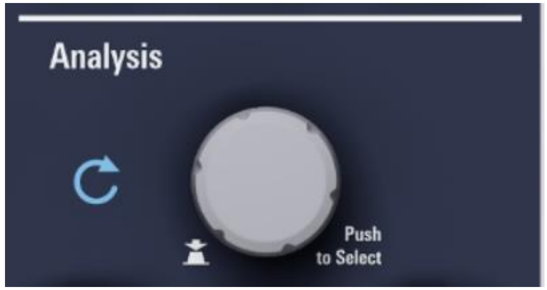
Enable "Amplitude Profile" in the Bode menu.

Bode Set-Up Amplitude



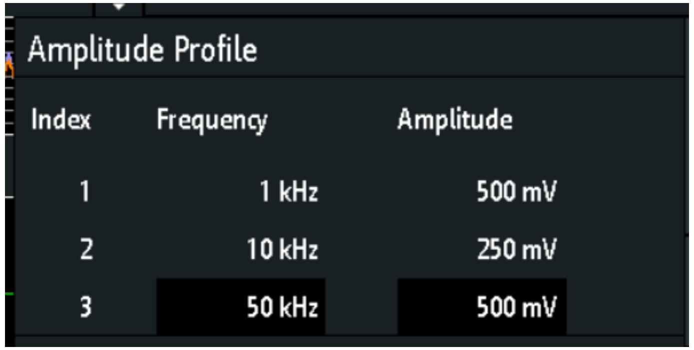
The green amplitude screen can be adjusted if “A” is activated with the vertical knobs.

Bode Set-Up Amplitude



The selected frequency and amplitude can be adjusted with the “Analysis” knob. Add points as needed.

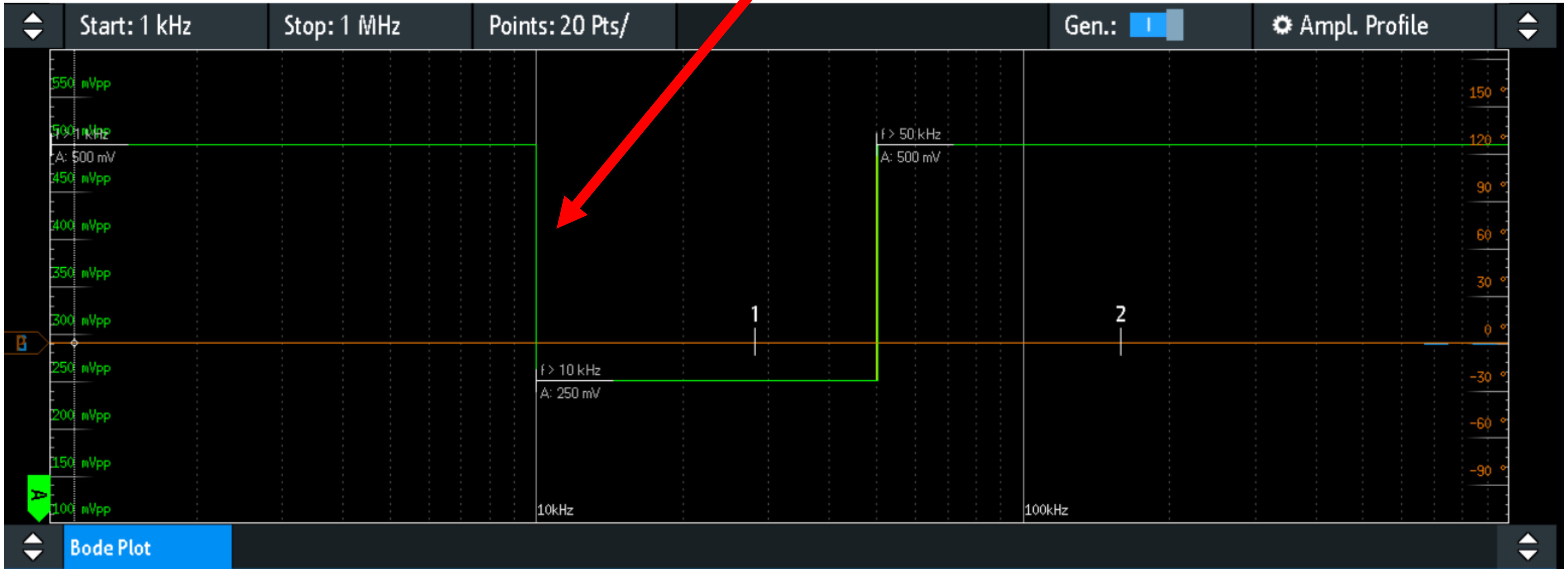
Bode Set-Up Amplitude



Amplitude Profile

Index	Frequency	Amplitude
1	1 kHz	500 mV
2	10 kHz	250 mV
3	50 kHz	500 mV

The downside of the amplitude profile is that it changes the amplitude in abrupt steps. This may yield to artifacts in the Bode plot, so only make slight changes, and use more steps if necessary.



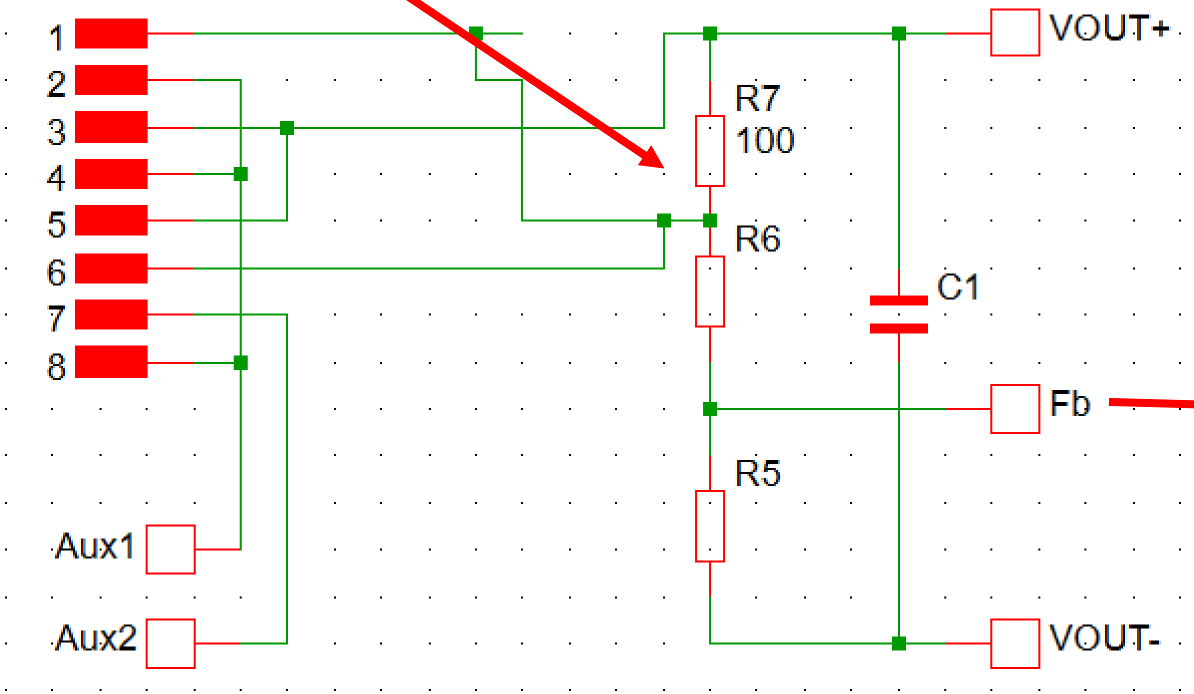
Set-Up CH3 and CH4

Run CH3 and CH4 high-impedance mode (1MΩ) and AC coupled. RTM3000 shows 300V max.

Caveat

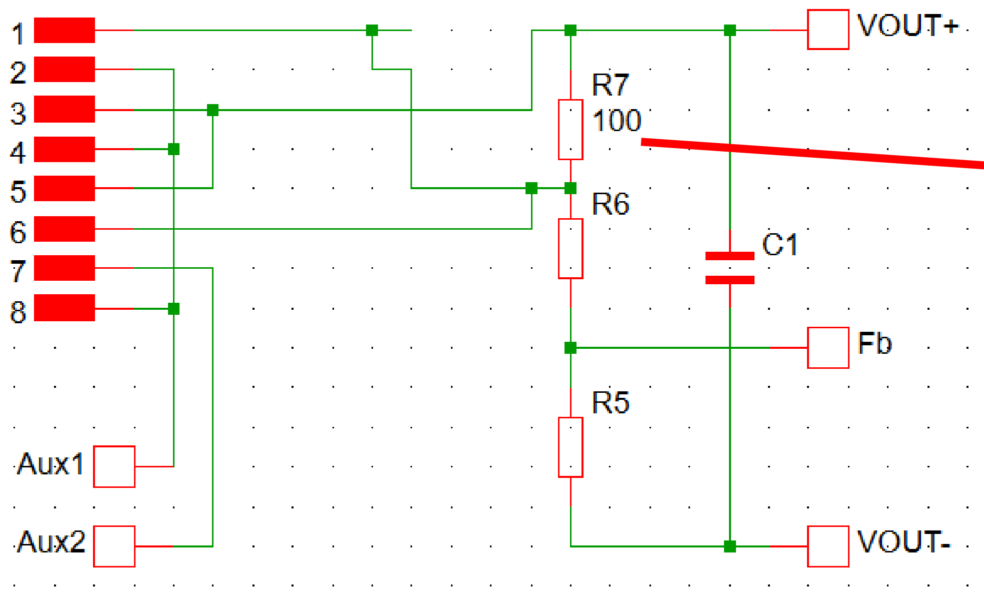
The FB loop is with the PSU board only closed over a small yellow wire. If that connection breaks on buck regulators, a typical $V_{IN} = V_{OUT}$ situation occurs. A boost regulator will destroy itself immediately by producing an over-voltage condition.

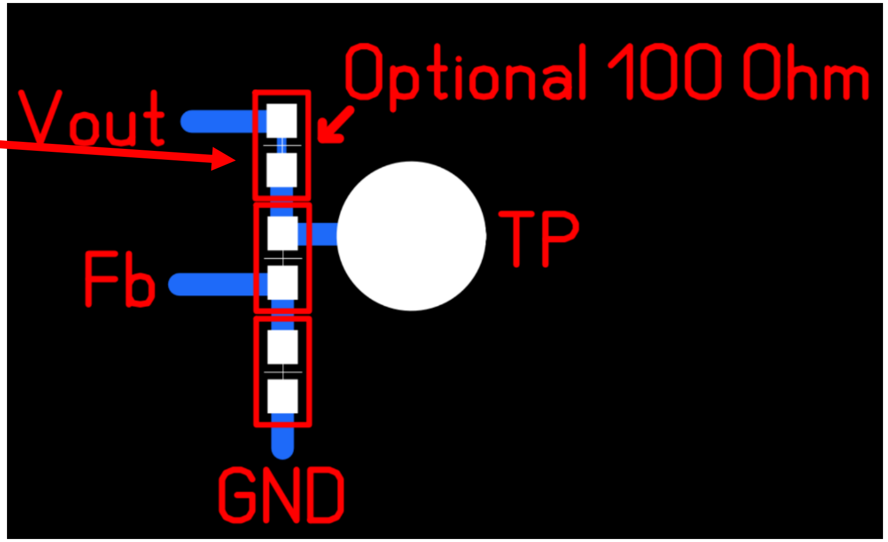
It is best if the optional R7 (100Ω) is placed on the final PCB immediately. Check to see if that is feasible.



Hint

If the PCB size allows, you can place a shorted 0402 placeholder for R7 on the PCB. For Bode tests, dremel the short open and place a 100Ω termination resistor there. A test point at this location will come in handy. This also prevents the FB loop from opening up when playing around with heat guns, mechanical loads, etc. That is the biggest danger when using only the yellow wire to close the FB loop.



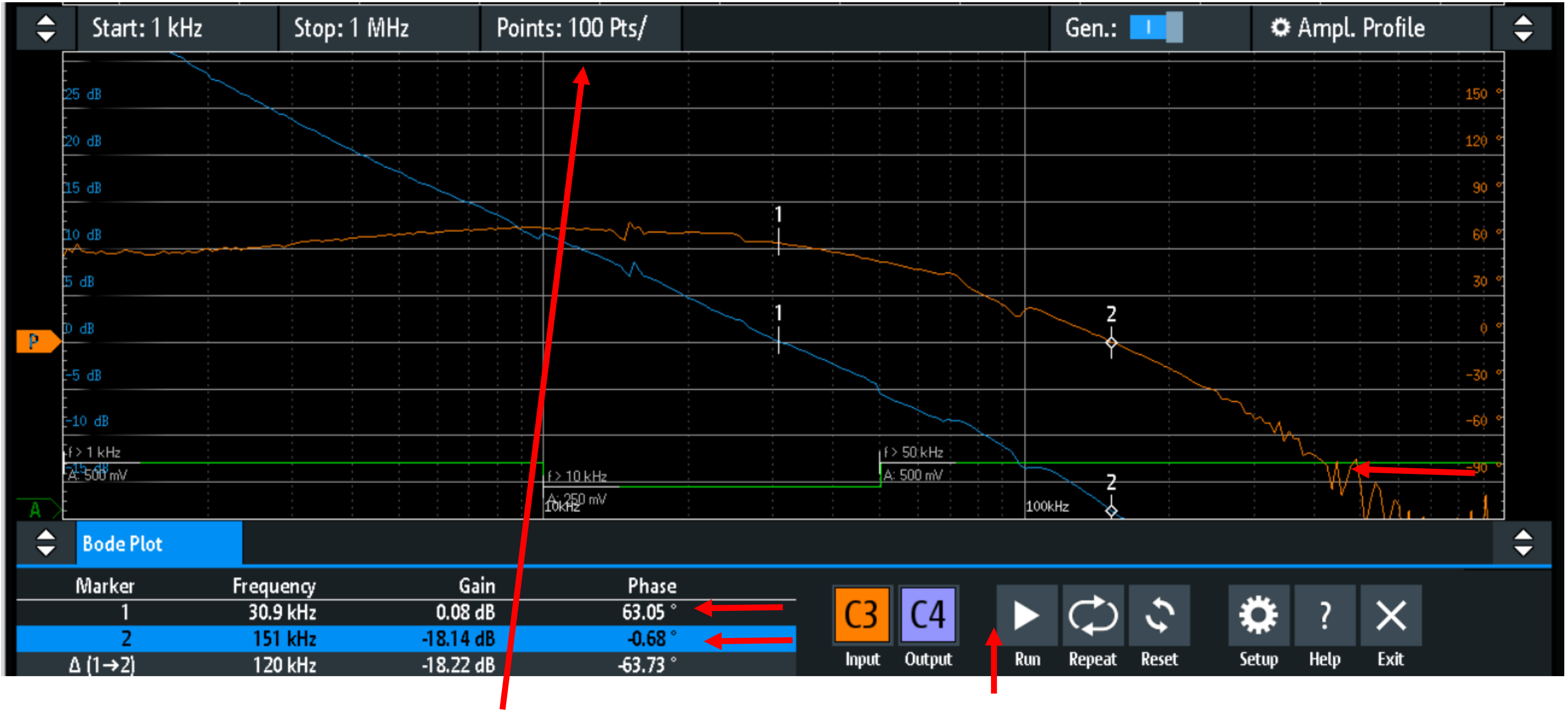


Bode Set-Up for Easy Interpretation for PSU

Ensure that the gain and phase graphs align on the 0dB and 0° phases.

