Report on the bootstrapped buffer for QuADC EMPIR

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Introduction

Following document briefly describes buffer developed for the EMPIR project QuADC [3]. Main requirement was flatness below 0.1 µV/V up to 10 kHz. Calibration uncertainty at 1 MHz requirement was 5 µV/V. Input capacitance as low as possible. Output impedance as low as possible.

Basic parameters

Parameter	Value
Supply voltage	(±13.5 up to ±15.5) V
Supply current	< 100 mA, plus fan current in positive supply
Input voltage range	1.5 Vpk
Input capacitance	< 1 pF
Input DC resistance	100 MΩ
Output impedance |Z|	< 4 mΩ up to 10 kHz < 12 mΩ up to 100 kHz < 150 mΩ up to 1 MHz
Output inductance	< 20 nH
Flatness	< 0.1 µV/V up to 10 kHz < 2 µV/V up to 100 kHz < 100 µV/V up to 1 MHz (depends on the cable and load)
Estimated THD	< 140 dB up to 100 kHz (10 harmonics) < 106 dB up to 1 MHz (bw. 6 MHz)

Description

It is derived from the Ilya Budovsky design [1]. Problem of the Budovsky-like designs is there are no feedbacks from the bootstrapped supply rails so the accuracy of them is low. Multi-staging the topology has no significant effect as each following stage is still limited by the finite speed of the floating rail drivers. Furthermore the input capacitance of that design is relatively high.

In the new design, all amplifiers are supplied from the bootstrapped rails so apparent input capacitance is near zero. Also, the printed circuit board (PCB) was designed with 4-layers with careful guarding, so the capacitance is further reduced. The whole board’s apparent input capacitance without connectors is below 1 pF.

Principle of the buffer is shown the Figure 1. For full circuit diagram see Figure 13 or Eagle files. Simplified diagram is shown in Figure 2.

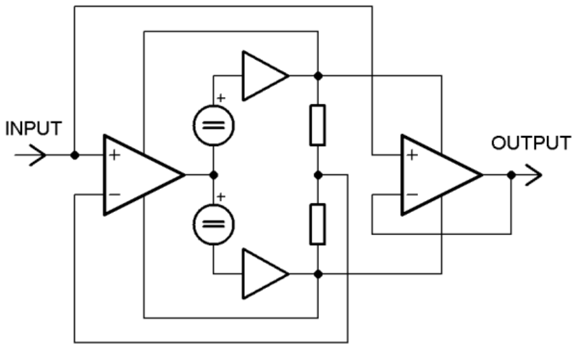

Figure 1 - Priniciple of operation.

The trick is the feedback took from the bootstrapped rails back to the first stage. The feedback drastically reduces error of the rails to less than 1 % at 1 MHz. The feedback has one more effect. It reduces THD of the rails at low frequencies.

Another trick is the first stage OA is supplied from the floating rails as well. This has two effects. First, it improves the accuracy, same as for the last stage, because the OA only amplifies difference between its supply (common mode voltage) and input. Second, the common mode voltage is following the input, so the apparent input voltage is almost zero. Therefore, the apparent input common mode capacitance is also almost zero.

Problem of this topology is to make it stable. There is a large capacitance between the output/guard and input. PCB guarding has capacitance, OAs have differential capacitance and so on. This large capacitance is basically positive feedback from the output to the input. If the output or guard contain resonant overshoot, it will inevitably lead to the oscillations. So the goal is to properly dump the guard driver so it has low overshoot but at the same time is as fast as possible. Otherwise the apparent input impedance will fall quickly with the frequency. It is also not easy to find feedback RC values to make it stable. Presented circuit was built in two prototypes and it seems repeatable with the listed components, but it does not mean it cannot be improved. For details on the tweaking of the component values see the list of components.

Regarding the stability, I often observed it became unstable if the input is connected to a low impedance source. The input can be shorted directly at the connector. However, when shorted via long coax cable, which acts as a resonator, it will start oscillating easily. It seems to be stable with resistive source as long it has at least few Ohms even via longer cables. It may be made stable using RC snubber network connected to the input or at least to the other side of the input cable, but of course for a cost of a higher input capacitance which will be frequency dependent. On the other hand the output may be loaded by 1 m coax with no observed effects on stability.

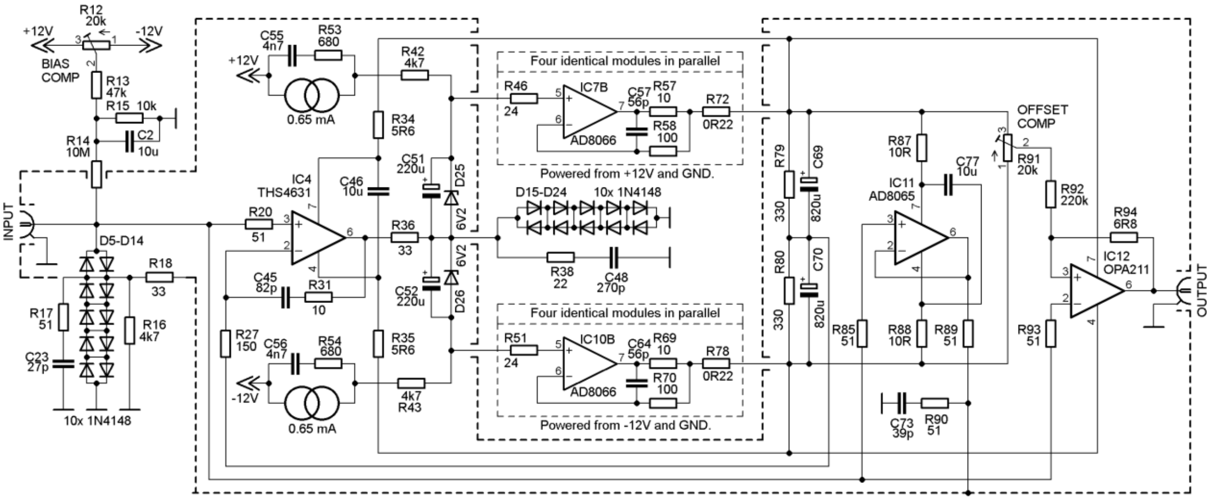

Figure 2 - Simplified circuit diagram.

