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Characterizing Passive Components of a DC/DC Buck Converter

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Practical Training using Board *DCDCbuck_Rev12*

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Characterizing Passive Components of a DC/DC Buck Converter

Abstract. The passive component RLC lowpass part of a DC/DC buck converter is characterized for understanding physical backgrounds, modeling and optimal control setting.

1 Introduction

1.1 Objectives

Goal of this practical training is the passive component characterization of a mixed analog/digital system using the example of a DC/DC buck converter with a digital control unit.

1.2 The *DCDCbuck* Daughter Board Hardware

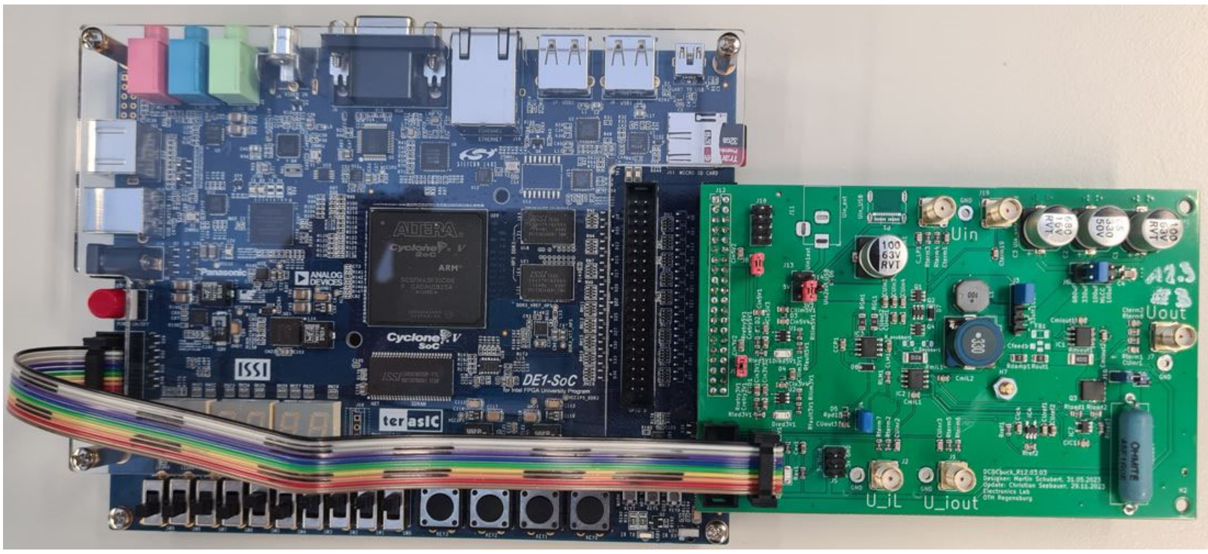


Fig. 1.1: *DE1-SoC* board (left) with plugged-in *DCDCbuck_R12.03* daughter board (right).

Fig. 1.1 shows the *DE1-SoC* board from Terasic [1-8] with *DCDCbuck_Rev10.02.06* daughter board fabricated by Florian Schwankner [10] in the Electronics Laboratory. The ribbon cable connects the input of the *DE1-SoC* on-board's *LTC2308* ADC [15] with output pins of the *DCDCbuck* boar

(a) Board photo,
jumpers:
red: power,
blu: settings,
grn: optional

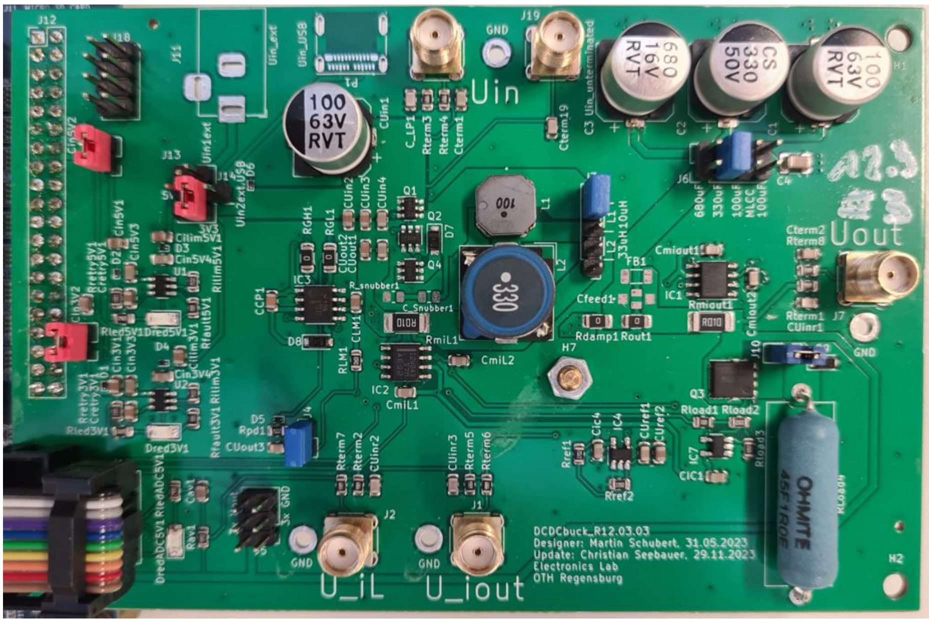


Fig. 1.2: daughter board *DCDCbuck Rev12.03.03*

Bord numbering scheme: *Rxx.yy.zz*, with
xx: Design/Designer, *yy*: No. of fabricated board, *zz*: No. of schematics update of design yy.