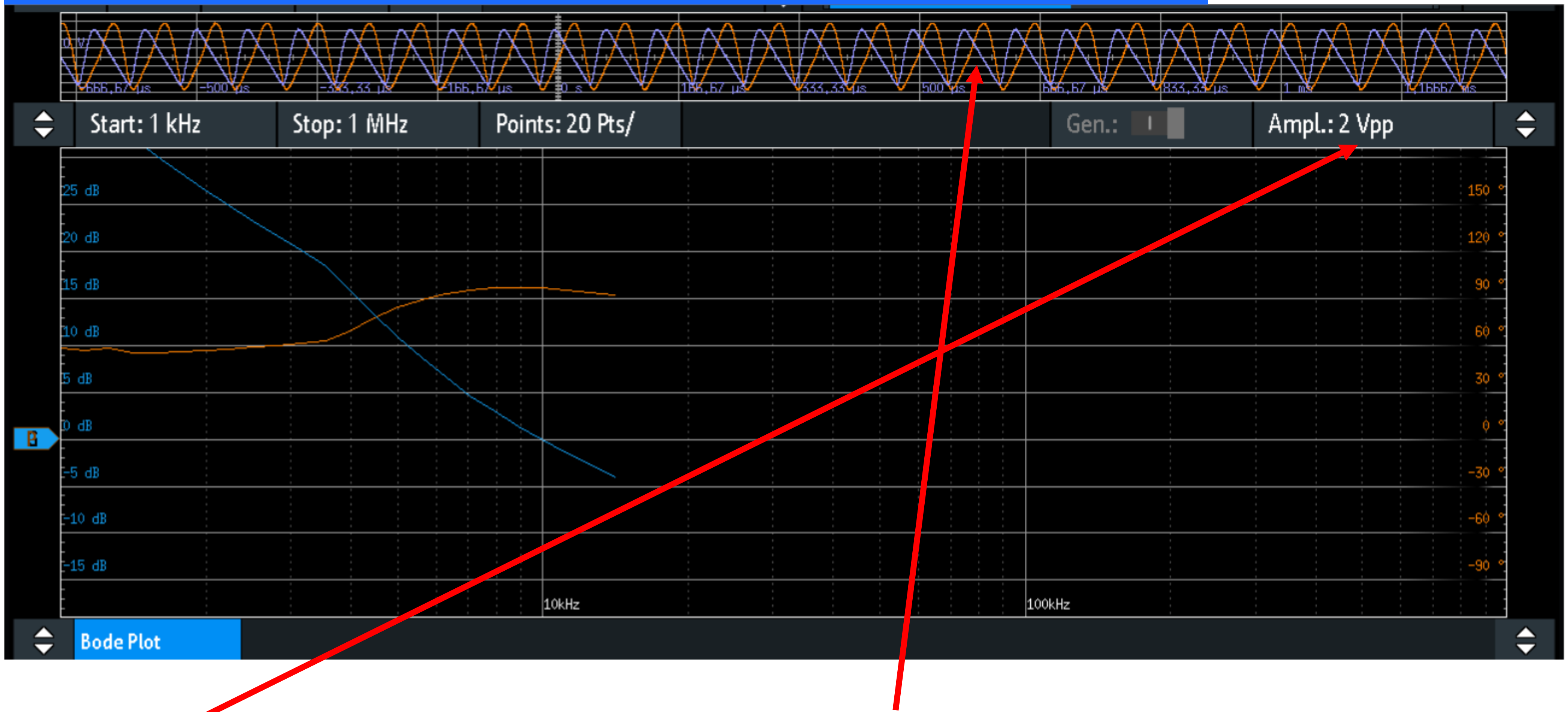
Use a marker for the 0dB and 0° phase points.

Bode Set-Up for Easy Interpretation for PSU



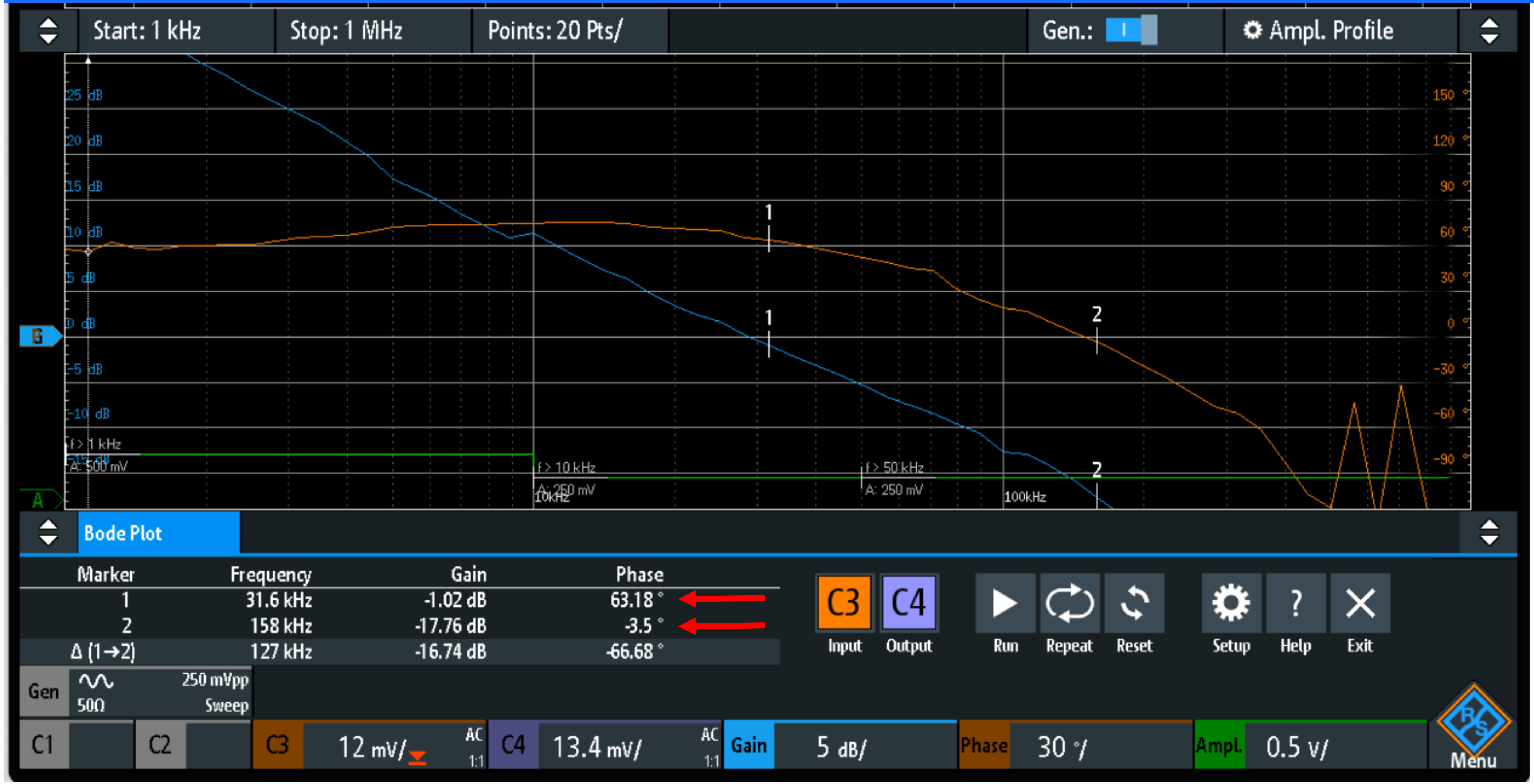
A higher points number slows down measurement (reduced RBW), but provides better resolution on the gain and phase plots. The artifacts in this case are mainly from the PSU's FSS function.

Bode Set-Up Too High Generator Amplitude



Too high of a generator amplitude provides the PSU AC response slew rate with limited artifacts, as well as false gain and phase curves. The upper window allows for some interpretation during the measurement run. Test smaller amplitudes until no additional artifacts occur and the Bode plot remains stable.

Adjust Source Level until Plots Are Invariant of Reduced Level

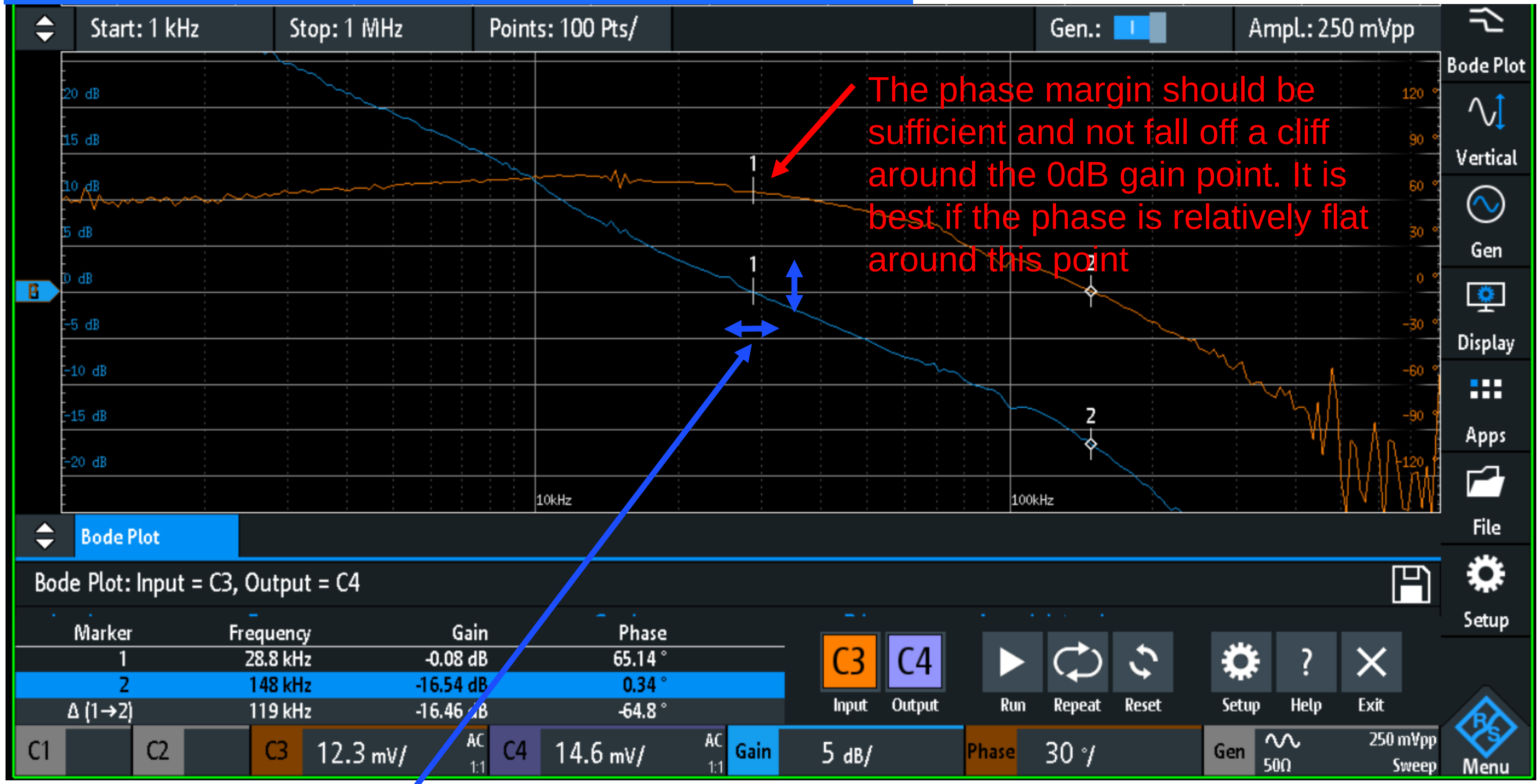


Hints

As a sanity test, always reduce the excitation amplitude by at least 3dB from the final setting to confirm that the Bode plot remains the same.

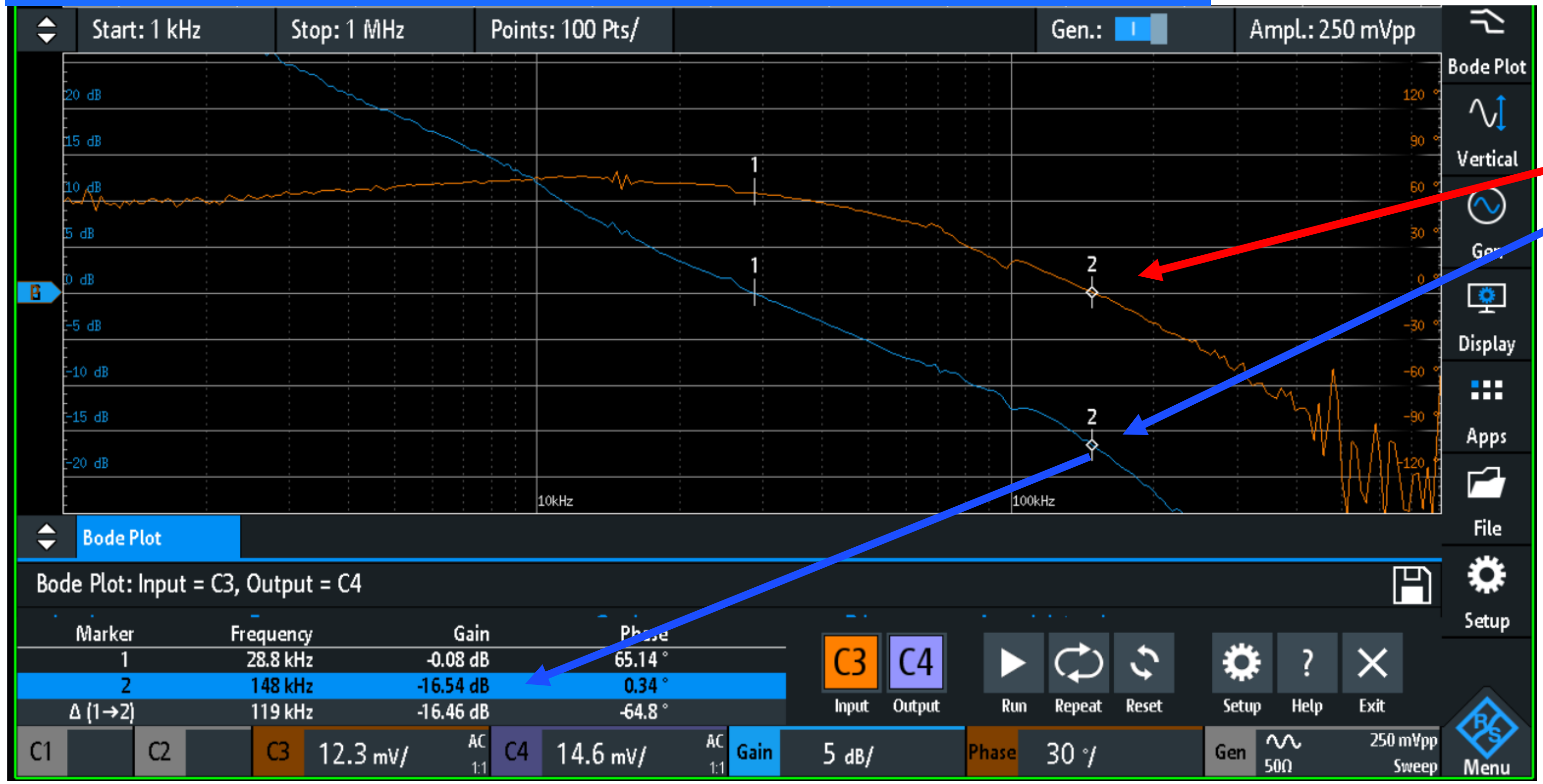
In most cases, there is no need for very low starting frequencies, as they do not add any useful information and slow down the measurements.