Regarding the PCB, it was designed to be small so it fits into the box Hammond HA1455K1602. Board is mounted on 10mm long M3-M3 spacers. Input and output connectors are N-type mounted on sides of the box and soldered directly to the PCB. Note the shields of the connectors has to be connected to the PCB via copper stripes in order to reduce series impedance. Input connector has also prepared solder pads for guard shield, see Figure 10.

The components that needs to be trimmed are placed in the 2.54 mm sockets. Example is shown in the Figure 3. It is ordinary precision socket with round contacts. It can perfectly hold 0207 or 0204 resistors or RM2.5 capacitors. I decided to use this for fine tuning rather than soldering.

Figure 3 - 0207 components in the 2.54 mm sockets.

The board also contains lot of unassembled poles and zeroes for tweaking the frequency response. It turned out these are not critical so I did not even tried those, see list of components for instructions.

The buffer prototype was equipped with small 35 mm, 12 V fan running at lower voltage. The fan is probably not needed, but it shortens the heat-up period so I guess it won't do any harm.

Components list

component	type	Note
R1	Trimmer Bourns 3214W, 50k	Negative supply level – multi-turn type!
R2	0805, 220k	
R3	0805, 68k	Negative supply current limiter
R4	0805, 510R	
R5	0805, 2k	
R6	Trimmer SMD 3364W, 2k2	Fan voltage
R7	0805, 110k	
R8	Trimmer Bourns 3214W, 20k	Positive supply level – multi-turn type!
R9	0805, 680R	Positive supply current limit
R10	0805, 330k	
R11	0805, 10k	
R12	Trimmer Bourns 3214W, 20k	Bias compensation – multi-turn type!
R13	0805, 47k	
R14	0805, 10M	Input shunt resistor – low Cp, rather low TCR
R15	0805, 10k	
R16	0805, 4k7	
R17	0207, 51R	0207 in socket 2.54mm
R18	0805, 33R	
R19	0805, 24R	Dumping resistor, may be increased
R20		Not used
R21 R22	0805, 2k7	
R23, R24, R25		Not used
R26	0207, 0R0	0207 in socket 2.54mm, critical for stability – may be changed
R27	0207, 150R	0207 in socket 2.54mm, critical for stability – may be changed
R28		Not used
R29	0805, 24R	Dumping resistor, may be increased
R30		Not used
R31	0805, 10R	0207 in socket 2.54mm, critical for stability – may be changed
R34, R35	0805, 5R6	May be worthy to fiddle the value for better step response
R36	0207, 33R	0207 in socket 2.54mm, critical for stability – may be changed
R37		This is empty socket 2.54mm. Preferably this should be used for exchangeable R38+C48 combination instead of assembling them in SMD. Critical for stability – may be changed
R38	0805, 270p	See R37!
R39, R40	0805, 3k3	

R41	0805, 51R	
R42, R43	0805, 4k7	
R44	0805, 51R	
R45 – R52	0805, 24R	Dumping resistors.
R53, R54	0207, 680R	0207 in socket 2.54mm, may affect response
R55, R57, R59, R61 R63, R65, R67, R69	0207, 10R	0207 in socket 2.54mm, may be useful to fiddle with the value for better step response of the bootstrapped rails.
R56, R58, R60, R62 R64, R66, R68, R70	0207, 100R	0207 in socket 2.54mm, may be useful to fiddle with the value for better step response of the bootstrapped rails.
R71 – R78	1210, 0R22	Dumping resistors, low ESL, must be there to prevent IC7 to IC10 “kicking” each other. May be useful to tweak the values.
R79 – R82	0805, 680R	
R83		Not used
R84	0207, 10R	Optional, just when bootstrapped voltage needs to be monitored.
R85	0805, 51R	Dumping resistor.
R86		Not used
R87, R88	0805, 10R	May be tweaked for lower overshoot of guard driver.
R89	0805, 51R	Guard driver dumping resistor
R90	0805, 51R	Part of guard snubber.
R91	Trimmer Bourns 3214W, 20k	Output offset compensation – multi-turn type!
R92	0805, 220k	
R93	0808, 51R	Dumping resistor, may be increased for better step response.
R94	6R8	Put 0805, 100nF on top of it.
C1, C2, C14, C15, C69, C70	RM5, D10.5mm, 820uF, 16V, polymer	Maybe 25V type is better, but it’s too big…
C7, C13, C16, C17, C36, C37, C51, C52, C67, C68	RM2.5, D7mm, 220uF, 16V, polymer	Input ones maybe 25V type is better, but it’s too big…
C11	1210, 22uF/16V, ceramic X7R	
C3, C4, C20, C26 – C33, C46, C54, C55, C74, C75, C77	1210, 10uF/25V, ceramic X7R	
C5, C6, C8 – C10, C12, C18, C19, C21, C22, C24, C25, C34, C35, C47, C49, C50, C53, C54, C65, C66, C71, C72, C78	0805, 100nF, ceramic X7R	>25V