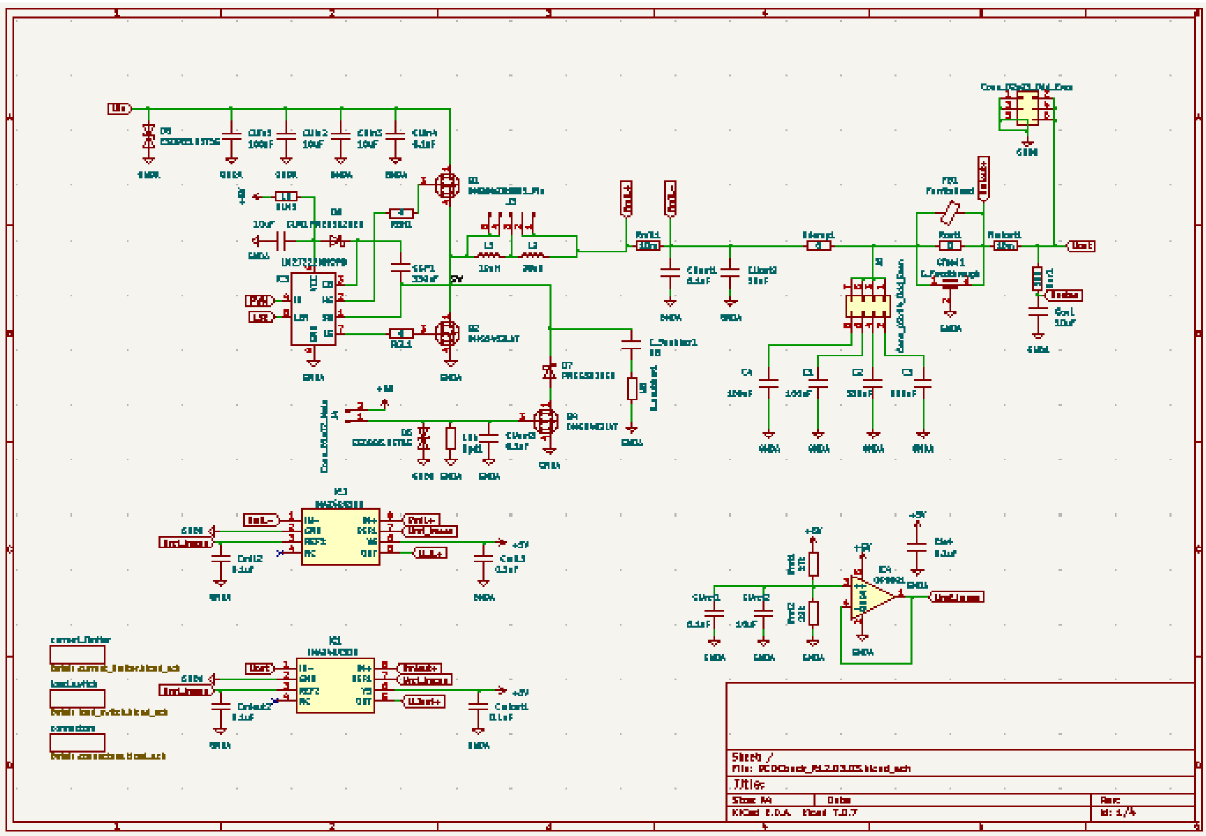
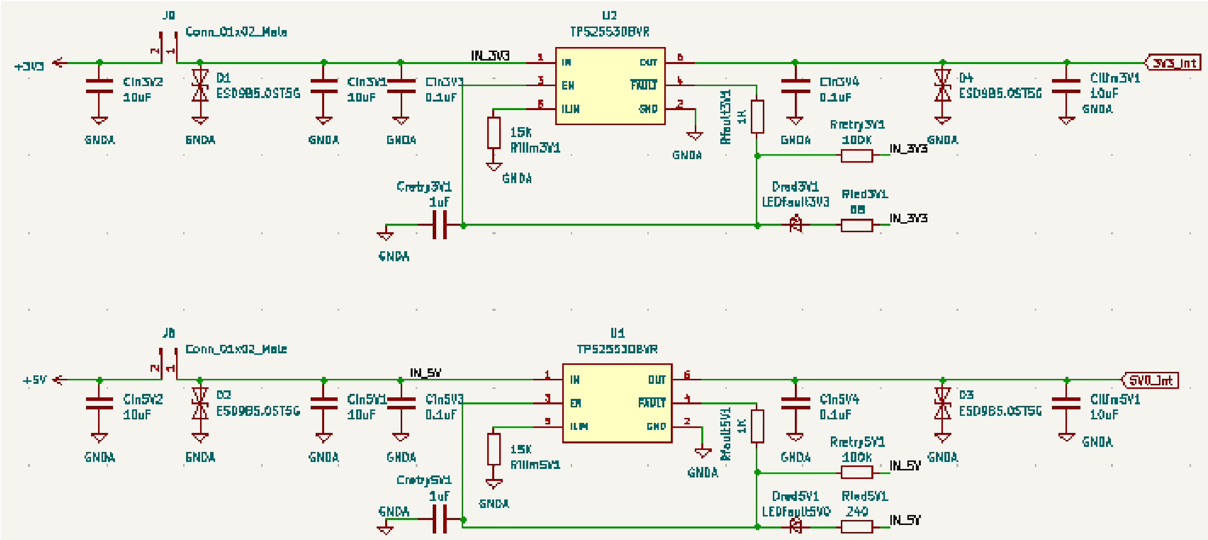
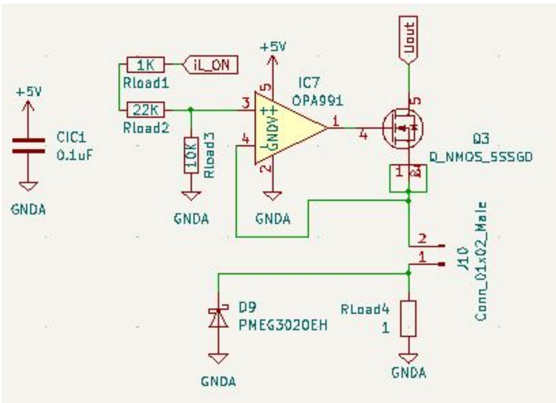


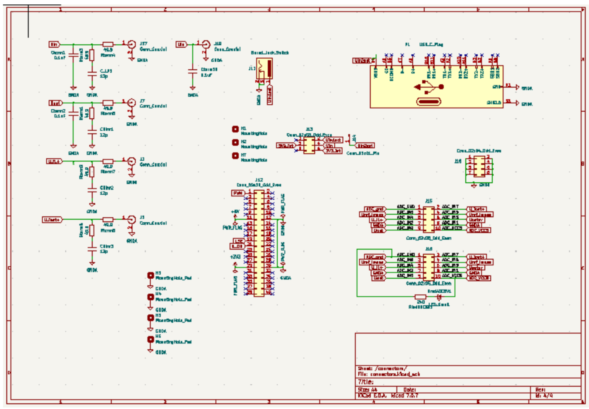
Fig. 1.3(a): *DCDCbuck_R12.03* board top level schematics (in *KiCad* software [19])