What to Look for: Phase Margin



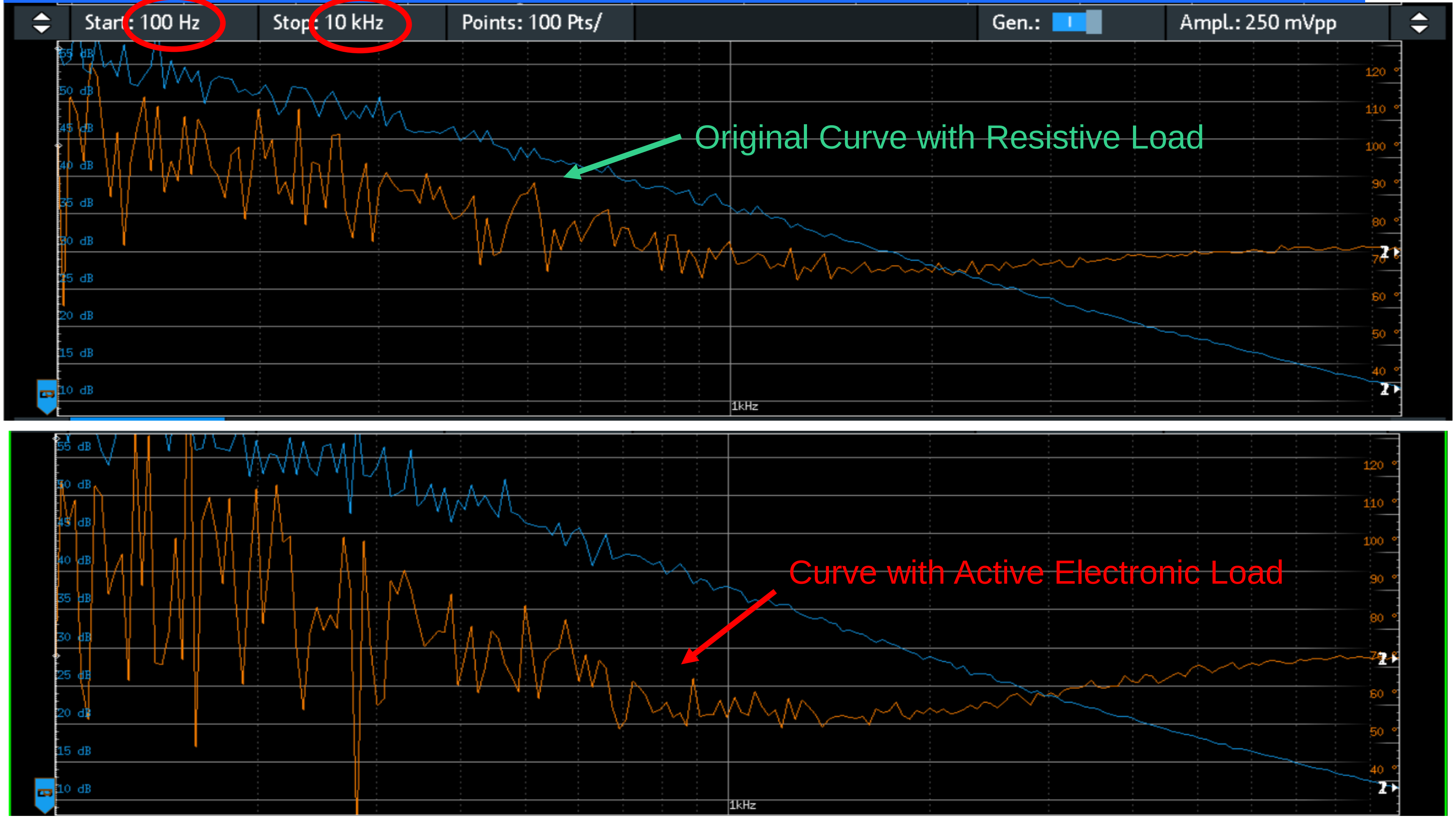
The gain curve changes a bit up and down across temperature and production variations, which moves the 0dB point a bit with frequency. It is important to have reserves for this.

What to Look for: Gain Margin



At the 0° phase reserve point, there should be enough attenuation (≤10dB) that the loop can not oscillate. Mechanisms like load resonance and current loop gain can easily provide some additional gain at those frequencies yielding in oscillation.

Always Use a Resistive Load for Bode Measurements



Do not include the frequency response of an active electronic load in a Bode measurement.

Typical PSU Loop Gain Effect of Temperature MPQ4320 Example

Cold is typically the most severe loop condition for MLCC C_{OUT} regulators in MOSFET technology.

The MLCC C_{OUT} goes down, resulting in a higher 0dB crossover frequency (see slide 6). At the same time, the error amplifier gain stage has higher gain. MOSFET amp structures typically decrease gain with rising temperatures. Bipolar amps typically increase with temperature.

Therefore, best practice is to keep a good phase margin for crossover increase at low temps.

RTM3004 100 Points

MPQ4430: 12V to 5V, 1.2A

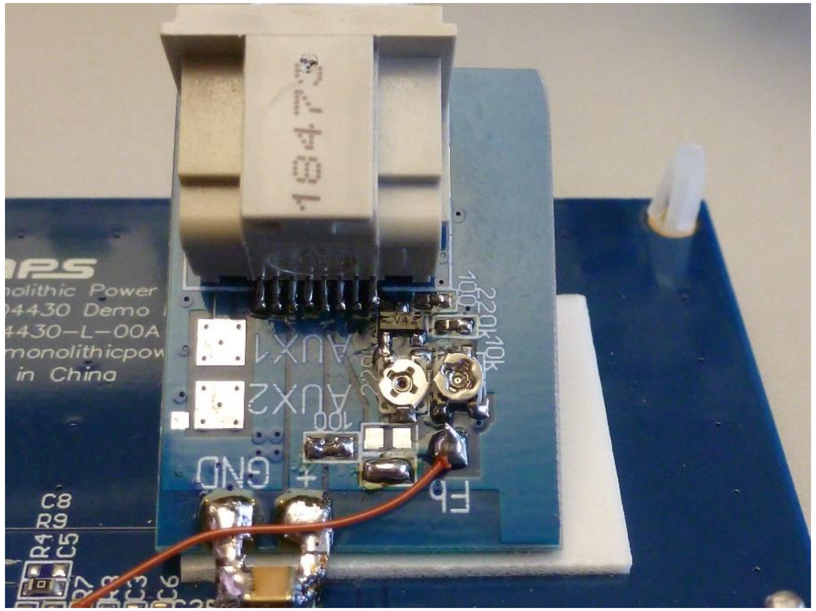
RTM3004 500 Points

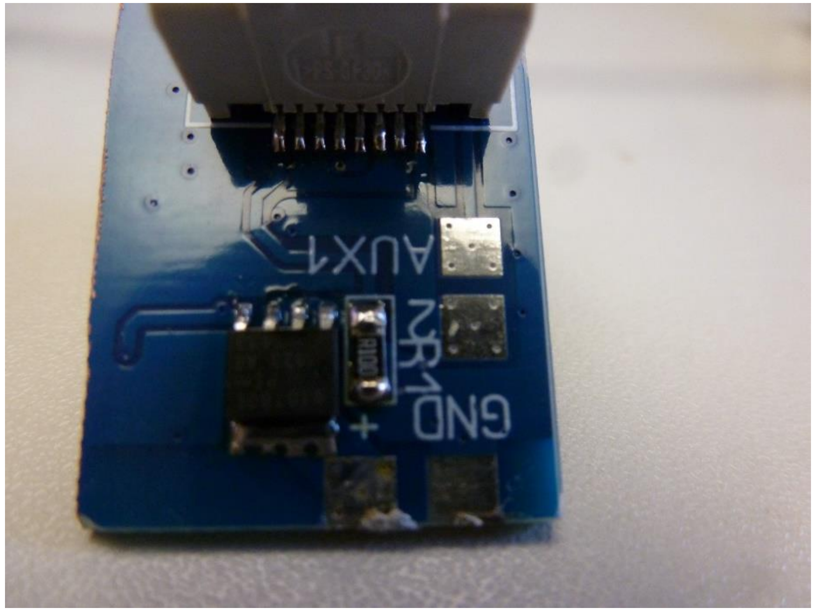
MPQ4430: 12V to 5V, 1.2A

Step Load

The AC (stepped) load should be done with the closest, lowest-impedance connection to the DUT C_{OUT}. Typically, a step load dissipating MOSFET with a current-sense resistor is placed on or near the DUT output capacitors. With the Bode hookup, we already have that connection to the C_{OUT} capacitors, so enhancing it to do step load is an easy task.

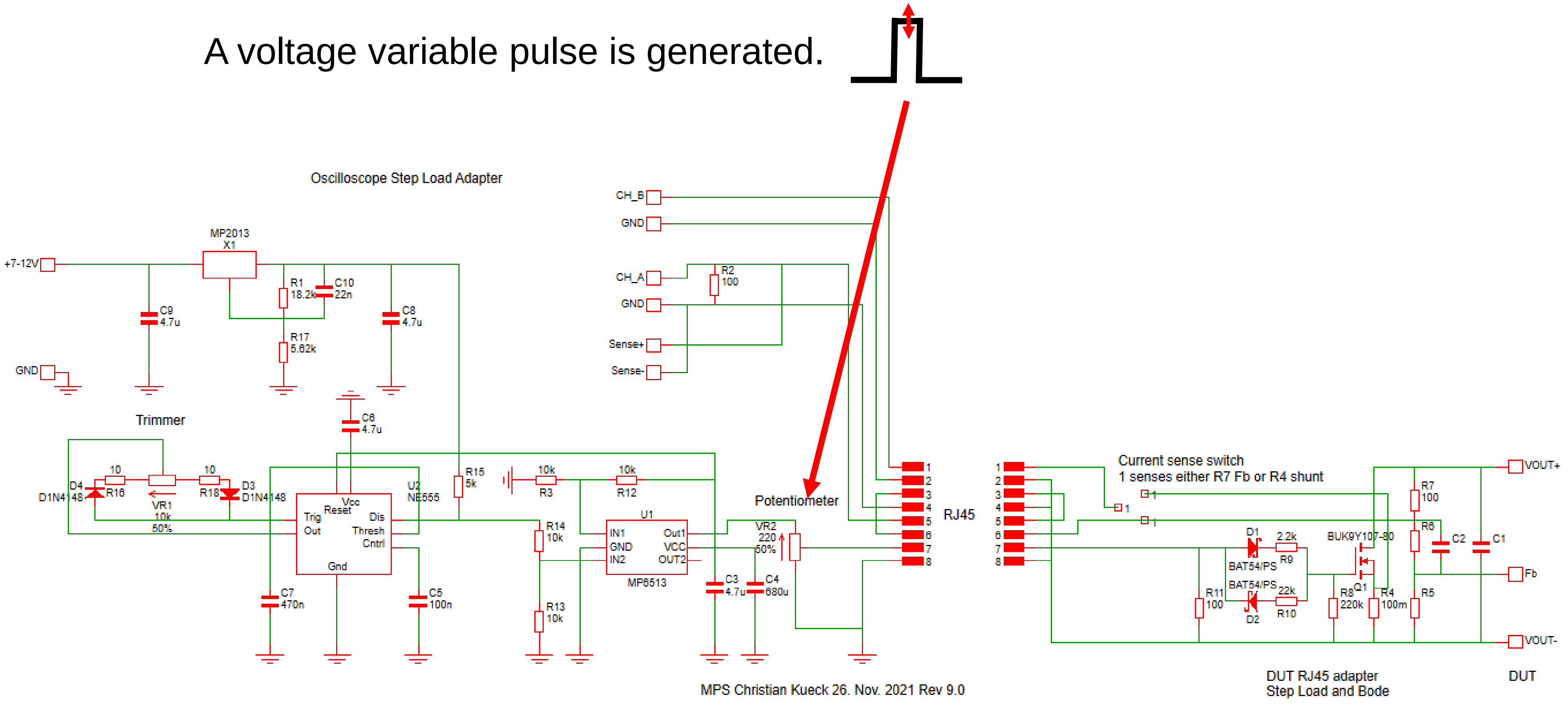
The DC load is always added off the board outside the temp chamber. Only the pulse step load is done inside.



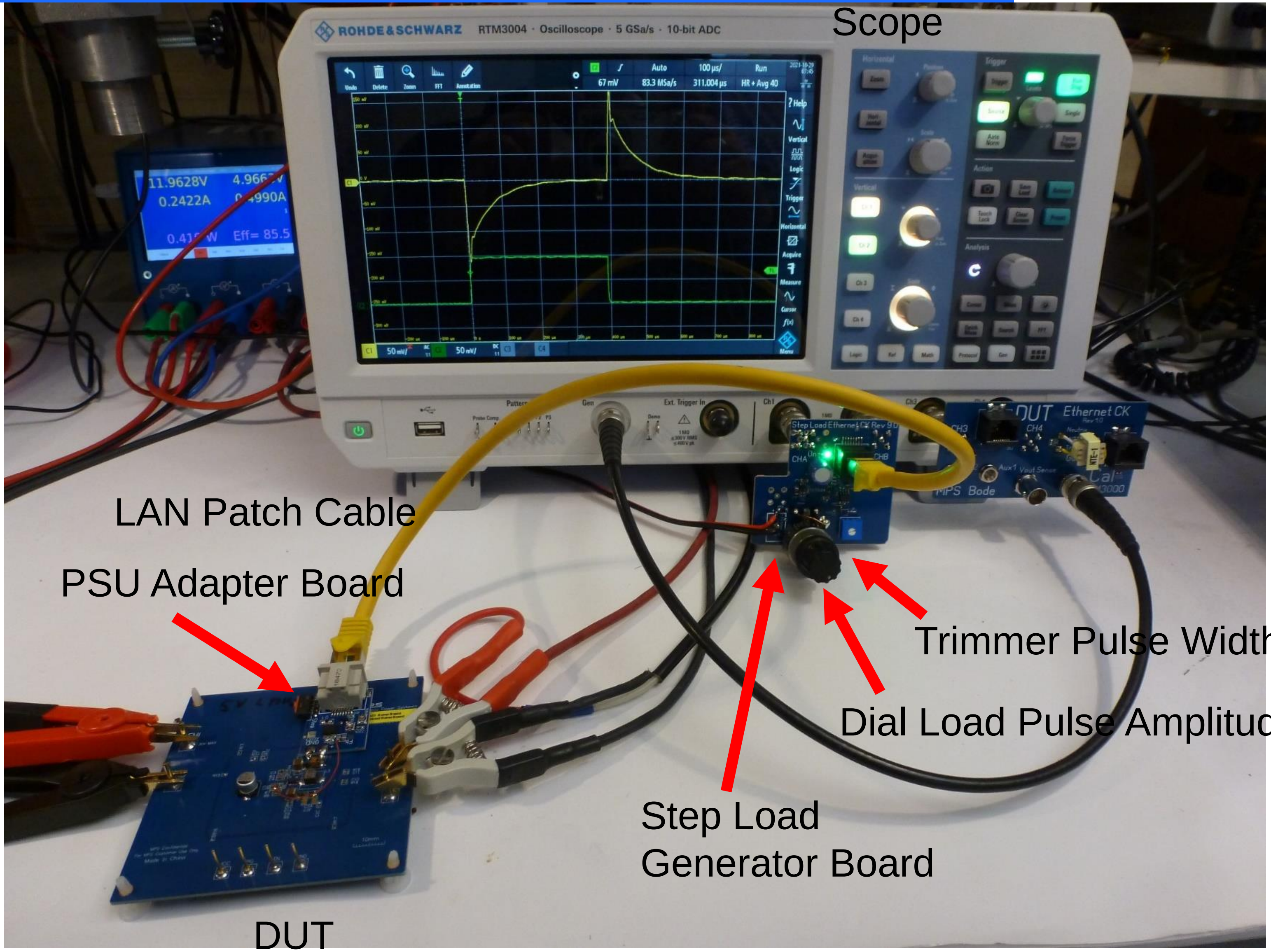


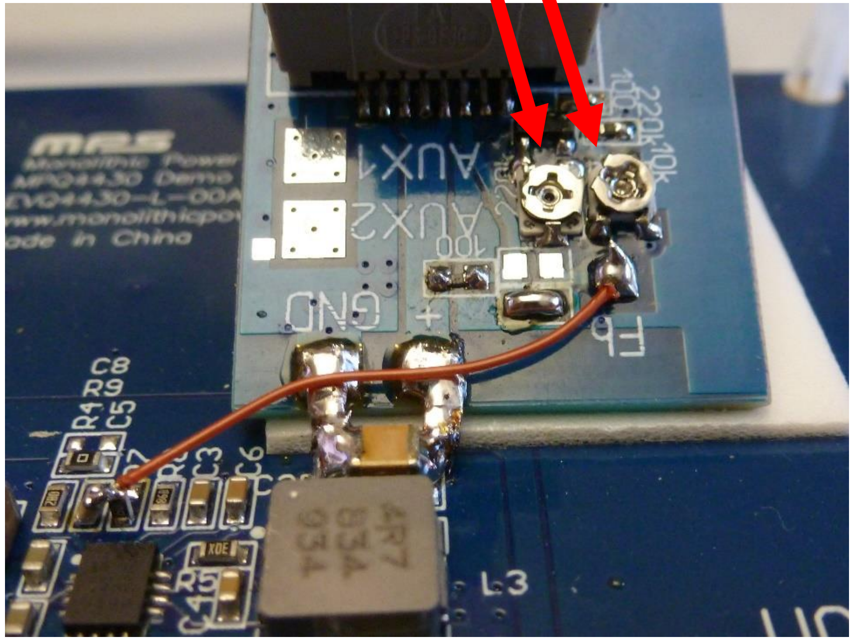
Step Load

A voltage variable pulse is generated.