C23	THT 2.5mm, 27p, ceramic NP0	In socket 2.54mm. Tweak for low overshoot.
C43		Not used
C48	0805, 270p, ceramic NP0	Tweak for stability. See R37!
C55, C56	THT 2.5mm, 4n7, ceramic NP0	In socket 2.54mm, may affect LF response
C38 – C42		Not used
C44	Johanson C-trimmer 9343, 30pF	May not be necessary, may be tweaked by C45 only.
C45	THT 2.5mm, 82pF, ceramic NP0	In socket 2.54mm, critical for stability. Tweak for stability and optimal response.
C57 – C64	THT 2.5mm, 56pF, ceramic NP0	In socket 2.54mm, may be useful to tweak the value for better bootstrapped rails step response.
C76		Not used.
C79	THT 2.5mm, 39pF, ceramic NP0	In socket 2.54mm. Tweak for low overshoot on guard.
L1, L2	Inductor, L3225M, 22uH	
D1, D2	DO214, 1N4007	May be replaced by 16V+ TVS. Just protection.
D3, D4	BAT43, Mini-MELF, Schottky	Critical! Without these the positive LDO may get stucked in negative voltage on startup!
D5 – D14	1N4148, uMELF	Input ESD protection.
D15 – D24	1N4148, uMELF	These are critical to keep inputs of IC7 to IC10 in safe operating range! May be necessary to short one of those five stages (lower input voltage range but more stable).
D25, D26	Mini-MELF, 6V2 Zener	
LD1, LD2	0603 LED	
IC1	LM317LD, SO8	Voltage regulator for fan.
IC2	LT3042, MSE Package	Positive LDO, don’t forget solder heat pad!
IC3	LT3090, MSE Package	Negative LDO, don’t forget solder heat pad!
IC4	THS4631, SO8	
IC5, IC6	LT3092, TS8 Package	Current source.
IC7 – IC10	AD8066, SO8	Maybe just two of those are necessary, must be tried…
IC11	AD8065, SO8	
IC12	OPA211, SO8	Maybe put some thermal paste under to help stabilizing the temperature.
X1	3x2.54 screw socket	Supply input.
X2	BNC, Radiall R141426161	Do not assemble, just increases capacitance! Just for test purposes.
X3	BNC, Radiall R141426161	Monitor of bootstrapped rails.
X4	BNC, Radiall R141426161	Monitor of equipotential (guard).

Measurements

The buffer was characterized for the basic characteristics using modified digital impedance bridge [2]. First, the input impedance was measured. The result without connectors is shown in the Figure 4. The impedance was measured by placing a known impedance in series with the input and observing change in the transfer. Output impedance show in Figure 5 and Figure 6 was measured similarly by connecting known load to the output and observing change in the transfer.

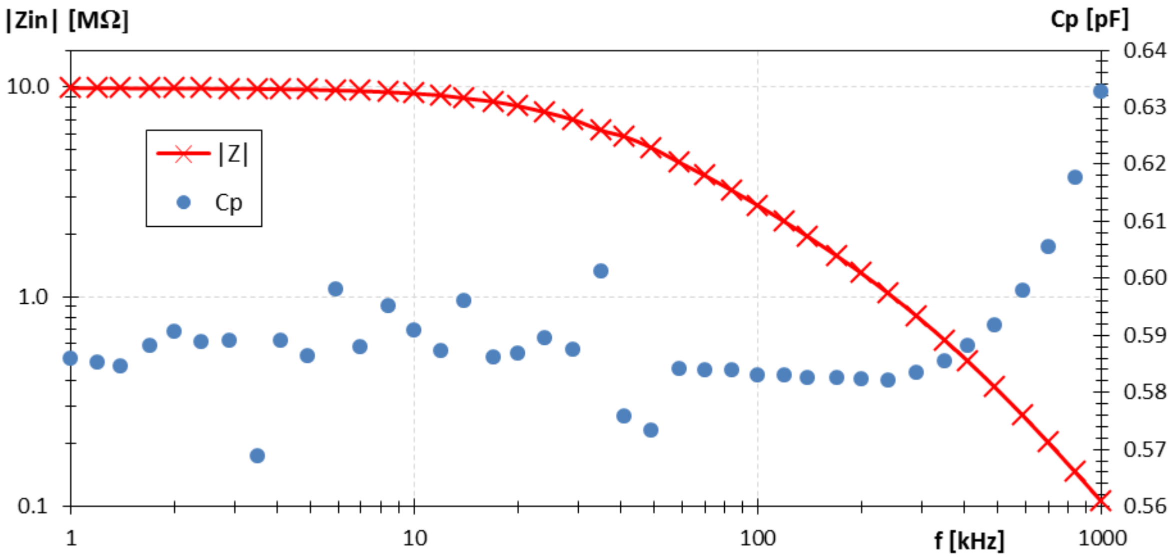

Figure 4 - Input impedance of the buffer without connector.