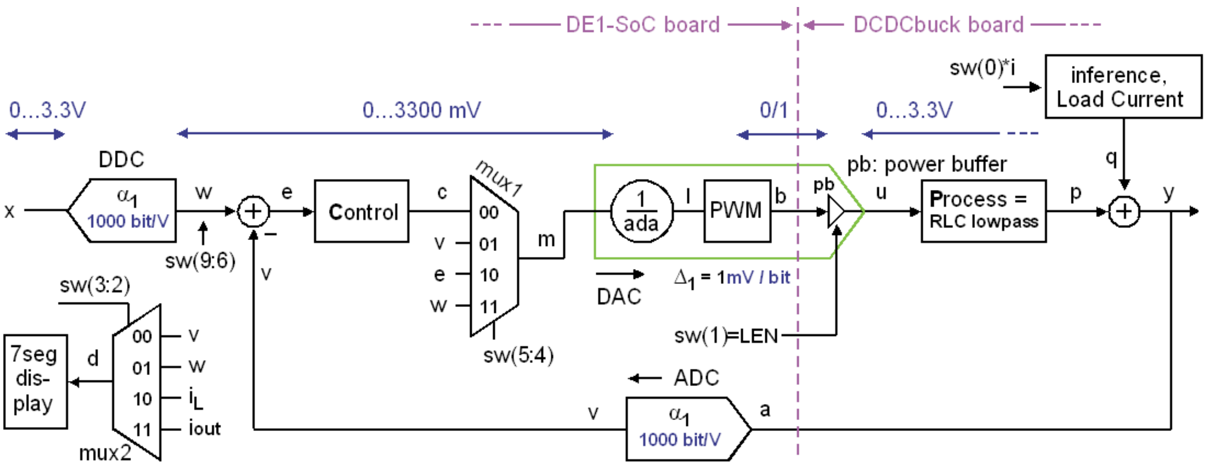
(b): *DCDCbuck_R12.03* board, subcircuit power supplies



(c) Subcircuit 1A Load Current



(d) Subcircuit Connectors



(e) Principal schematics of the DCDCbuck_R12.03 daughter board

Fig. 1.3: *DCDCbuck_R12.03* board, main circuit and subcircuits

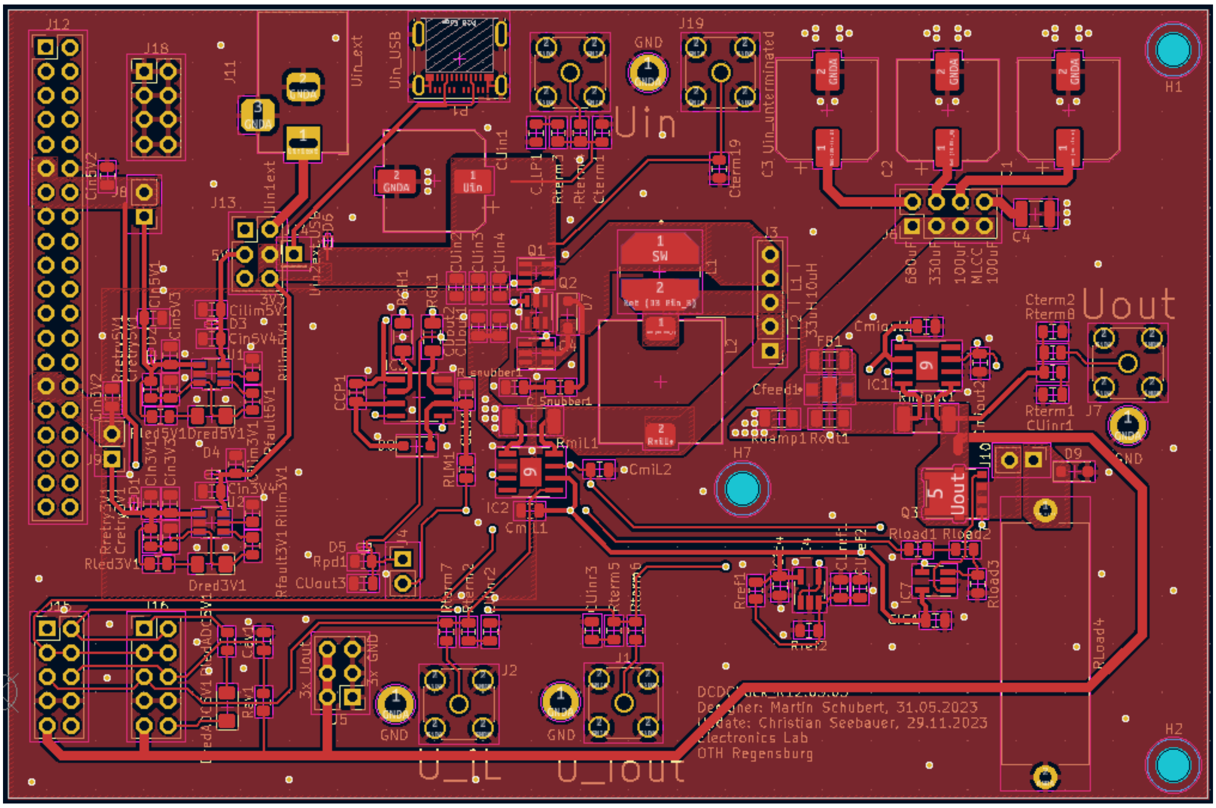


Fig. 1.4(a): *DCDCbuck_R12.03* front-side copper layer (*KiCad* [19])