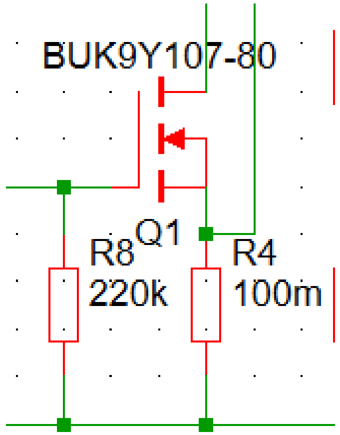


Step Load Set-Up





Step Load MOSFET Selection Is Not Trivial



Important is the SOA (safe operating area). Load MOSFETs see voltage and current = power at the same time. Most MOSFETs are not designed for that. The gate threshold (V_{GS}) has a strong negative temperature coefficient, which makes the MOSFET unstable in a high power dissipation area with analog drive. In addition, the Q_G drive capability is limited across the 100Ω cable system. Beware higher V_{OUT} (>5V) value with larger currents and load on times/duty cycles. Check the SOA graph carefully before making a load MOSFET selection.

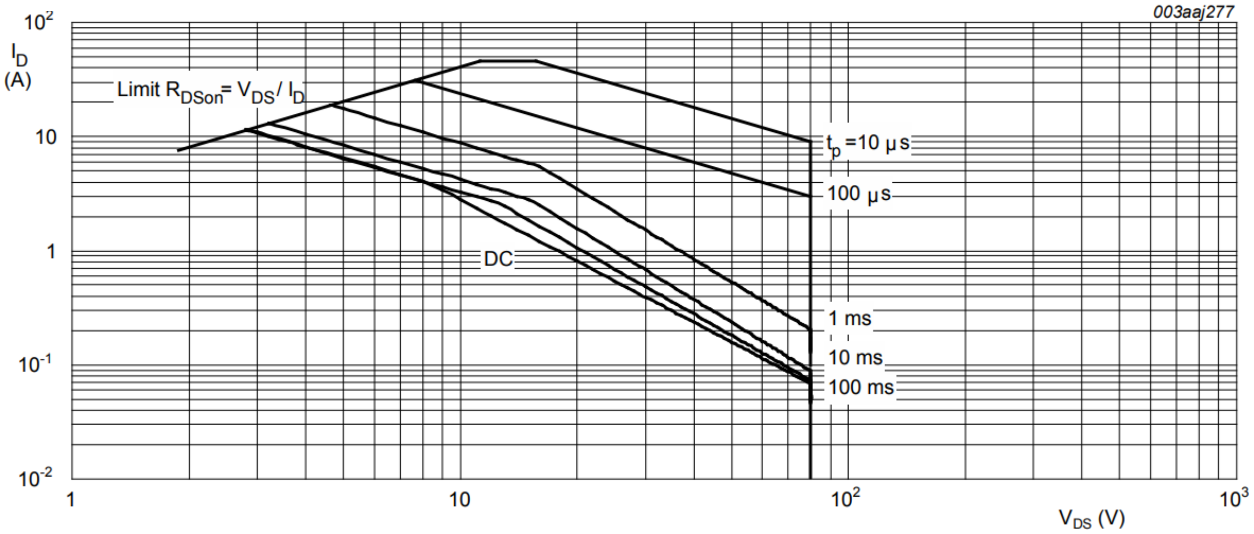


Fig. 4. Safe operating area; continuous and peak drain currents as a function of drain-source voltage

$T_{mb} = 25°C$; I_{DM} is a single pulse

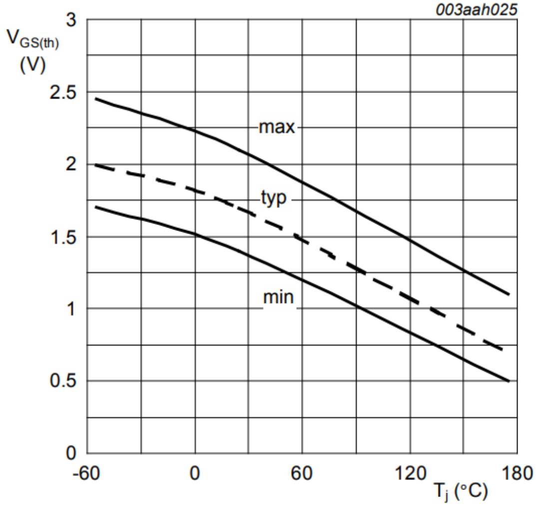


Fig. 9. Gate-source threshold voltage as a function of junction temperature

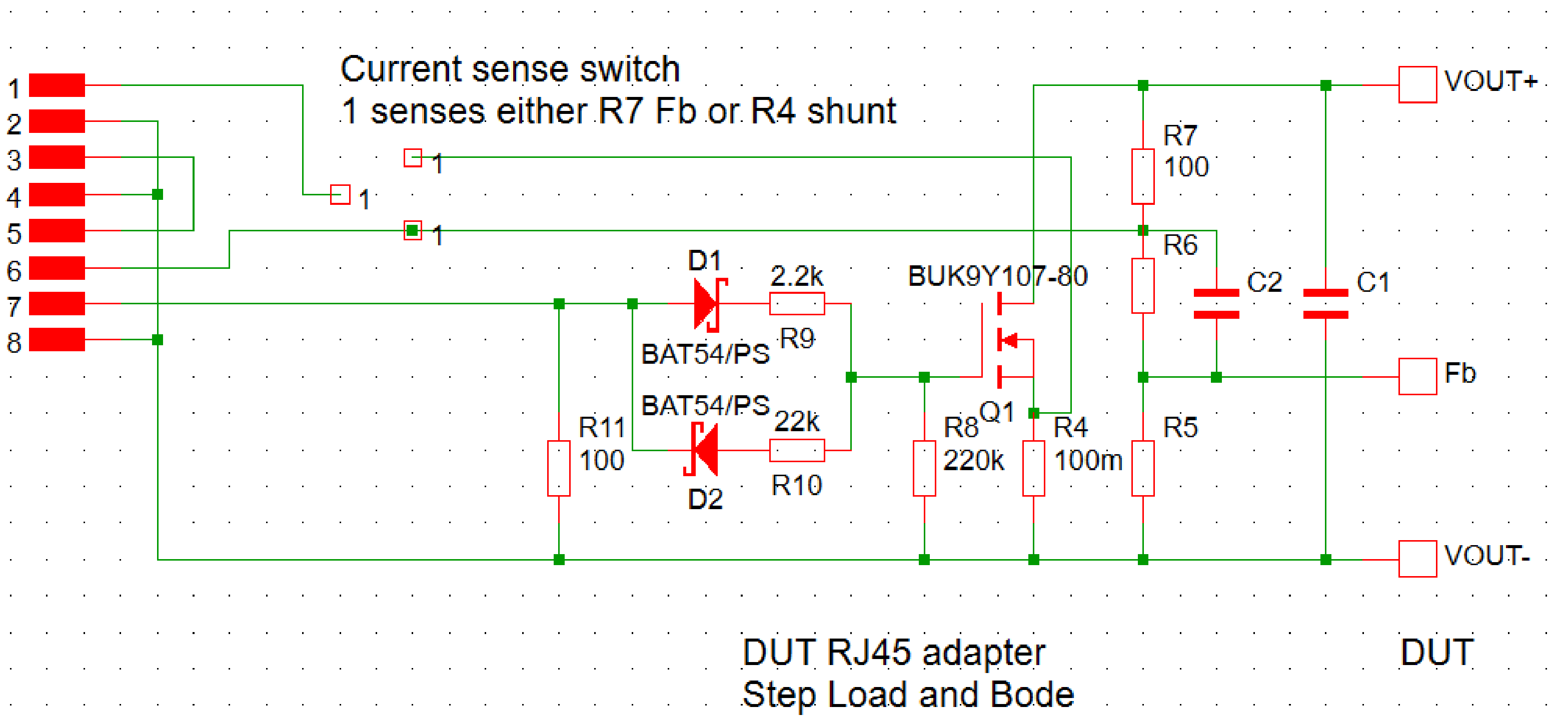
$I_D = 1$ mA; $V_{DS} = V_{GS}$

N-channel 80 V, 107 mΩ logic level MOSFET in LFPAK56

2.5	-	nC

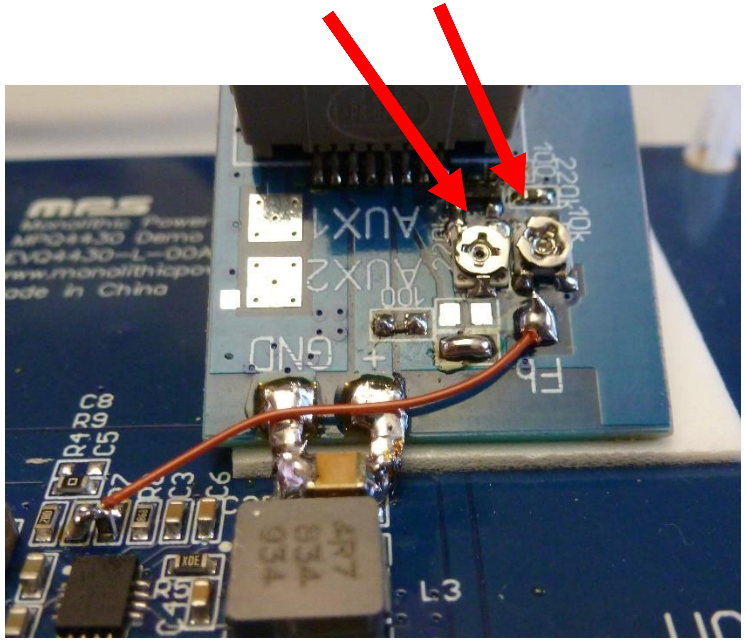
Combined Bode and Step Load Adapter with Switch

The Bode and step load adapters are on the same PCB, and share the GND and V_{OUT} connections on the DUT output capacitor. The step load switch is directly attached to the PSU C_{OUT}, so round-trip loop inductance is low and does not interfere with Bode measurements.



Trimmer R9 R10

Falling and Rising Edge Slope

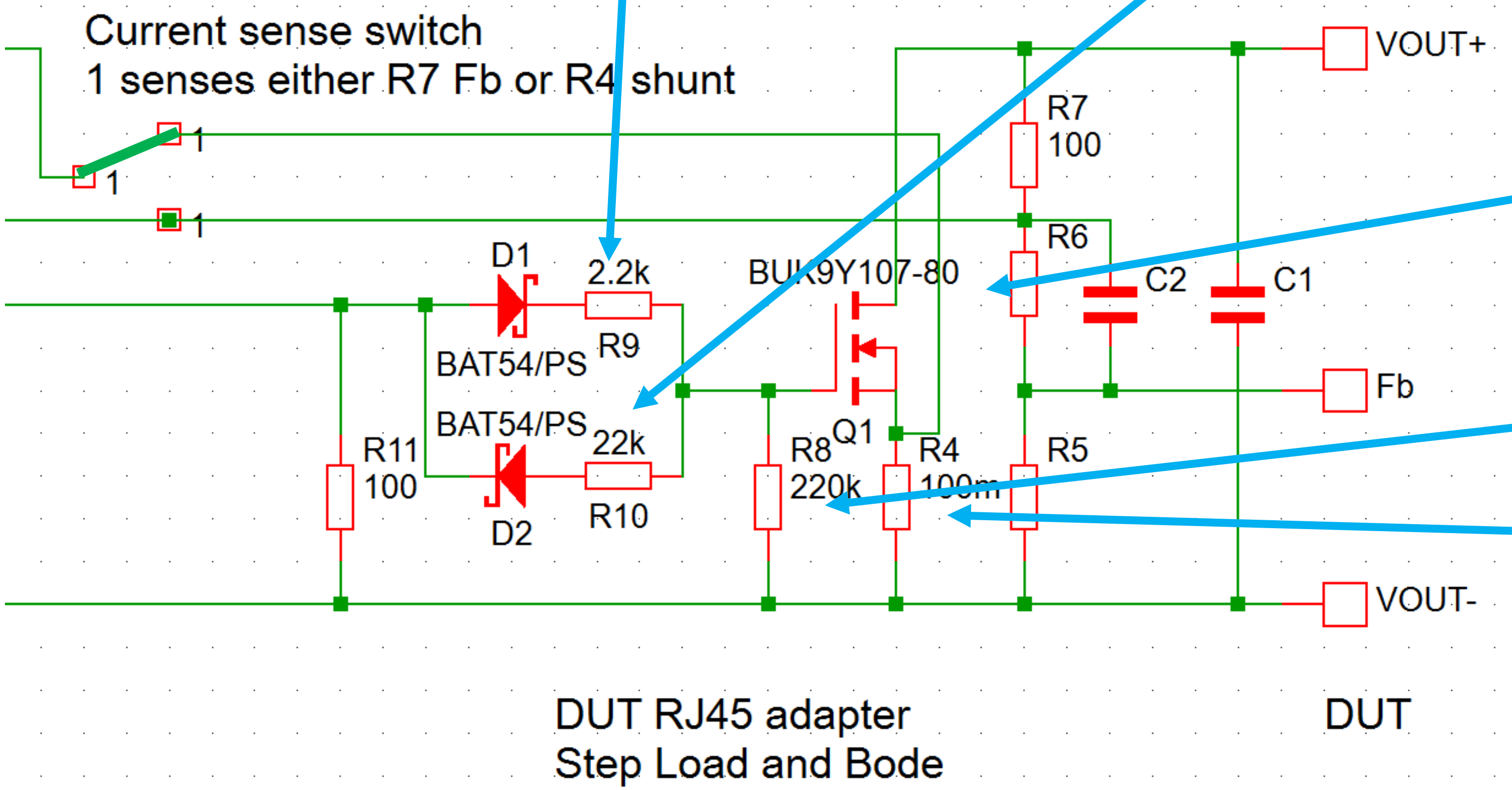


Step Load Adapter Details

R9 selects the rising edge. A 10kΩ trimmer can be used for R9 if adjustment is desired.