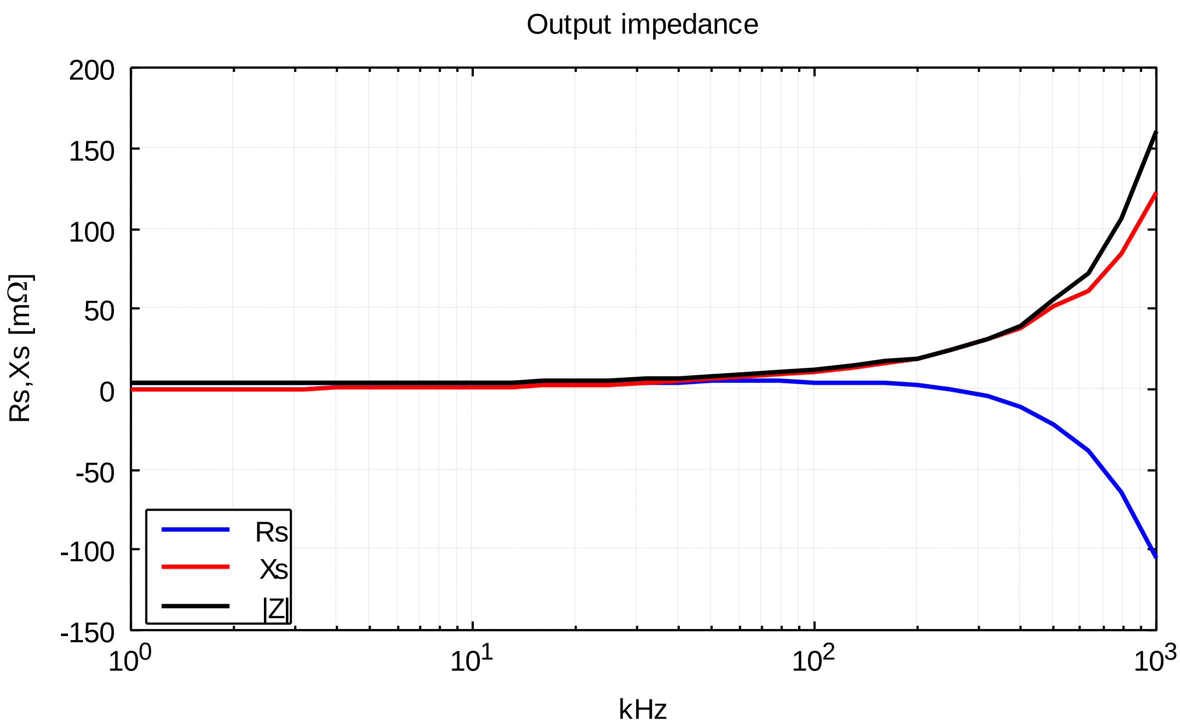

Figure 5 - Output impedance with N connector.

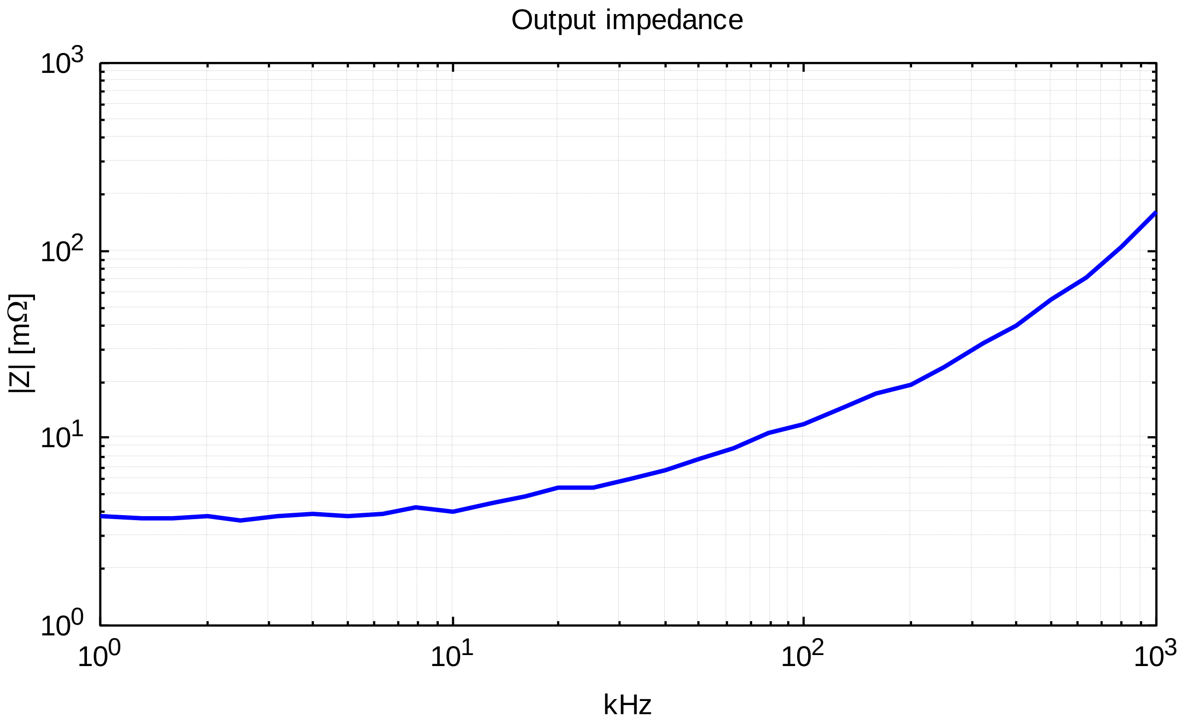

Figure 6 - Output impedance with N connector (modulus).

Complex transfer was measured indirectly using the impedance bridge. The raw transfer was then recalculated for apparent no load of the output of the buffer using measured loading impedance of the bridge input and output impedance of the buffer. Then it was virtually loaded by the model of the cable based on its impedance characterization and the desired load. The result is shown in the Figure 7 and Figure 8. Direct measurement was not possible due to the specific load impedance.