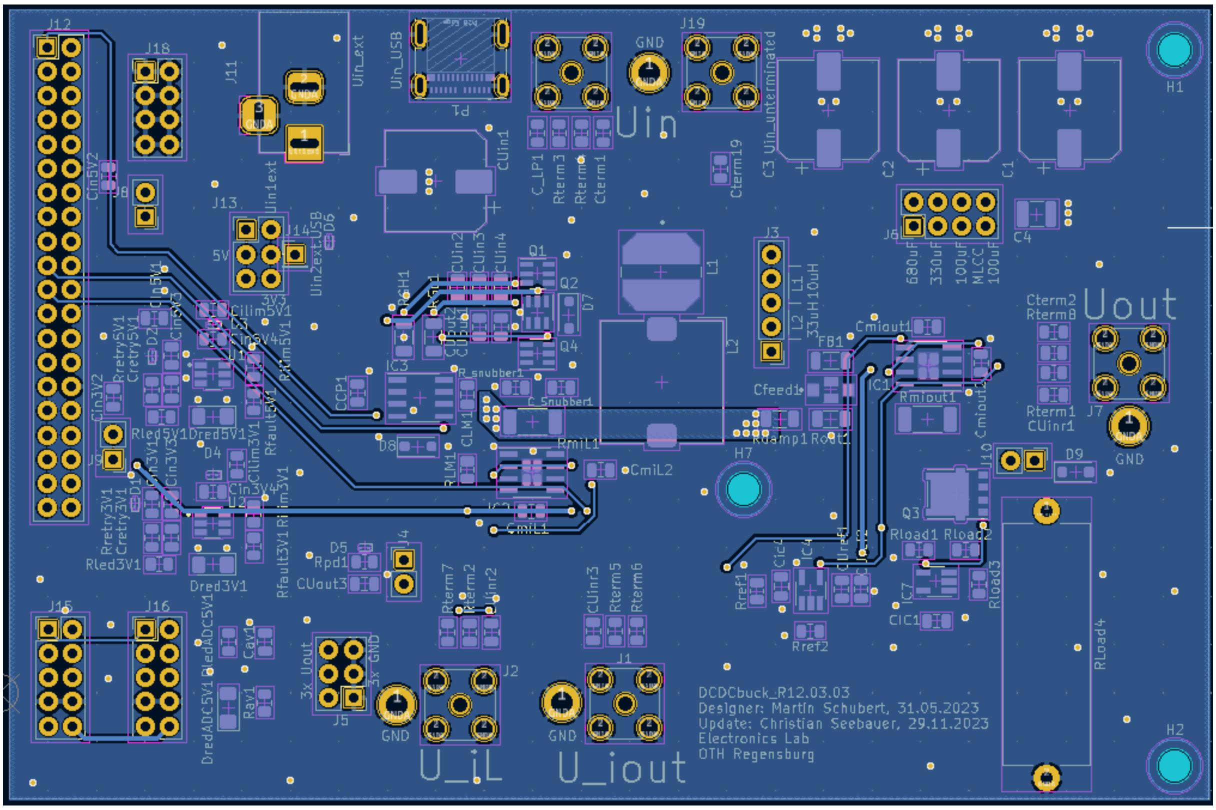


Fig. 1.4(b): *DCDCbuck_R12.03* back-side copper layer (*KiCad* [19])

Fig. 1.4 illustrates the layout (a) and photo (b) of the *DCDCbuck_Rev12.03.03* board. Vias connect different metal layers and may hold pins of plugs.

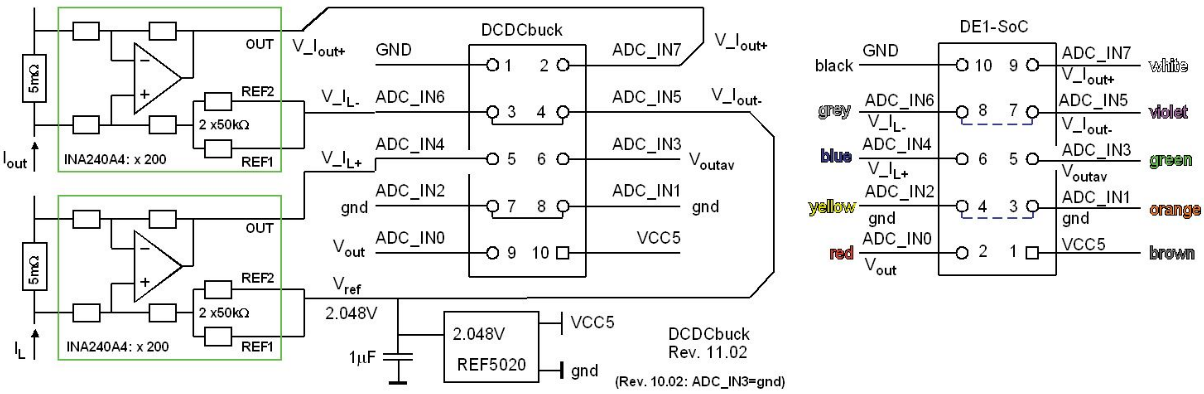


Fig. 1.5: Pin assignment of the 10-pin ADC input plug (connected by the 10 wire ribbon cable). It is a cross cable! Color code valid for $V_{CC}(ADC)$ = black. Numbers within the plug-box are the pin-numbers of the plug. Labels *ADC_IN#* (# = 1…8) indicate input channel number # of ADC *LTC2308* [15]. *ADC_IN3* is ground for board revisions *Rev* ≤ 11.01.

Fig. 1.5 illustrates the pin assignment of the 10-pin ADC input plug (connected by the 10 wire ribbon cable seen in the photo). Numbers within the plug-box are the pin-numbers of the plug. Label *ADC_IN#* (# = 1…8) indicates input channel number # of the ADC *LTC2308* [15]. *ADC_IN3* is ground for board revisions *Rev* ≤ 11.01.

1.3 Outline

The organization of this communication is as follows:

Section 1 introduces into this document.

Section 2 makes the student familiar with required tools.

Section 3 characterizes the passive *RLC* lowpass (labeled *Process* in Fig. 1.3) on the isolated *DCDCbuck* daughter board.

Section 4 draws conclusion and

Section 5 offers references.

2 Getting Started with the Tools

This chapter makes you familiar with some basic tools and formulae.

2.1 Fundamental Electronics

2.1.1 Inductor: Extract *L* and series wire resistor R_w from *Bode* Diagram

$$X_L = sL \xrightarrow{s=j\omega} j\omega L \text{ , consequently } L = \frac{|X_L|}{2\pi f}$$

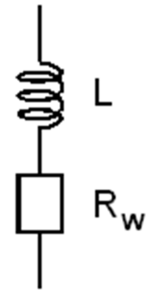


Fig. 2.1.2: *L, R* in series which models a real-world inductor. Example: Fig. 2.8.2.

Inductor with serial wire resistor R_w:

$Z_{RL} = R_w + j\omega L$, consequently

$$L = \frac{\sqrt{|Z_{RL}^2| - R_w^2}}{2\pi f} \quad (2.1)$$

If $R_w \ll |X_L|$ negligible: $L = \frac{\sqrt{|Z_{RL}^2| - R_w^2}}{2\pi f} \xrightarrow{|X_L| \gg R_w} \frac{|Z_{RL}|}{2\pi f} = \frac{|X_L|}{2\pi f}$ (2.2)

PS: Data sheet note R_w as DC resistor, or *DCR*.

2.1.2 Capacitor: Extract *C* and series resistor R_C from *Bode* Diagram

$$X_C = \frac{1}{sC} \xrightarrow{s=j\omega} \frac{1}{j\omega C} \text{ , consequently } C = \frac{1}{2\pi f |X_C|}$$

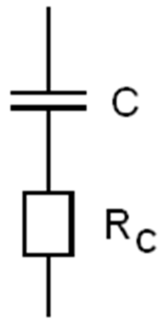


Fig. 2.1.2: *C, R* in series which models a real-world capacitor.

Capacitor with equivalent series resistor R_C:

$Z_{RC} = R_w + \frac{1}{j\omega C}$, consequently

$$C = \frac{1}{2\pi f \sqrt{|Z_{RC}^2| - R_C^2}} \quad (2.3)$$

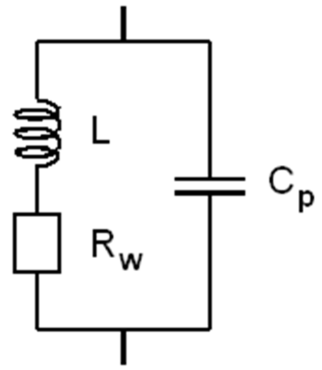
If $R_C \ll |X_C|$ negligible: $C = \frac{1}{2\pi f \sqrt{|Z_{RC}^2| - R_C^2}} \xrightarrow{|X_L| \gg R_w} \frac{1}{2\pi f |Z_{RC}|} = \frac{1}{2\pi f |X_C|}$ (2.4)

PS: Data sheets label R_C as *equivalent series resistor*, or *ESR*.