R10 selects the falling edge. A 220kΩ trimmer can be used for R10 if adjustment is desired.

D1 D2 is a single SOT23 BAT54S

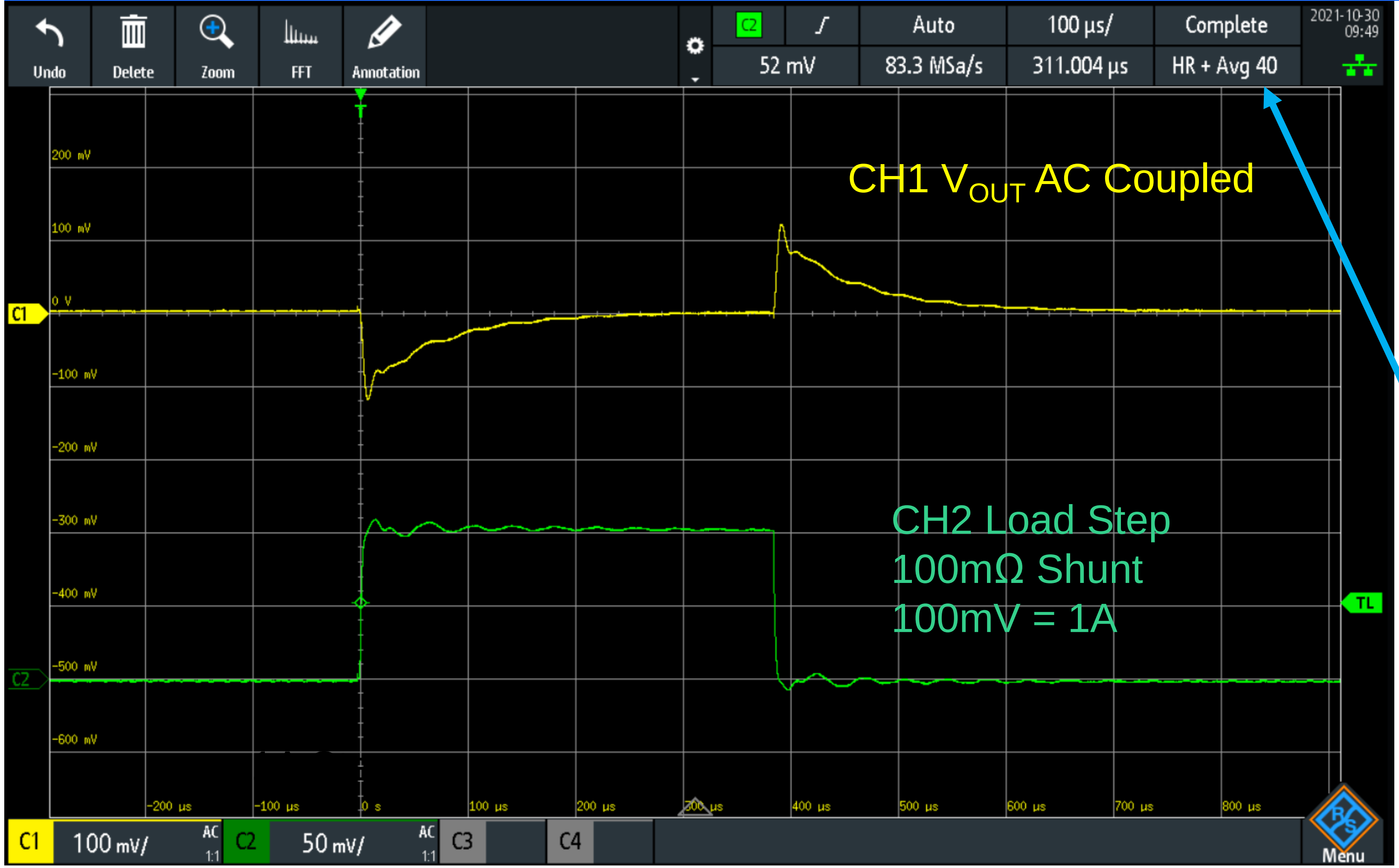


Select MOSFET M1 for the SOA and not too high of a Q_G (6.2nC in this example).

R8 prevents current from creeping up during the on time due to D3 leakage.

R4 sets the current measurement sensitivity (100mV = 1A in this example).

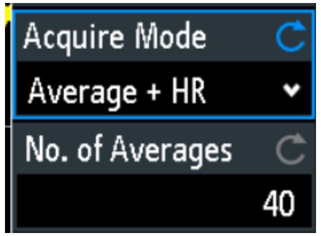
1A Load Step Measured over 2m UTP Patch Cable at -40°C



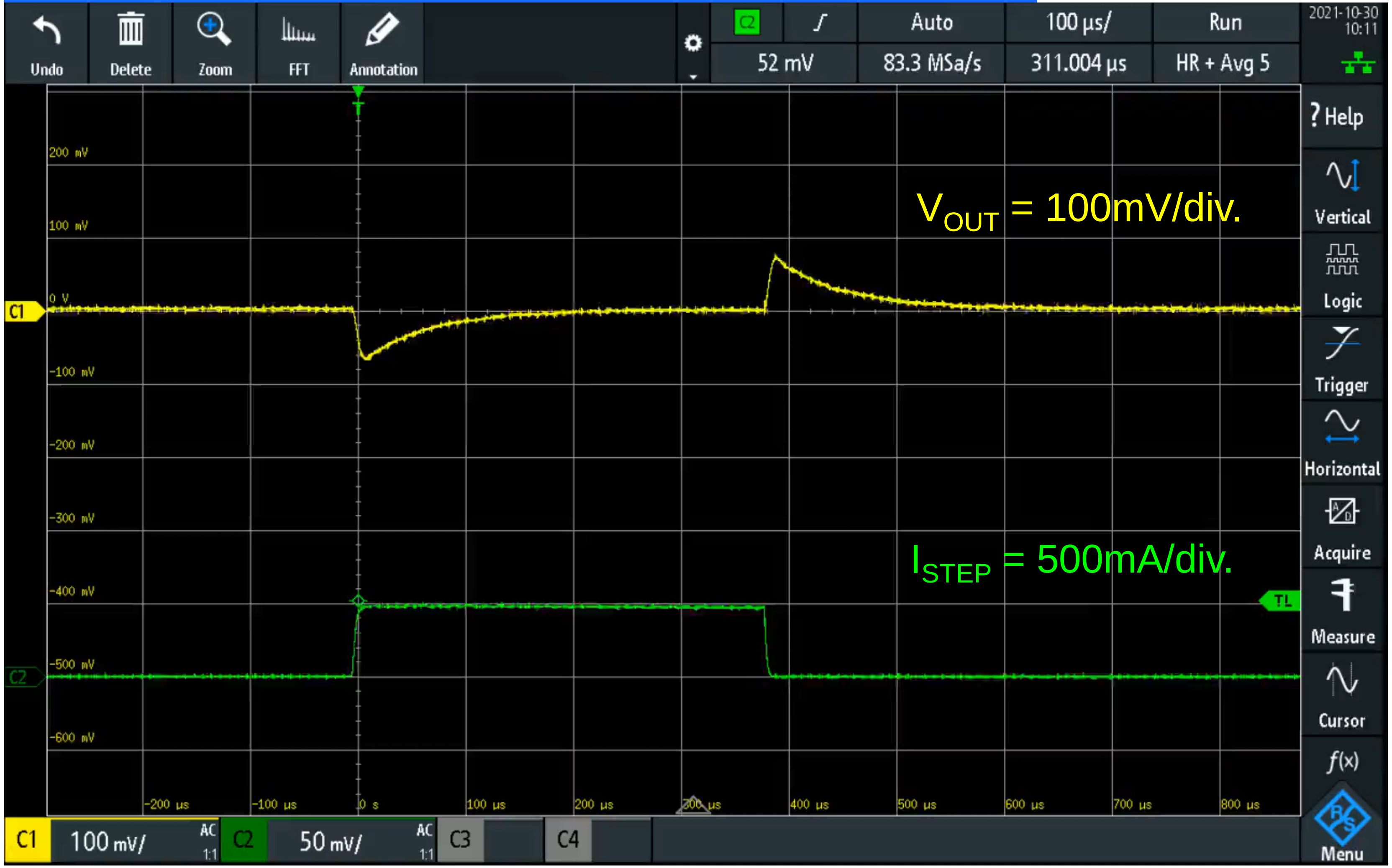
Asymptotic behavior is seen as expected with a 51° phase margin.

The measurement is noisy, and can be filtered with averaging.

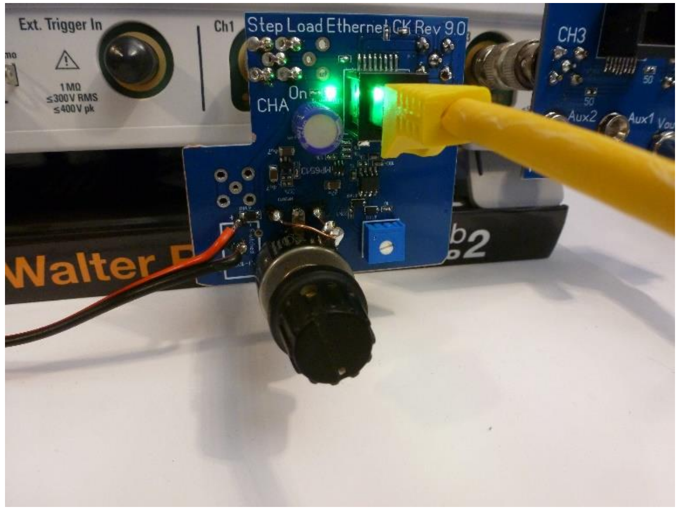
Use a decent number of averages



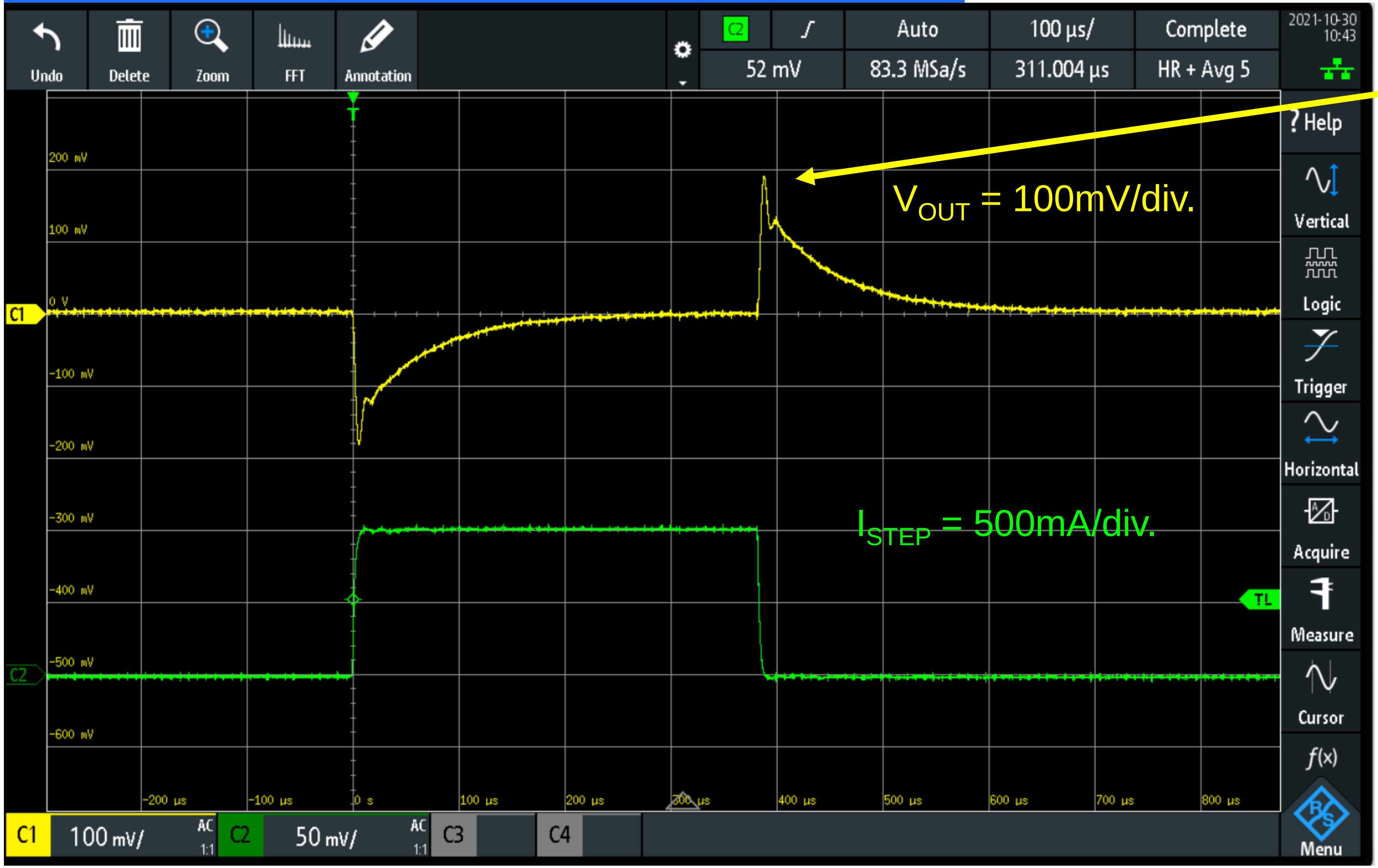
Video Load Step MPQ4323



The V_{OUT} step load response is proportional to the step magnitude.