Before it will be used for the quantum voltmeter it will have to be done this way as well, as the impedance of the system may differ from the buffer measurement condition. The method was validated by varying the load impedance, observing the changes in transfer and calculating the differences.

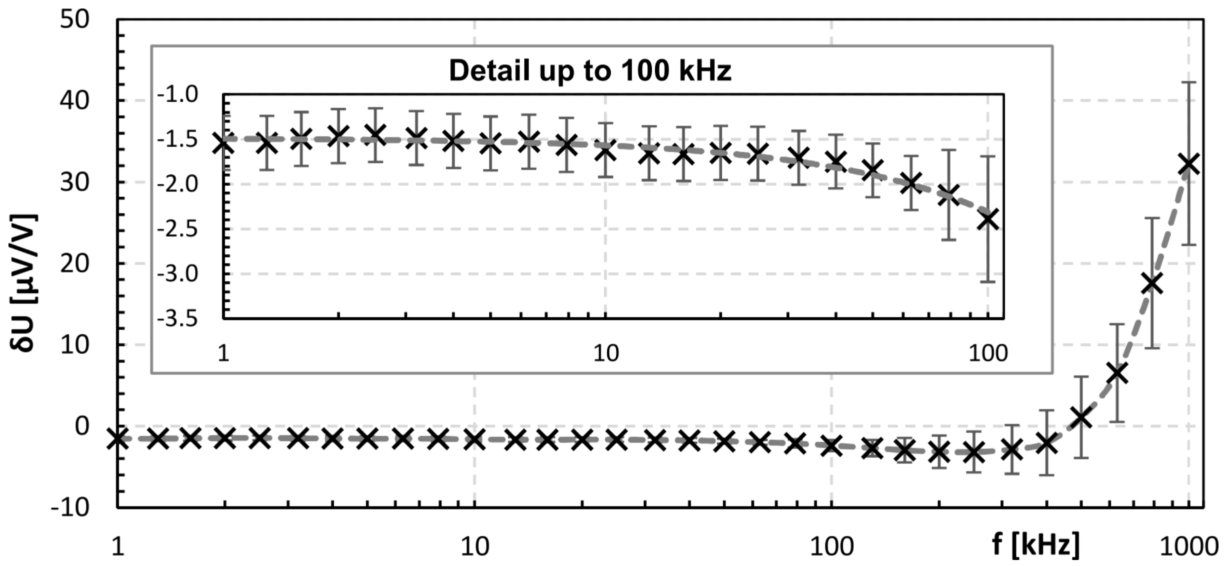

Figure 7 - Amplitude transfer of the buffer with (10 kΩ || 10pF) load via 20 cm coax cable RG318. Output was measured on the load. Note the amplitude drop -1.5 µV/V is caused by the load resistance and output resistance. The small fluctuations in the gain are caused by insufficient zeroing of the complex ration measurement setup.

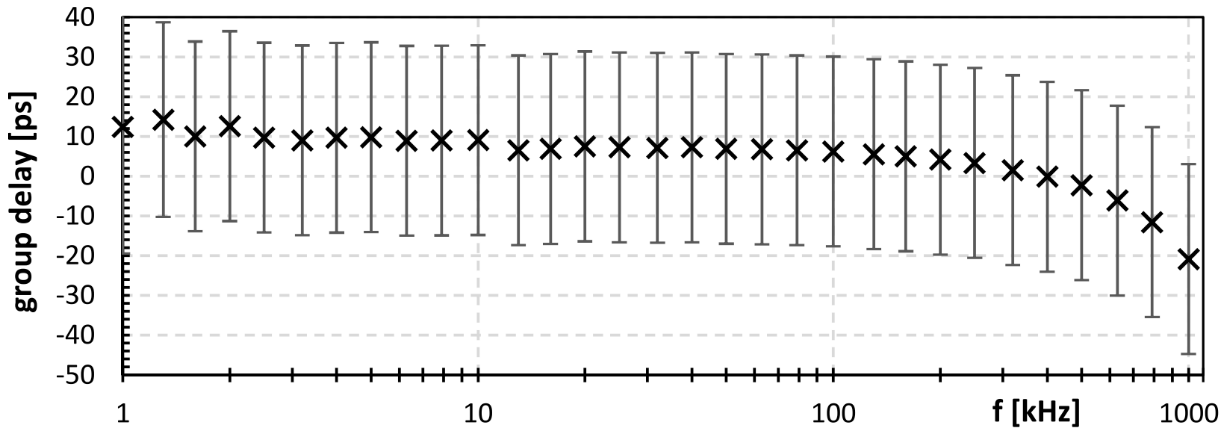

Figure 8 – Group delay of the buffer with (10 kΩ || 10pF) load via 20 cm coax cable RG318. Output was measured on the load. Note the amplitude drop -1.5 µV/V is caused by the load resistance and output resistance. The small fluctuations in the gain are caused by insufficient zeroing of the complex ration measurement setup.

The THD of the buffer was also measured by the digital impedance bridge setup. The ratio setup measured directly ratio of the input and output harmonics. From the differences it was possible to calculate the THD. It required up to few tens of minutes of total integration time to get stable. Results are < 140 dB up to 100 kHz and < 106 dB at 1 MHz. The 1 MHz value is really just an estimate. No validation was done at this frequency. It is likely the THD is actually much lower.

Acknowledgement

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References

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[3] EMPIR project QuADC, URL: https://www.ptb.de/empir/quadc-project.html

Images

Figure 9 - Enclosure opened.