2.1.3 Parallel LRC Oscillator: (*LR*||*C*: Real World Inductor)

Inductor with serial resistor *R* and parallel capacitor *C*:

$$Z_{LRC} = (R + sL) \| \frac{1}{sC} = \frac{R + sL}{1 + sRC + s^2 LC} \tag{2.5}$$



Using $s = j\omega$ delivers

$$Z_{LRC}(j\omega) = \frac{R + j\omega L}{1 - \omega^2 LC + j\omega RC} \tag{2.6}$$

which peaks for small time constants *RC* near

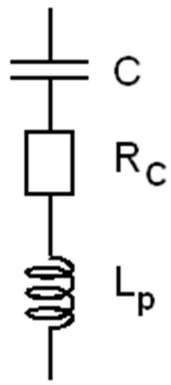
$$\omega_0 = \frac{1}{\sqrt{LC}} \quad \Leftrightarrow \quad f_0 = \frac{1}{2\pi\sqrt{LC}}. \tag{2.7}$$

Fig. 2.1.3: LRC parallel, which models a real-world inductor. Example: Fig. 2.8.3 peak up (right).

2.1.4 Series *RLC* Oscillator (Real-World Capacitor)

In series with the capacitor and its resistor R_C we have a series inductor *L*

$$Z_{CRL}(s) = R + sL + \frac{1}{sC} = R_C + \frac{1 + s^2 LC}{sC} \tag{2.8}$$



and with $s = j\omega$

$$Z_{CRL}(\omega) = R - j\frac{1 - \omega^2 LC}{\omega C}. \tag{2.9}$$

At $\omega_0 = \frac{1}{\sqrt{LC}} \quad \Leftrightarrow \quad f_0 = \frac{1}{2\pi\sqrt{LC}}$ we get

$$Z_{CRL}(f) \text{ is minimal} \tag{2.10}$$

and

$$Z_{CRL}(f_0) = R. \tag{2.11}$$

Fig. 2.1.4: LRC parallel oscillator, which models a real-world capacitor. Example: Fig. 2.8.3, peak down (left).

In summary, at the impedance minimum in the frequency domain we also have phase 0. At this point we can read the series resistor (i.e. R_C of a capacitor) and the resonant frequency f_0.

2.2 Basic Metering

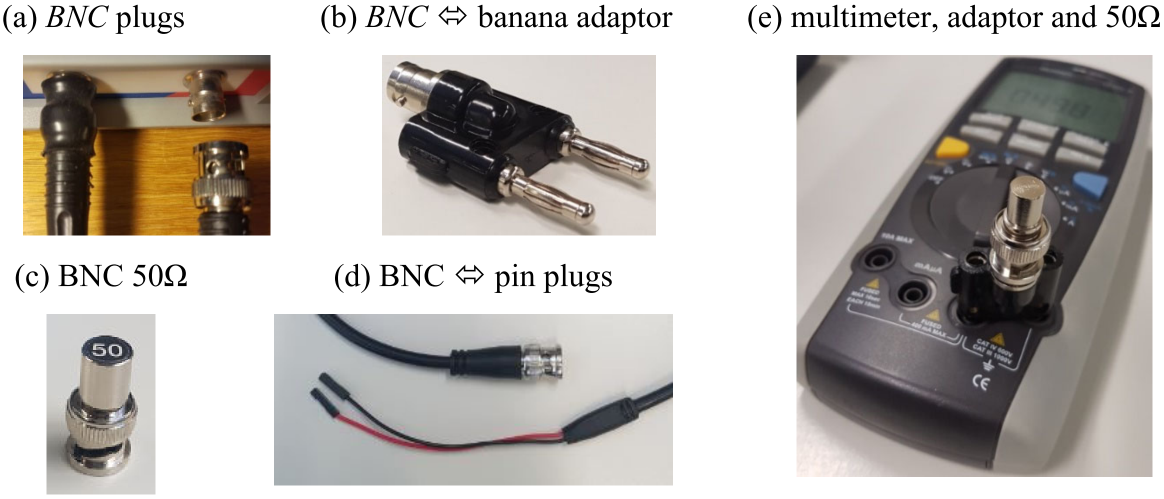


Fig. 2.2: Different *BNC* related measurements aids

Most measurements are based on *BNC* and pin cables and plugs as illustrated in Fig. 2.1.

2.3 *KiCad* Layout and Schematic Editor

Download the DCDC converter schematics from the author's homepage > [Schubert.OTH] >…*Edu* > *Labs* > *labs with DE1-SoC Board and Daughte Boards* > *Models_ADA+DCDCbuck_edu_R10_&12.zip* > unzip > Layout+Schematic > Layout_DCDCbuck_Rev12.03.03_Seebauer.upd_2024s.zip > unzip > DCDCbuck_R12.03.03_Seebauer.upd_ordered_2024s*.*brd*: physical board layout

- *.*pro*: project file, from there open ->
- *.*sch*: board schematic
- *.*pcb*: board layout

2.4 *HM8118 LCR* Bridge for Device Characterization

LCR bridge *HM8118* [HM8118] is available in the electronics lab and suitable to measure components such as capacitors and inductors. Check for the *HM8118 LCR* bridge in the lab and measure some arbitrary inductors and capacitors.

Note that we measure series resistors only, so the *MODE* button must be *AUTO* and/or *SER*. Typically it is enough to press *AUTO* and let the *HM8118* detect the rest.