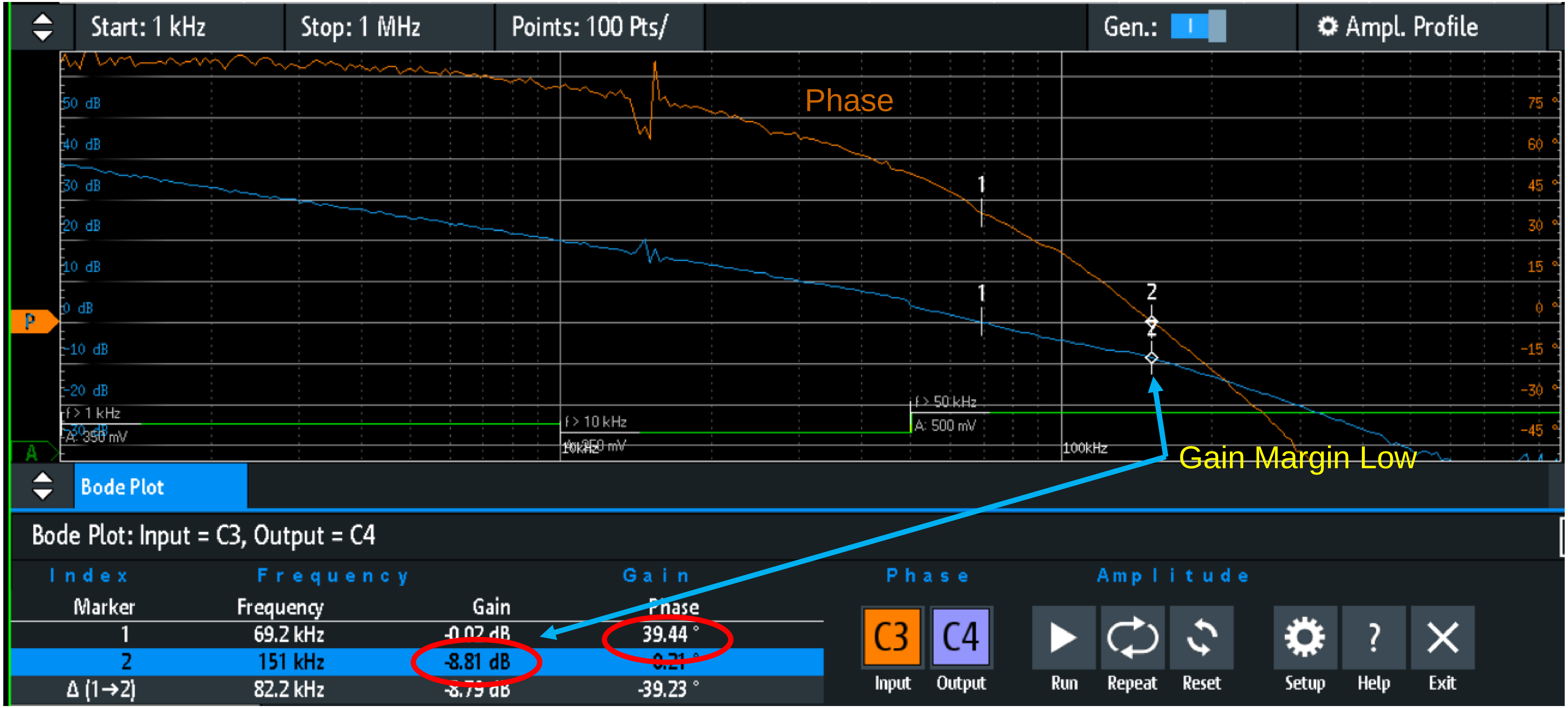


MPQ4323 with 22µF C_{OUT}



The Bode plot on the next slide shows a 39° phase margin. The step response starts to show some ringing.

MPQ4323 with 22µF C_{OUT}



Conclusion

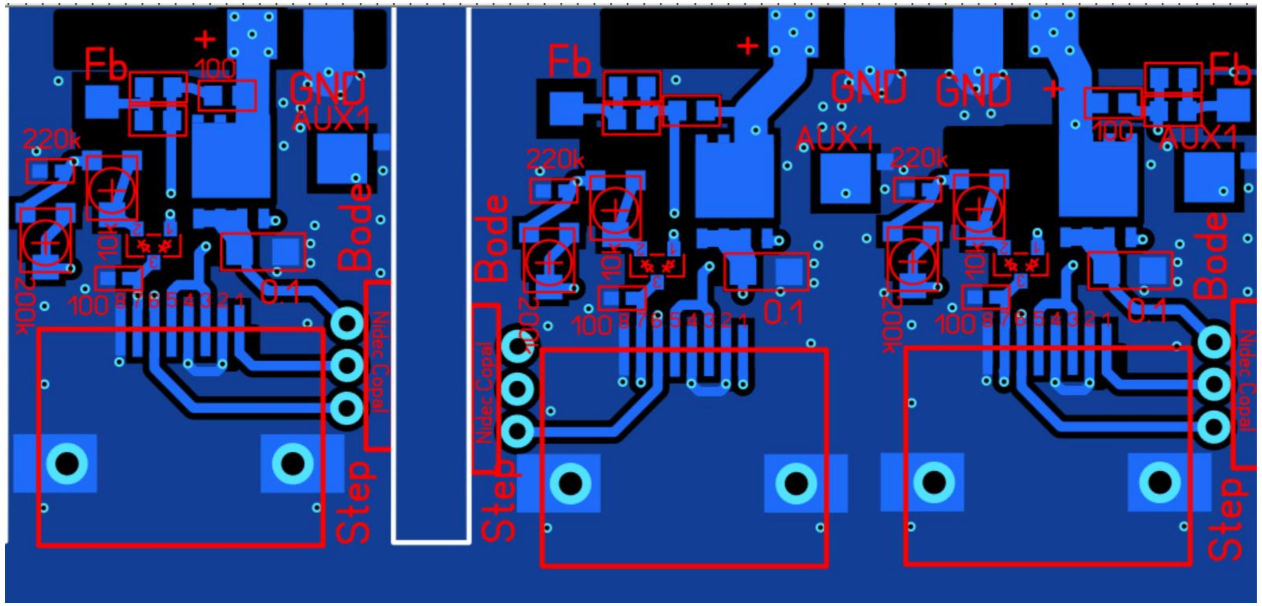
- An Ethernet Patch Cable Is a Versatile Connection for Bode and Step Load Measurements
- The PSU Adapter Is Small and Connects to the DUT C_{OUT} with Low Parasitic Inductance
- The Load MOSFET on the DUT Adapter Enables Low Parasitic Artifacts for Fast Step Load Tests
- Bode Measurements Are Lower Noise than those with Conventional Scope Probe Hookups
- Bode Measurements Can Run Faster with a Lower Number of Points
- Simple Single-Point Connections Can Be Used for Easy Hookups in Temperature Chambers
- Quick Change between Bode and Step Load: Only One Switch and One RJ45 Change
- Patch Cables Up to 3m Can Be Used