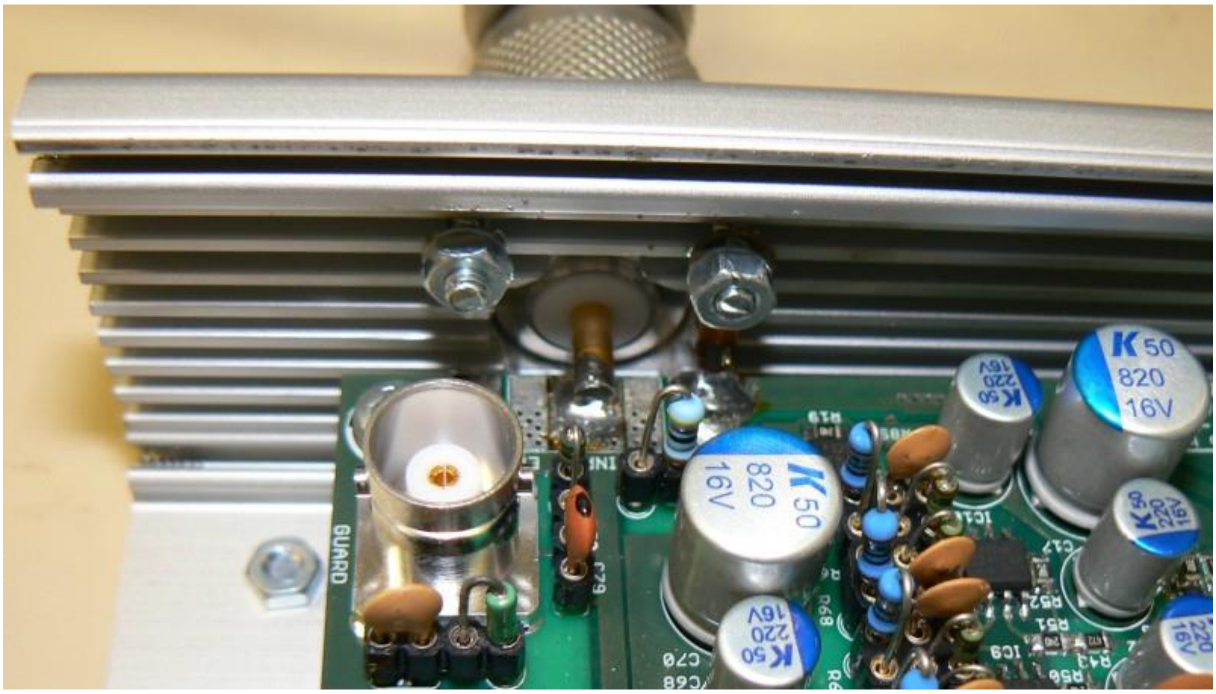

Figure 10 - Assembly of the input N connector. Note the solder pads around the center contact are prepared for soldering of equipotential shield.

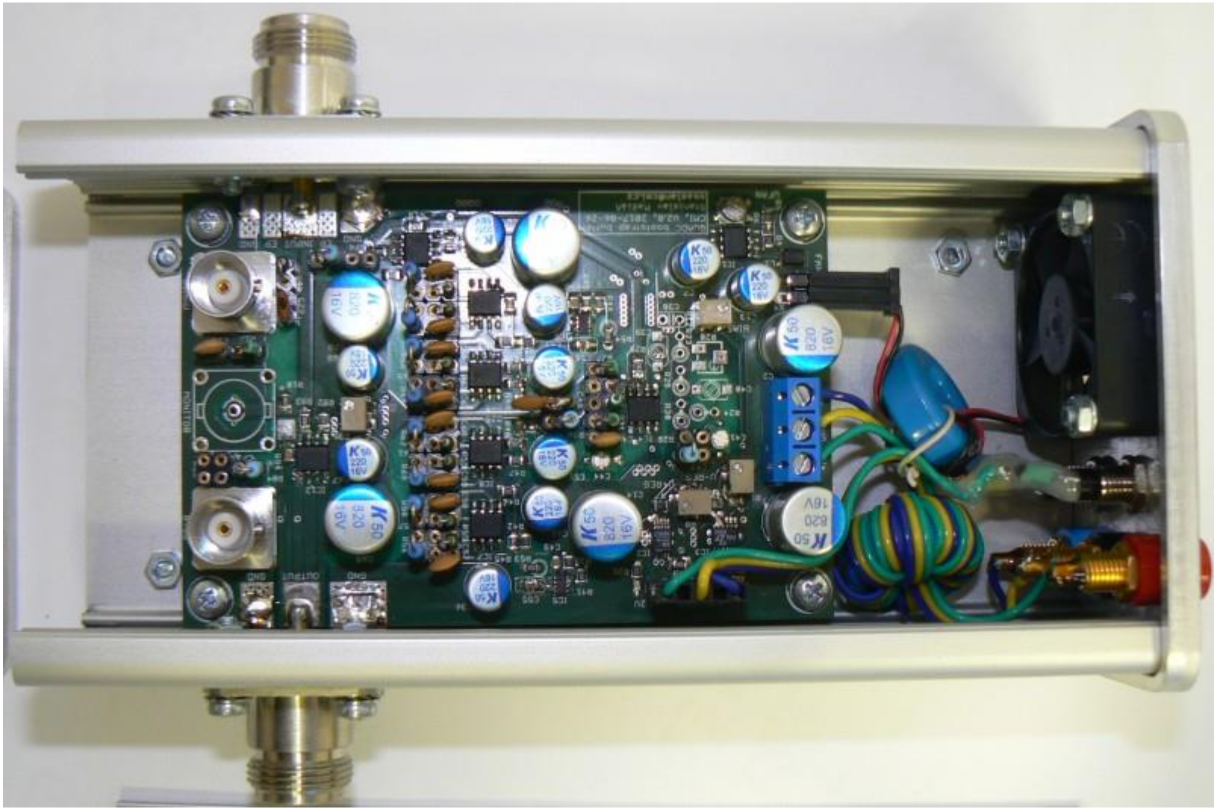

Figure 11 - Opened enclosure.