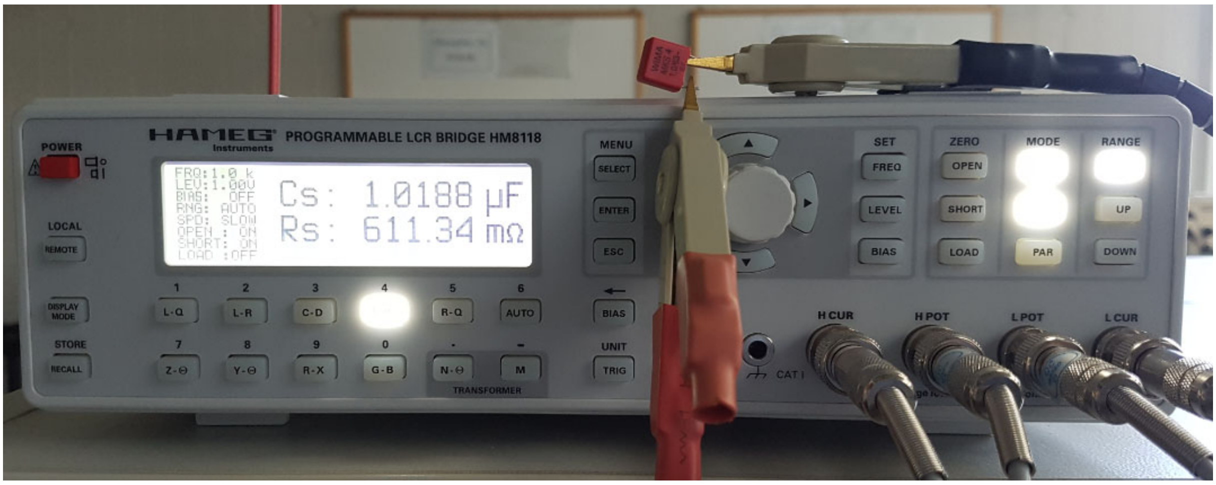


Fig. 2.4: Measuring a capacitor and its equivalent series resistor with HM8118

2.5 Screen Copies with *Microsoft Windows 10*

Screen copies with *MS Windows 10* can be made with the snipping tool: Start menu: → hit keys "*sn*" → (Snipping tool opens)→ *New* → (draw the widow to copy) → *File* → *Save as* → (filename). From the authors experience *Snipping* tool screen copies make smallest file sizes with *PNG* formatted files

2.6 Waveform Generator (*DSO-X 2024A*)

Use the waveform generator within oscilloscope *DSO-X 2024* [*DSO-X 2024A*] if available.

Observe generated waveforms by connecting *GEN OUT* with input channel 1 (*CH1*).

Measure the output impedance of your waveform generator. For more background information on this measurement see [I/O-Imp] at the author's homepage > *Offered Education* > *Lessons* > *Characterization* > *Considering I/O Impedances*.

- Create any waveform or a DC voltage with the waveform generator. Note the unloaded output voltage as U_{Gint}, which is measured as U_{Gext} with no load, i.e. $R_L \to \infty$, in Tab. 2.6.
- Load the source with a load resistor R_L, which should be of similar size as the output impedance to be measured, i.e. for typical waveform generators $R_L \sim 50\Omega$. Use an Ohm-meter to determine R_L exactly. Note the results in table 2.6.
- Measure U_{Gext} with load resistor and compute $\alpha = U_{Gext} / U_{Gint}$.
- Compute R_G from $R_G = \frac{1-\alpha}{\alpha} R_L$.

Table 2.6: Computing output impedance of waveform generator

Bench # 00	ideal	real	|	formula	ideal	real
U_{Gint}	2 V	1 V	|	xxx	xxx	xxx
U_{Gext}	1 V	499 mV	|	$\alpha = \frac{U_{Gext}}{U_{Gint}}$	0.5	0.499
R_L	50 Ω	50.3 Ω	|	$R_G = \frac{1-\alpha}{\alpha} R_L$	50 Ω	50.5 Ω

Listing 2.6: Matlab code computing the generator's output resistor R_G.

```
% Computing an output Resistor
UGint = 1;
UGext = 499e-3;
RL    = 50.3;
alpha = UGext / UGint;
RG    = RL*(1-alpha)/alpha;
```

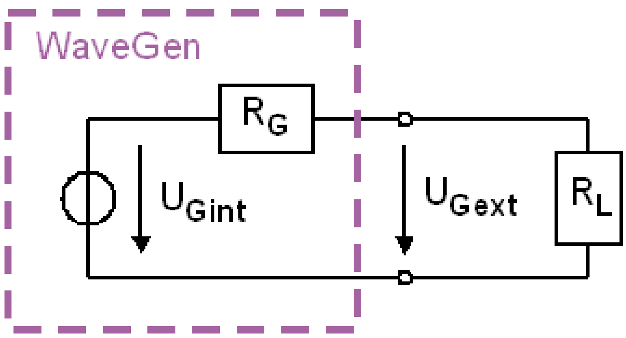


Fig. 2.6: Waveform generator with inner resistor R_G, external load resistor R_L, assumed inner generator voltage U_{Gint} and measured external voltage U_{Gext}.

2.7 Oscilloscope (*DSO-X 2024A*)

Use the waveform generator within oscilloscope.

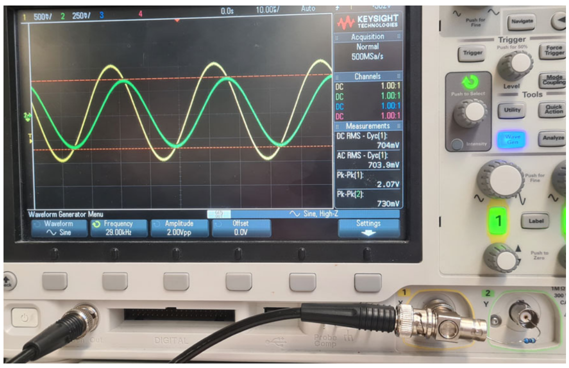
- Generate a sinusoidal waveform and observe it with channel 1 (CH1) of your oscilloscope.
- Feed the same signal over a shunt resistor of R_S = 1 MΩ to channel 2 (CH2) as illustrated in Fig. 2.7.
- Measure the voltage drop of CH2 versus CH1 at low frequencies. To avoid the measurement of noise, it might be the best to measure the *RMS value of N cycles* with the oscilloscope. The voltage drop should be some 50%, e.g. from 2V → 1V.
- Increase frequency until you observe further -3dB (i.e. factor $1/\sqrt{2}$) decrease compared to DC-amplitudes, measured at 10Hz, e.g. from 1V → 0.71V

Table 2.7: Computing input impedance of waveform generator

Bench #	ideal	real	|	formula	ideal	real
$U_{Ch1}(f)$	2 V	703 mV	|	$R_{in} = \frac{\alpha}{1-\alpha} R_S$	1 MΩ	996 KΩ
R_S	1 MΩ	1.01MΩ	|	$R_p = R_S \parallel R_{in}$	500 KΩ	501 KΩ
$U_{Ch2}(10Hz)$	1 V	349mV	|	$f_p = f\left(\frac{U_{Ch2,DC}}{\sqrt{2}}\right)$	29 KHz	~29 KHz
$\alpha = \frac{U_{Ch2}(10Hz)}{U_{Ch1}}$	½	0.4964	|	$C_{in} = \frac{1}{2\pi f_p R_p}$	11 pF	~12 pF

Listing 2.7: *Matlab* code computing $R_{in}+C_{in}$.

```
% Compute parallel RC input impedance
% at (*) insert your measured value
Uch1       = 703e-3;          % (*)
Uch2_10Hz  = 349e-3;          % (*)
alpha      = Uch2_10Hz/Uch1;
RS   = 1.01e6;                % (*)
Rin  = RS*alpha/(1-alpha);
Rp   = RS*Rin/(RS+Rin);
fp   = 29000;                 % (*)
Cin  = 1/(2*pi*Rp*fp);
Cin_datasheet = 11.0e-12;
```



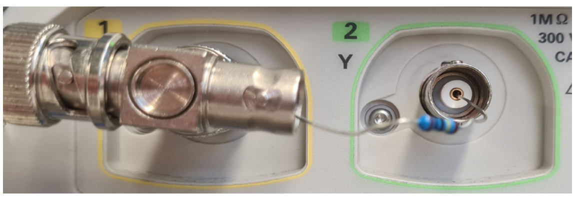


Fig. 2.7: *CH1* is directly connected to the 50Ω signal source, *CH2* is connected via a 1MΩ resistor.