Addendum Simple DUT Single + Dual Adapter PCB 2-Layer 60x35mm

Top Bode

Single Adapter

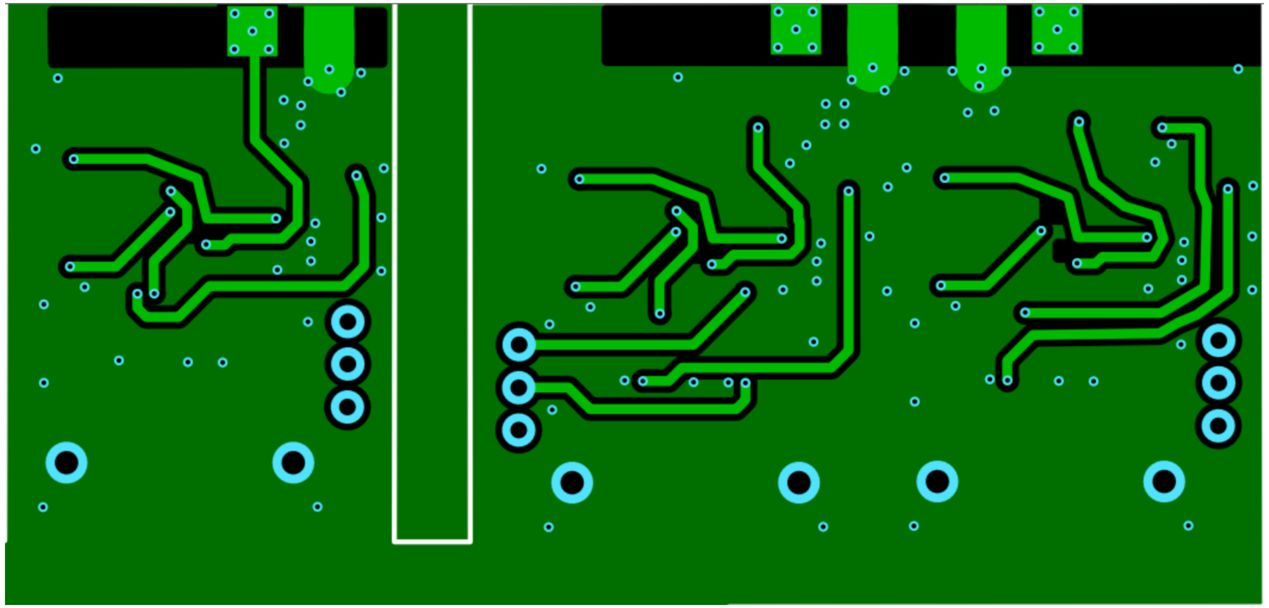
Dual Adapter



Bottom Step Load

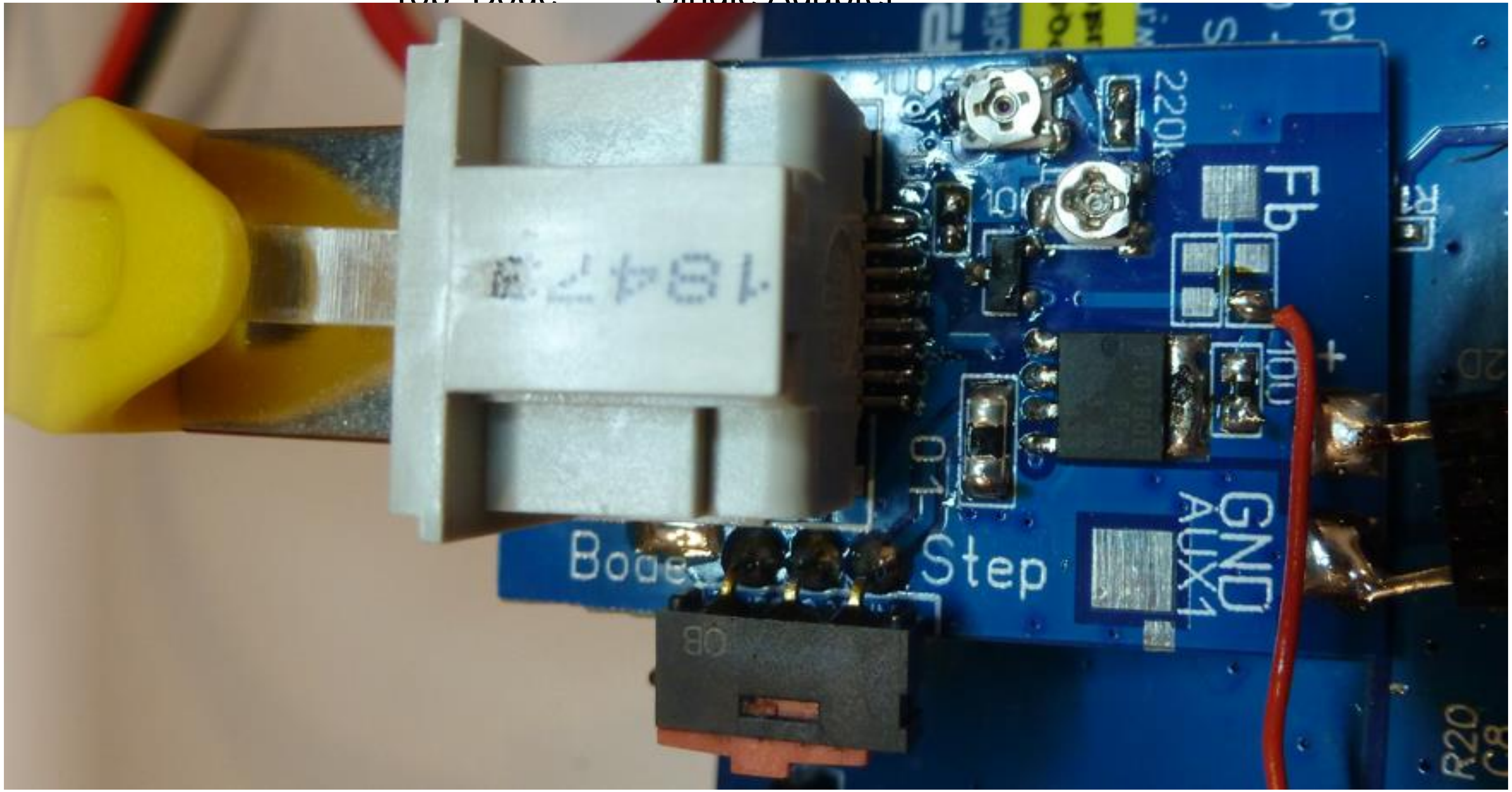
Single Adapter

Dual Adapter

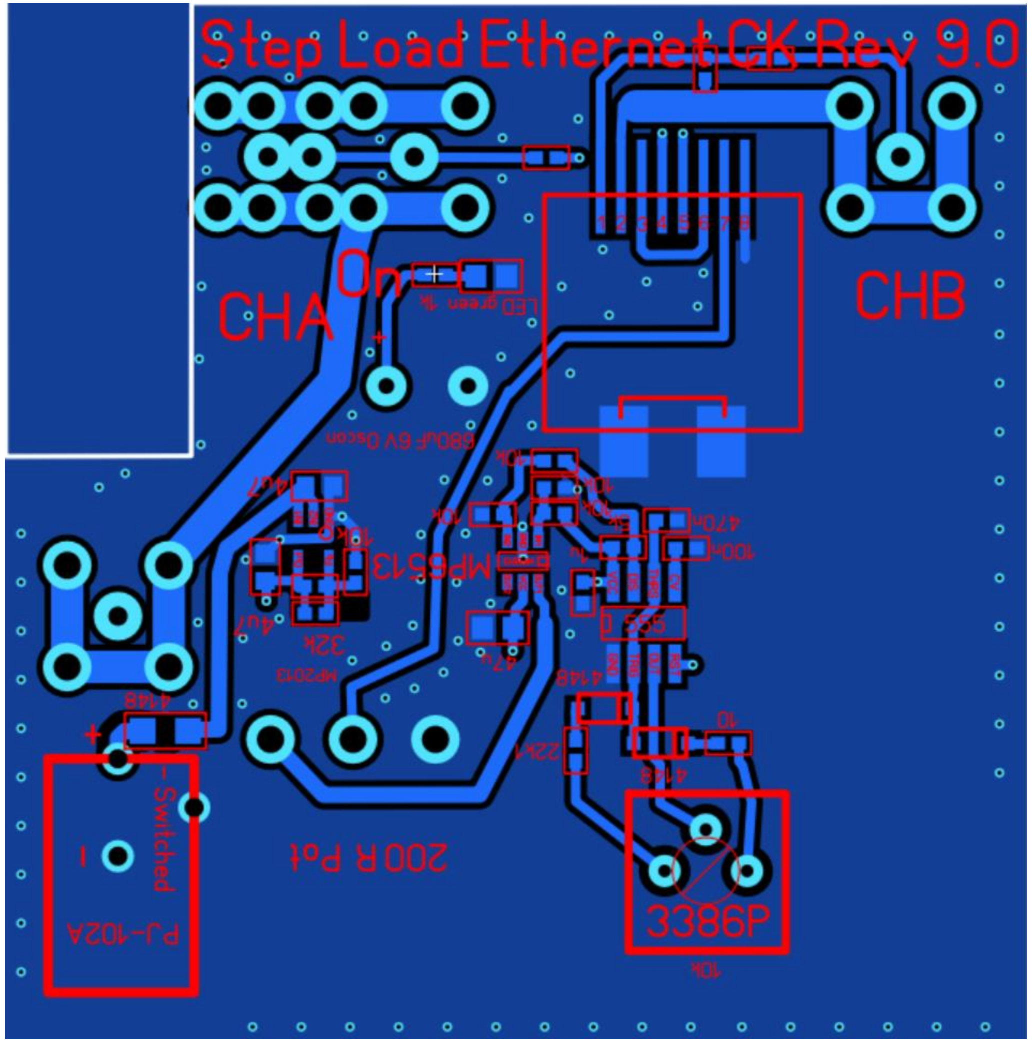


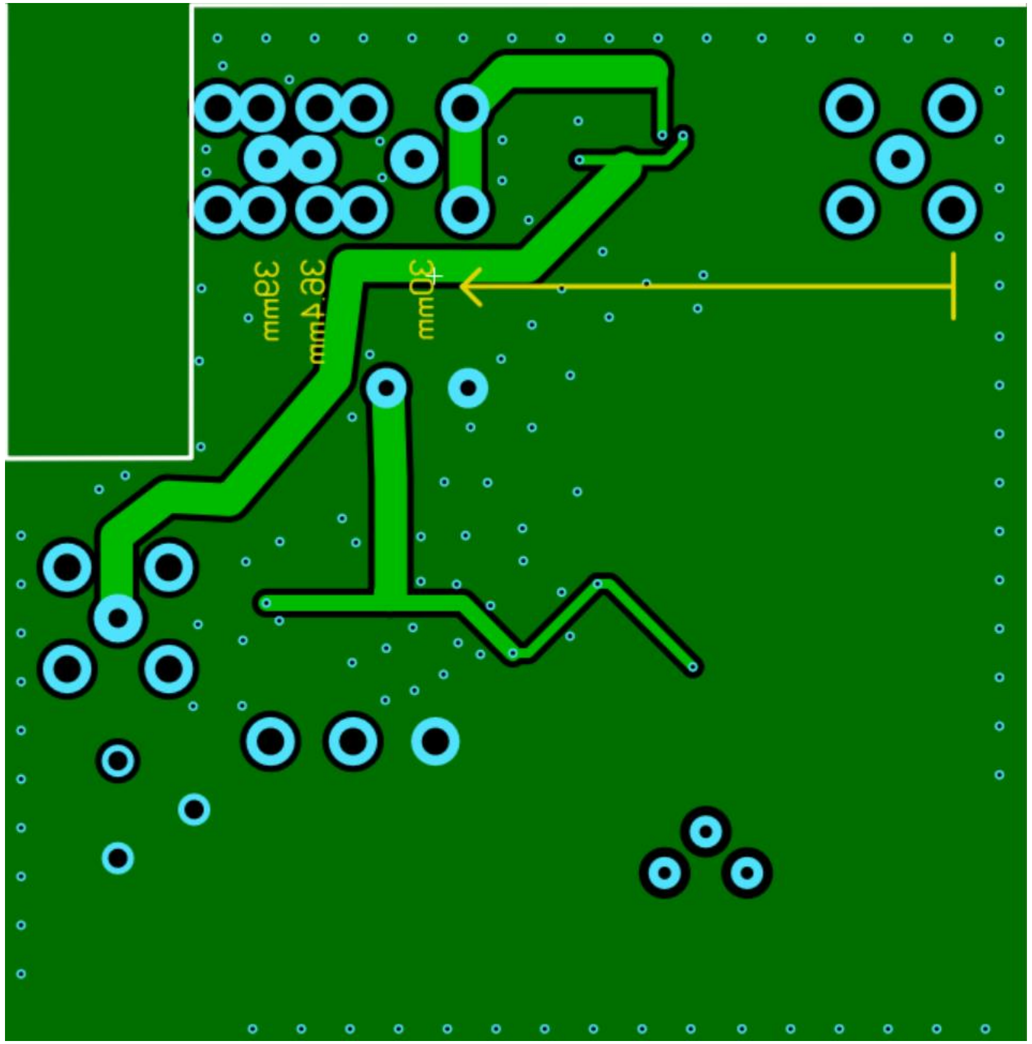
Addendum DUT Single PCB 2-Layer 35x27mm

Top Bode Single Adapter

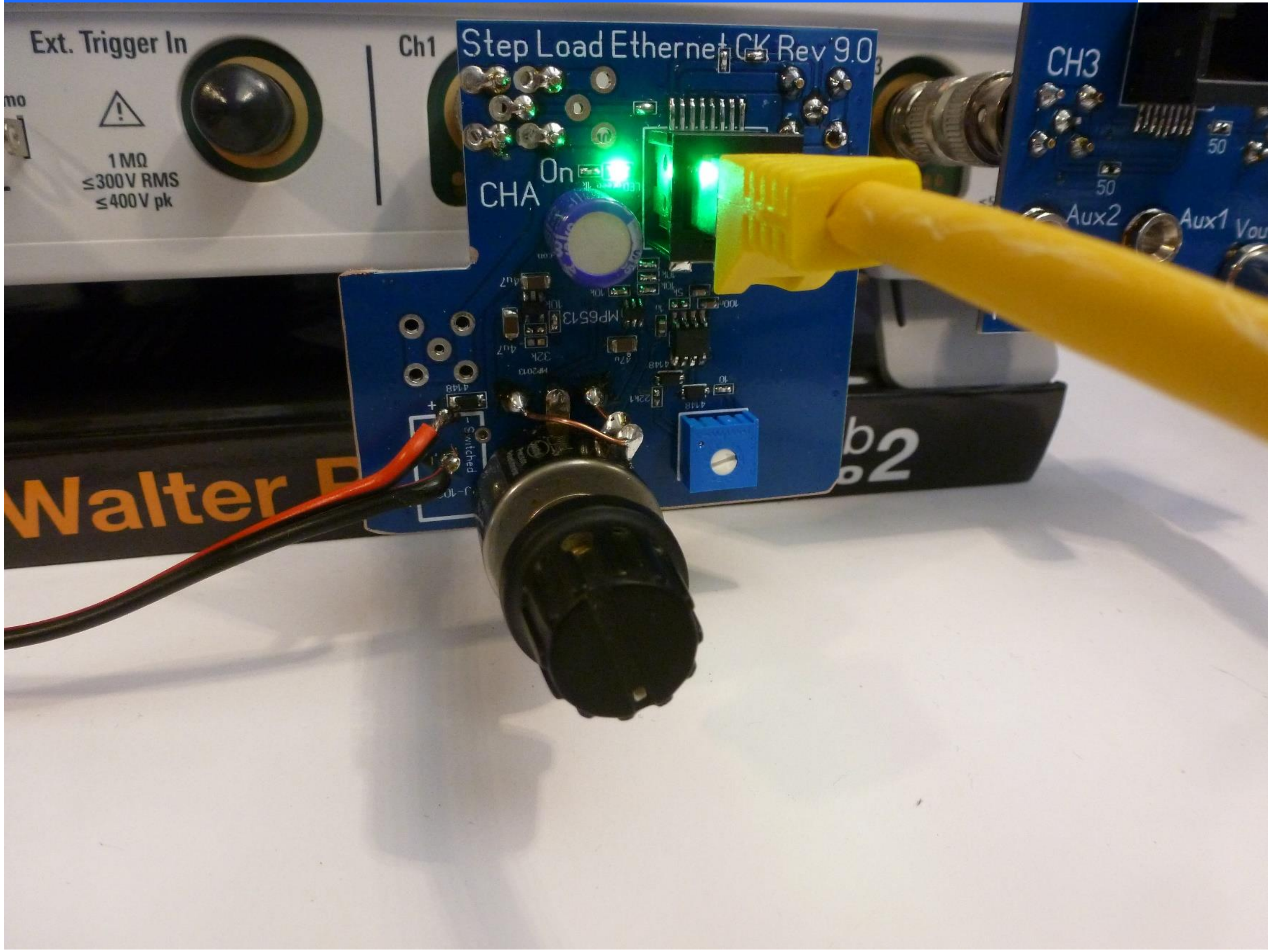


Addendum Step Load Adapter Scope 2-Layer 44x63mm

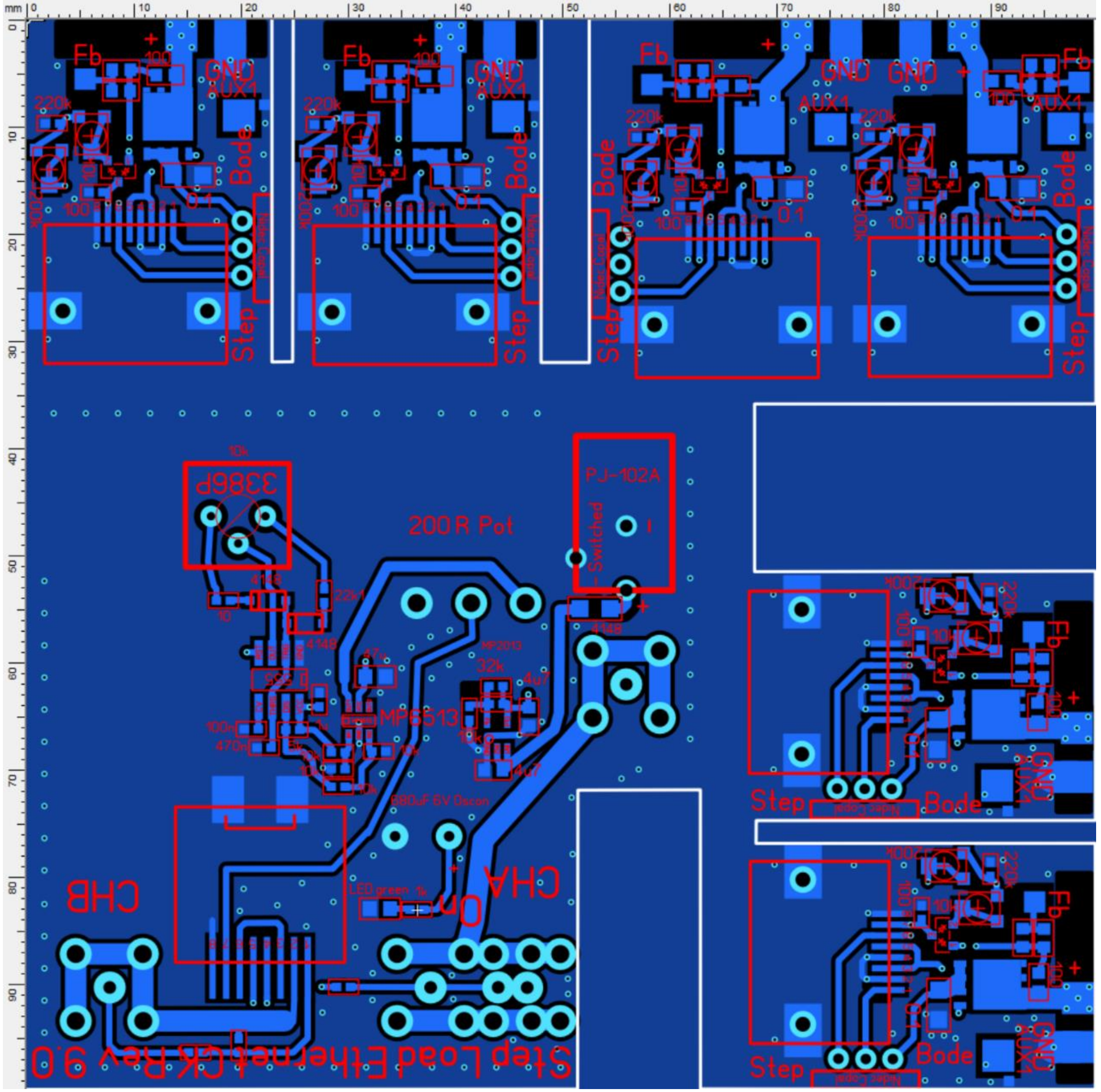


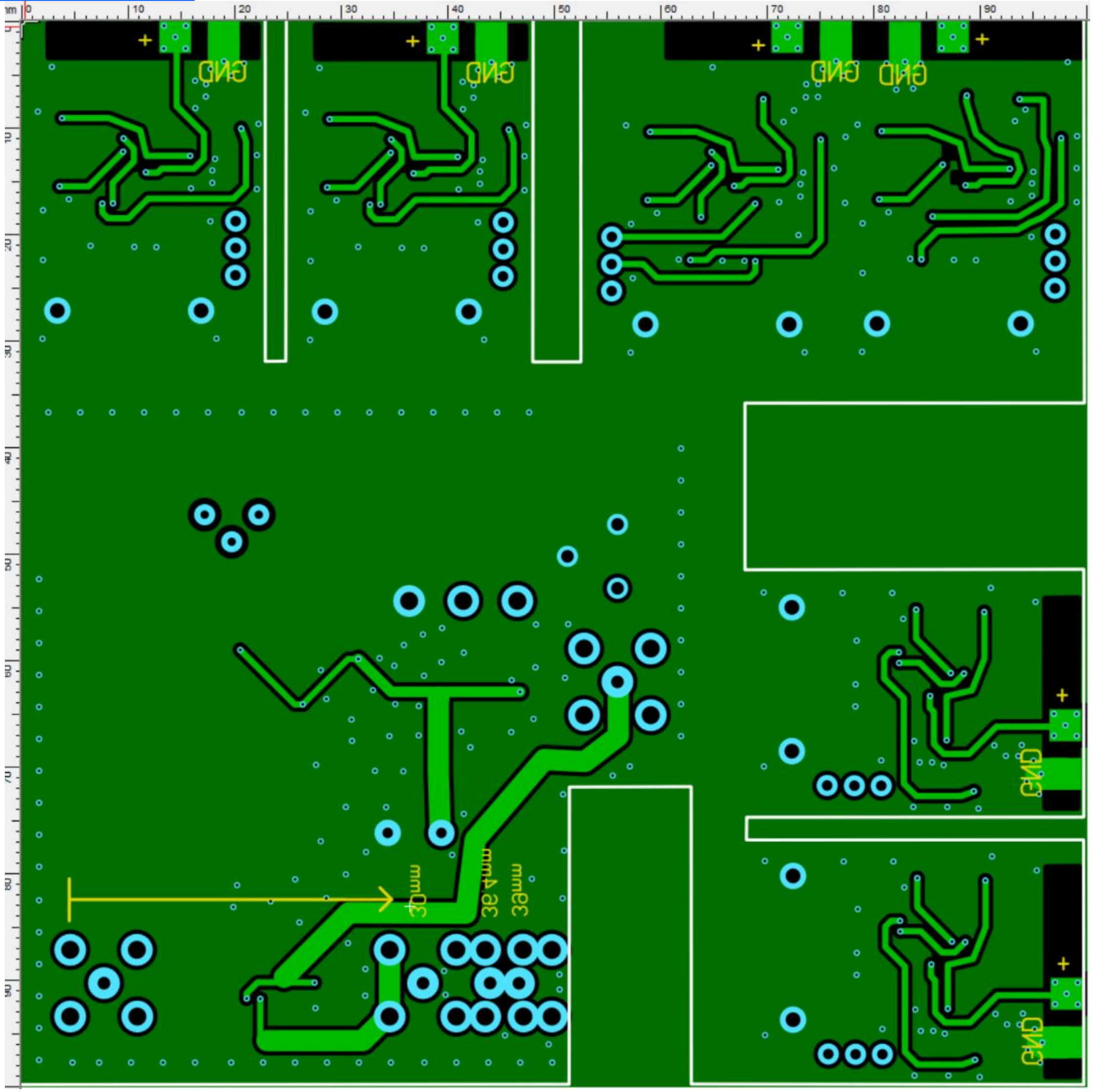


Addendum Step Load Adapter Scope

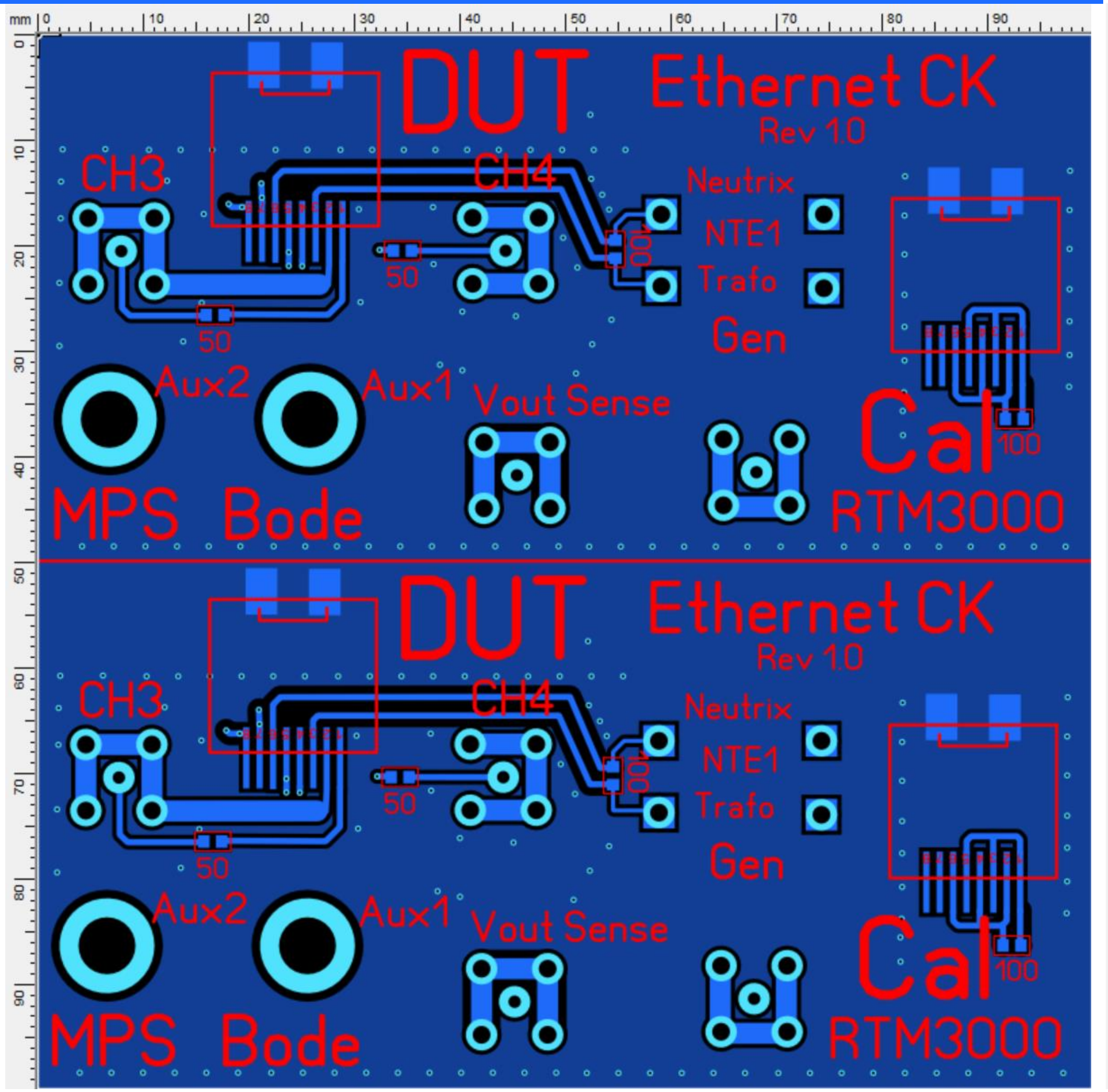


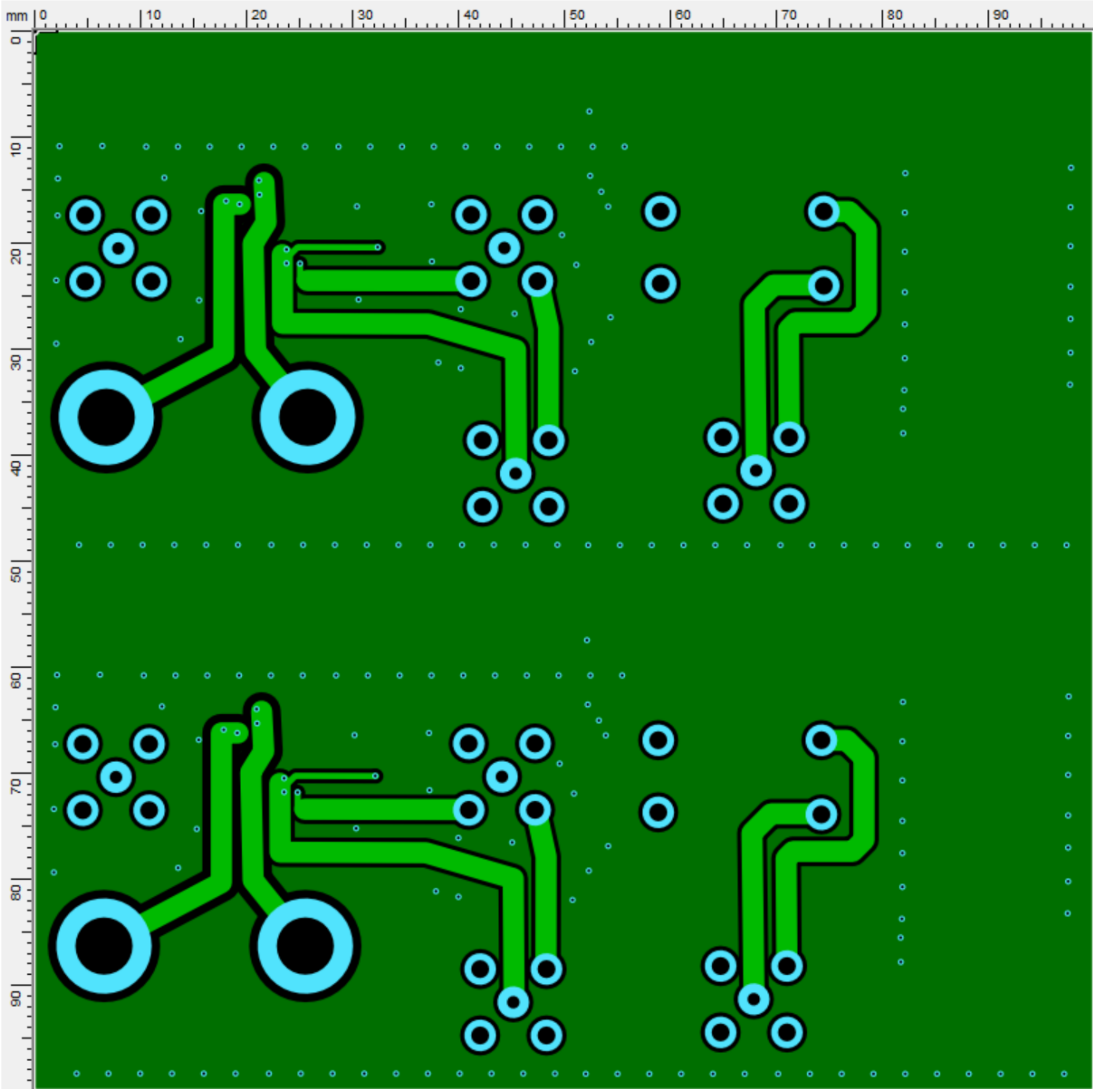
Addendum Real Multi-PCB 100x100mm



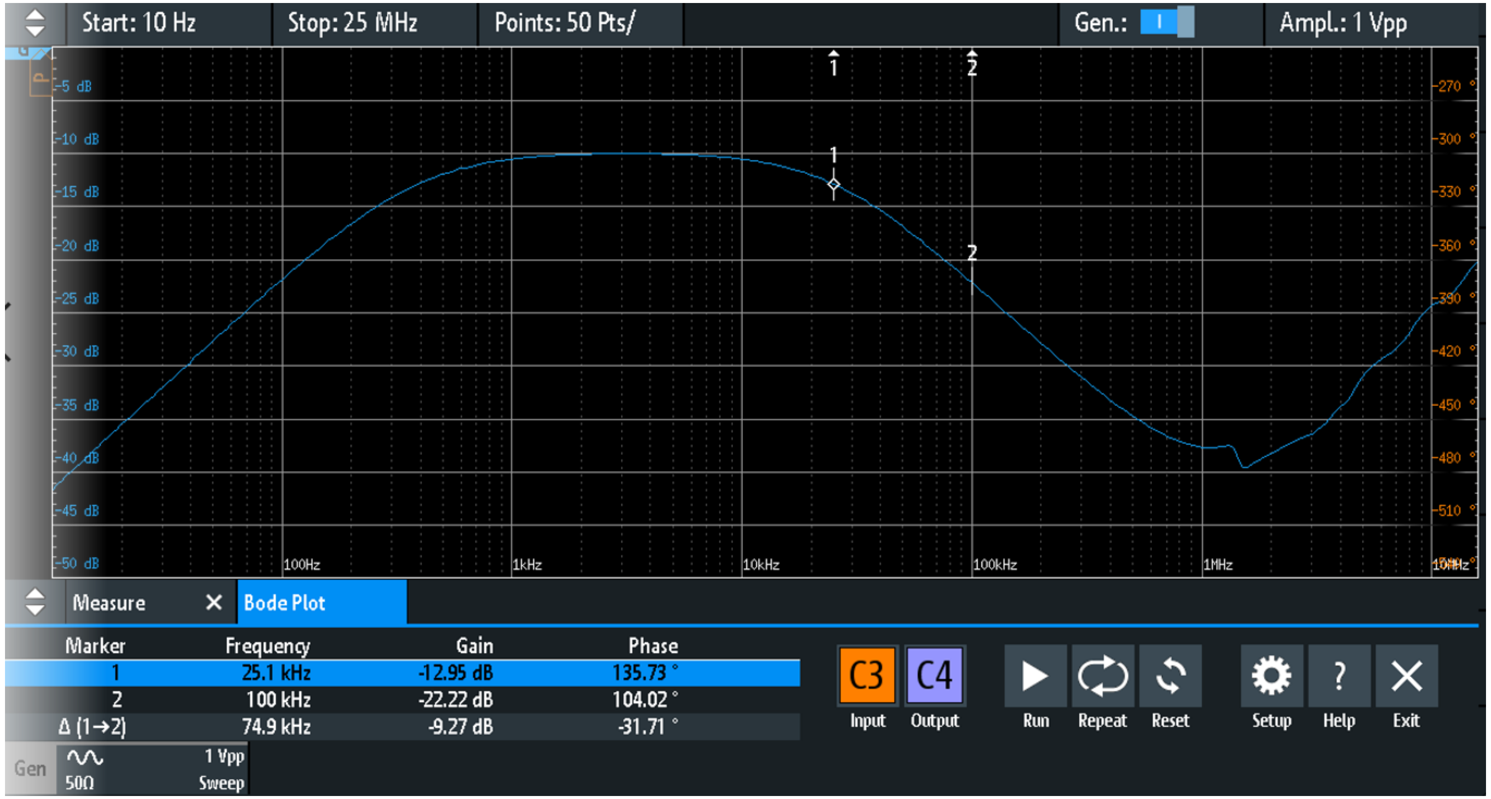


RTM3000 Series Bode Adapter





NTE1 Transformer Damping with 50Ω Load



Given that the used 2 x 100Ω parallel = 50Ω load the transformer shows flat (-3dB) response from 1kHz to 25kHz, and has about a third-order low-pass damping, down to 1MHz. This frequency-dependent damping comes in handy and, in most PSU cases, only requires minor additional corrections with the shape-level feature.

The general frequency and phase response of the transformer does not affect the measured phase plot, other than the frequency dependent amplitude. Its only purpose is to isolate the generator voltage from the V(X) = CH1 and V(Y) = CH2 measurement nodes.

Some Special BOM Articles

Christians Bode Step Load Adapter

o.k.	QTY.	Ref.	Description	Package	Manufacturer	Manuf._PN	Source	Order #	Price ea. €	Price Total.	Website
	2	NA	Vertical RJ45	RJ45	Amphenol	98435-311LF	Digikey	609-6038-1-ND	0.99	1.98	98435-311LF Amphenol ICC (FCI) | Steckverbinder, Verbindungen | DigiKey
	2	NA	Horizontal RJ45	RJ45	TE	5406721-1	Digikey	A121540CT-ND	1.13	2.26	5406721-1 TE Connectivity AMP Connectors | Steckverbinder, Verbindungen | DigiKey
	2	P1,P1	4mm jacket solder	THC	Keystone		Digikey	36-575-8-ND	0.682	1.364	https://www.digikey.de/product-detail/de/keystone-electronics/575-8/36-575-8-ND/318495
	1	U	MP6513GJ-Z	SOT-23	MPS	MP6513GJ-Z	Digikey / MPS	1589-1709-1-ND	0.81	0.81	MP6513GJ-Z Monolithic Power Systems Inc. | Integrierte Schaltungen (ICs) | DigiKey