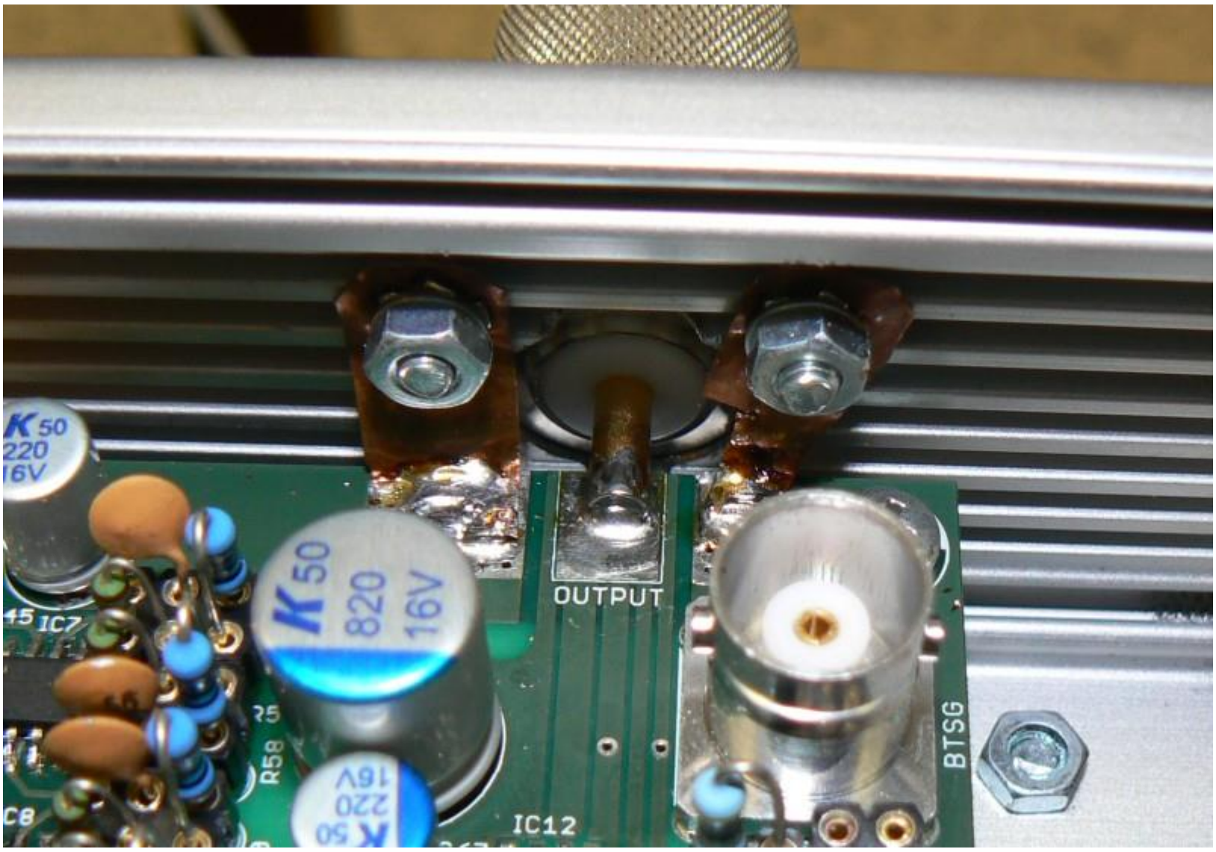

Figure 12 - Output N connector assembly.