2.8 *Bode* Diagram Measurements Using *Bode100*

2.8.1 Transfer Function Measurements

This chapter helps you getting started with using the *Bode100* [Omicron] instrument and the *Bode Analyzer Suite* [Bode100] operating it. **At Bode100 hardware, do not remove the BNC cable connecting *OUTPUT* with *CH1* input unless you are explicitly asked to do so.**

Connect the *Bode100 OUTPUT* to oscilloscope *CH1* input. Let *Bode100* output 0 dB (e.g. at 1KHz). To what effective ("*rms*") voltage and peak-to-peak voltage does that correspond?

Bode100 OUTPUT = 0 dB correspond to: U_{rms}(0dB) = **447mV** ⇔ U_{pp} = **1.26V**
. . . .

What power will this output dissipate at a 50Ω load? (Consider the 50Ω output impedance.)

P_{out} = $U^2 / R = (0.447V/2)^2 / 50\Omega = 1mW$
. . . .

Measure with *DSO-X 2024A* oscilloscope

- Press button: *Autoscale*
- *Meas > Add measurement > Source 1, Type: Peak – Peak*
- *Meas > Add measurement > Source 1, Type: AC RMS, N Cycles*

***Gain/Phase* measurement with *Bode100* (according to Fig. 2.8.1)**

- Use a short *BNC* cable to connect *OUTPUT* with *CH2* input.
- Start *Bode Analyze Suite* while *Bode100* being on and connected to your PC.
- Start a *Gain/Phase* measurement with default settings
- Shut down *Bode Analyze Suite* discarding changes.

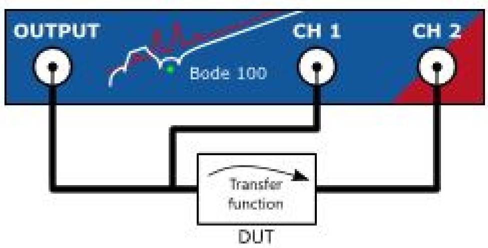
Impedance Analysis* with *Bode100

- Plug a 50Ω BNC termination resistor onto the Bode100 output
- Restart *Bode Analyze Suite*, select *Impedance Analysis > Start Measurement* with default settings.
- Click into the *Bode* diagram and select *Optimize* with right mouse button.

Note: The File → Save [as] command of *Bode100* saves both setup and measured data.

Exercise: Perform a *One-Port Impedance Analysis* at any capacitor, as illustrated in Fig. 2.8.2. Compute the capacitance and its parasitic series inductance.

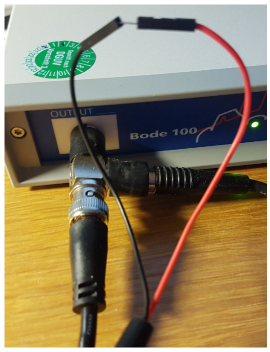
Fig. 2.8.1: Measure a *Bode* diagram with *Bode100* operated with *Bode Analyzer Suite 3* [Bode100], *Gain/Phase* Measurement.



2.8.2 OnePort Impedance Measurement: Cable BNC - pin

(a) Right: Photo of the measurement setup.

(b) Bottom: *One-Port Impedance* measurement with *Bode100*. We see a parasitic inductor at high frequencies.