	1	BNC Connector	BNC PCB Female	BNC	TE	5-1634503-1	Digikey	A97581-ND	1.92	1.92	5-1634503-1 TE Connectivity AMP Connectors | Steckverbinder, Verbindungen | DigiKey
	1	U	Timer IC 3MHz	SO-8	Ti	LMC555CMX	Digikey	LMC555CMX/NOPBCT-ND	1.04	1.04	https://www.digikey.de/product-detail/de/texas-instruments/LMC555CMX-NOPB/LMC555CMX-NOPBCT-ND/1010550
	1	T	N-MOS	LFPAK56	Nexperia	BUK9Y107-80EX	Digikey	1727-1119-1-ND	0.43	0.43	BUK9Y107-80EX Nexperia USA Inc. | Diskrete Halbleiterprodukte | DigiKey
	1	R	0.1 Ohm 1206 shunt	1206	Stackpole	CSR1206FTR100	Digikey	CSR1206FTR100CT-ND	0.3	0.3	CSR1206FTR100 Stackpole Electronics Inc | Widerstände | DigiKey
	2	R1,R2	100mOhm Shunt	1206	Stackpole	CSR1206FTR100	Digikey	CSR1206FTR100CT-ND	0.103	0.206	https://www.digikey.de/product-detail/de/stackpole-electronics-inc/CSR1206FTR100/CSR1206FTR100CT-ND/3477073
	1	U	MPQ2013AGJE	SOT-23	MPS	MPQ2013AGJE-AEC1C672	MPS			0	
	1	D4	BAT54S	SOT-23	Nexperia	BAT54S,235	Digikey	1727-1868-1-ND	0.047	0.047	https://www.digikey.de/product-detail/de/nexperia-usa-inc/BAT54S-235/1727-1868-1-ND/5015536
	3	D5,D6,D7	1N4148	SOD123	Diodes	1N4148W-13-F	Digikey	1N4148W-13FDICT-ND	0.059	0.177	https://www.digikey.de/products/de?keywords=1N4148W-13FDICT-ND
	1	Optional	Con. BNC Long	THC	Molex	731000133	Digikey	WM5278-ND	2.83	2.83	https://www.digikey.de/product-detail/de/molex/0731000133/WM5278-ND/2713558
	1	R	Trimmer 10k	THC	Bourns	3386P-1-103LF	Digikey	3386P-103LF-ND	0.985	0.985	https://www.digikey.de/product-detail/de/bourns-inc/3386P-1-103LF/3386P-103LF-ND/1088523
	1	Pot 220 Ohm	Potentiometer 220 Ohm	THC	Piher	PC16SH-10IP06221A2020MTA	Conrad	2050000749537	1.69	1.69	Piher PC16SH-10IP06221A2020MTA Dreh-Potentiometer Mono 0.2 W 220 Ω 1 St. kaufen (conrad.de)
	1	Transformer	NTE1	THC	Neutrix	NTE1	Conrad	2050000159879	16.99	16.99	https://www.conrad.de/de/p/neutrik-nte1-audio-uebertrager-impedanz-200-primaerspannung-1-2-v-inhalt-1-st-515940.htm
	1	Trimmer 10k	10k SMD Trimmer	SMD	TT-Electronics	35WR10KLFTR	Digikey	987-1694-1-ND	0.3	0.3	35WR10KLFTR TT Electronics/BI | Potentiometer, Variable Widerstände | DigiKey
	2	BNC-BNC	BNC-BNC Adapter	BNC	Cal Test	CT2766	Digikey	CT2766-ND	2.31	4.62	CT2766 Cal Test Electronics | Steckverbinder, Verbindungen | DigiKey