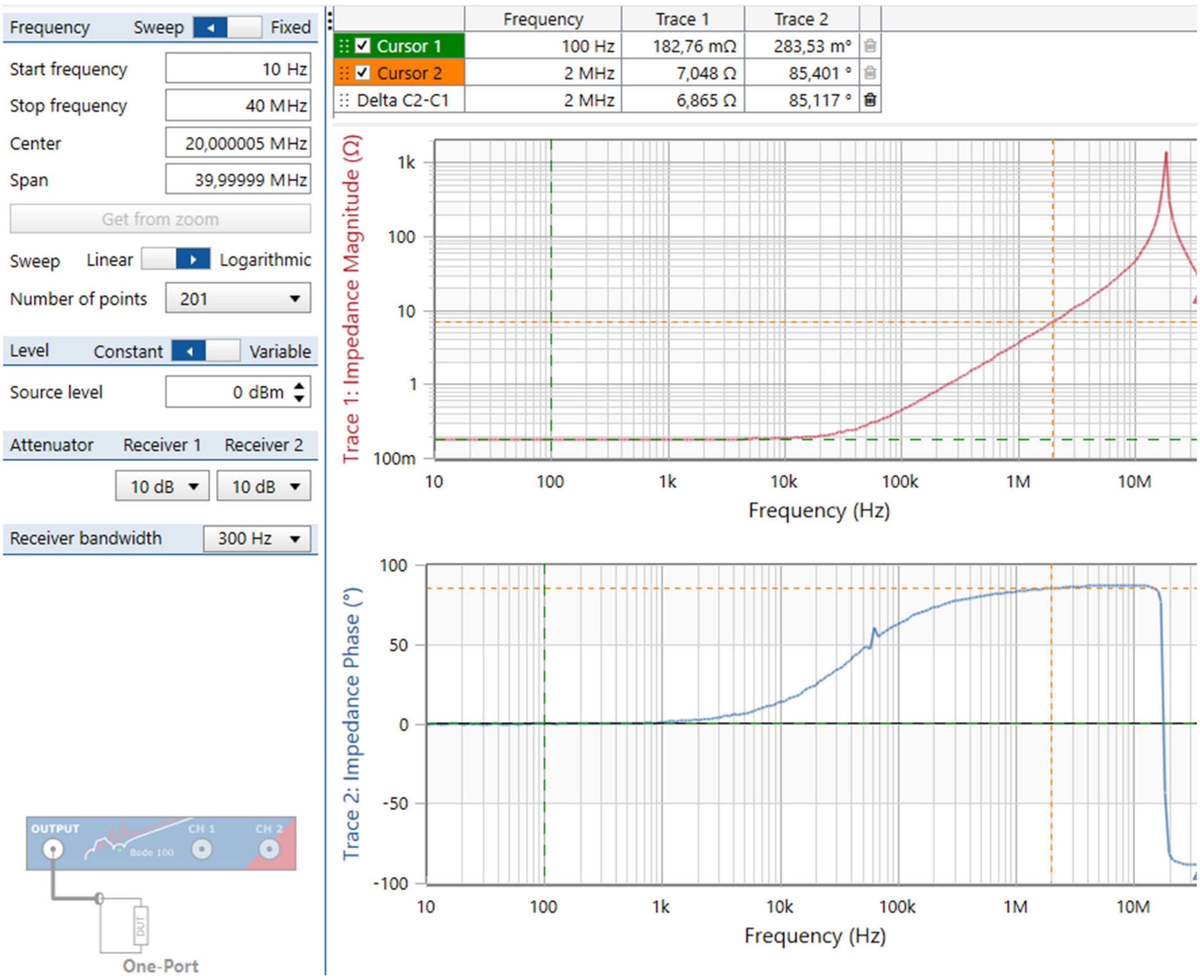


Fig. 2.8.2: *Bode100 One-Port Impedance* measurement of some mm of wire.

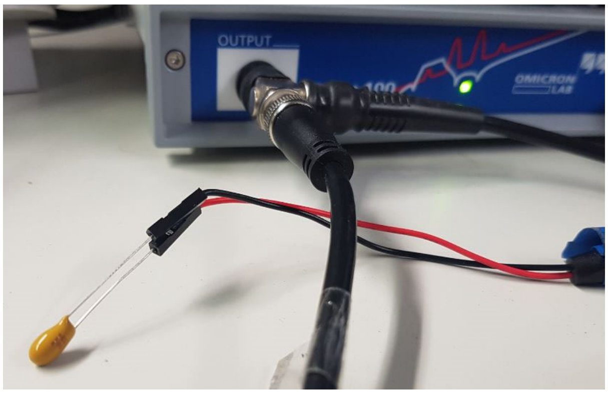
The *One-Port Impedance* measurements at straight logarithmic slopes delivers …

at f = 100Hz: **R_{cable} = ... 183 mΩ .....**

f = 2MHz: $X_L = R_w + j\omega L \rightarrow L = \frac{\sqrt{|X_L|^2 - R_w^2}}{2\pi f} =$ **560 nH** $\cong \frac{|X_L|}{2\pi f} = \frac{7.048\Omega}{2\pi \cdot 2MHz}$ **=564 nH**

2.8.3 OnePort Impedance Measurement: Capacitor BNC – pin

(a) Right: Photo of the measurement setup.



(b) Bottom: *One-Port Impedance* measurement with *Bode100*. We see a capacitor at low frequencies and a parasitic inductor at high frequencies.

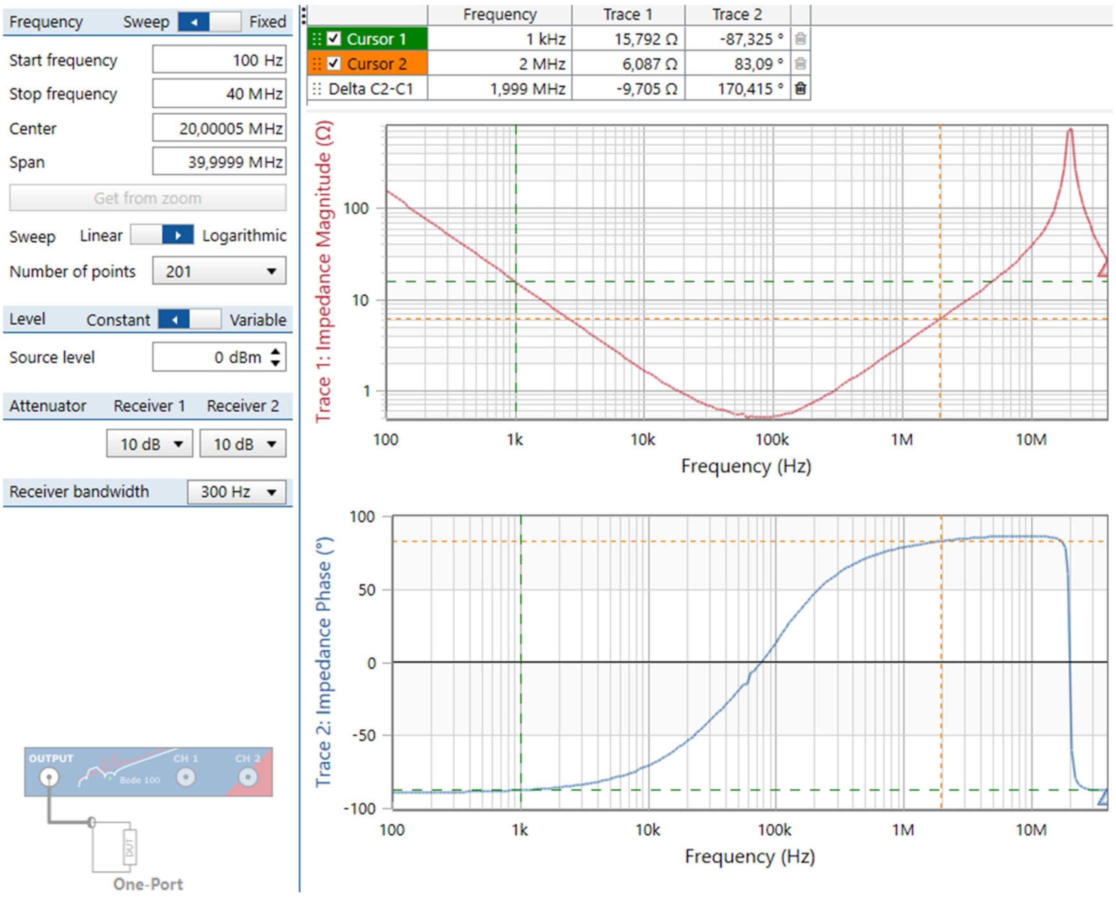


Fig. 2.8.3: *Bode100 One-Port Impedance* measurement of a capacitor of nominal 10 µF.

The *One-Port Impedance* measurements at straight logarithmic slopes delivers …

$$\text{at f = 100Hz:}\quad X_C \cong \frac{1}{j\omega C} \;\rightarrow\; C \cong \frac{1}{2\pi f |X_C|} = \frac{1}{2\pi \cdot 100Hz \cdot 15.792\Omega} = 10.08\ \mu F$$

$$\text{at f = 2MHz:}\quad X_L \cong j\omega L \;\rightarrow\; L \cong \frac{|X_L|}{2\pi f} = \frac{6.087\Omega}{2\pi \cdot 2MHz} = 484\ nH$$

How do you explain that inductor *L* is smaller now than above with the short only?
Wire opening. Measure short again with wires close together!