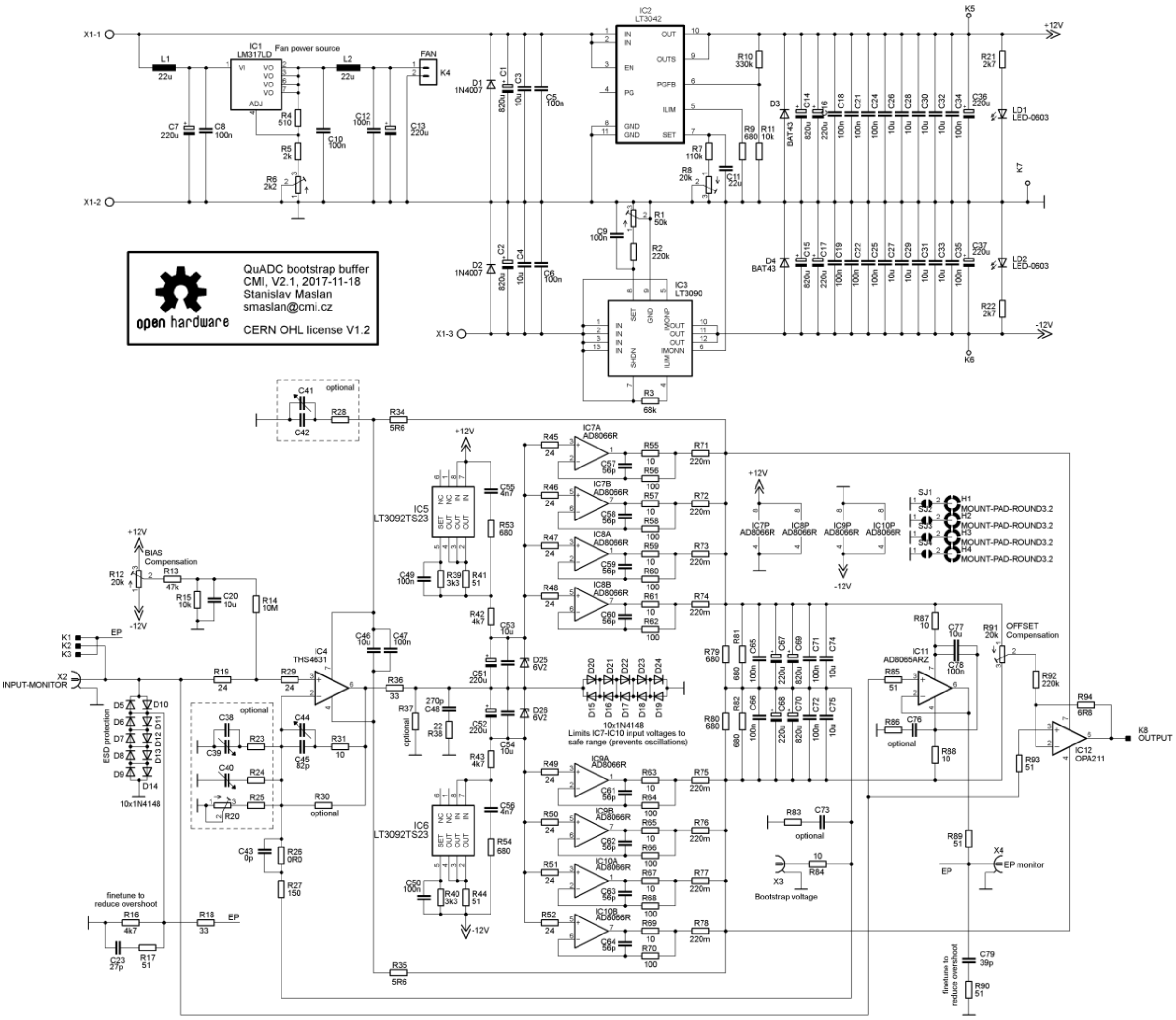

Figure 13 - Full circuit diagram.

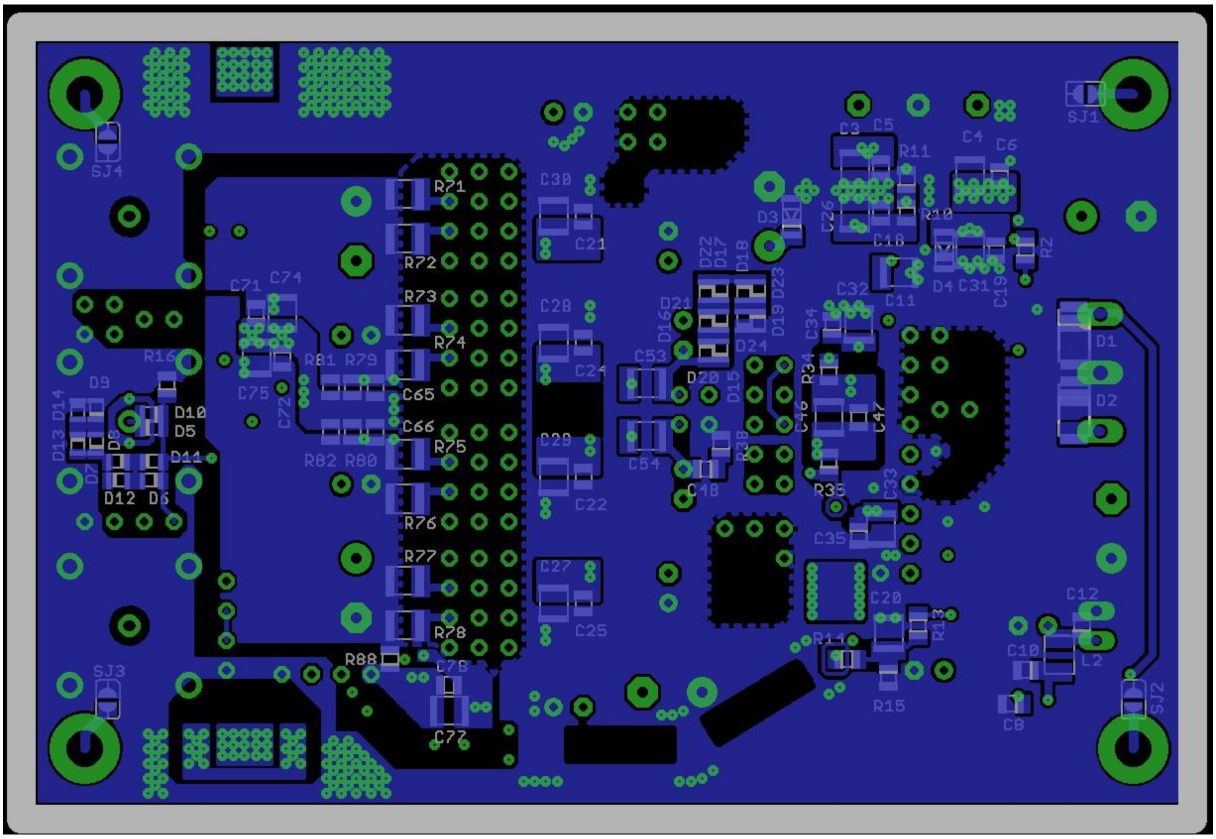

Figure 14 - Assembly - bottom side.

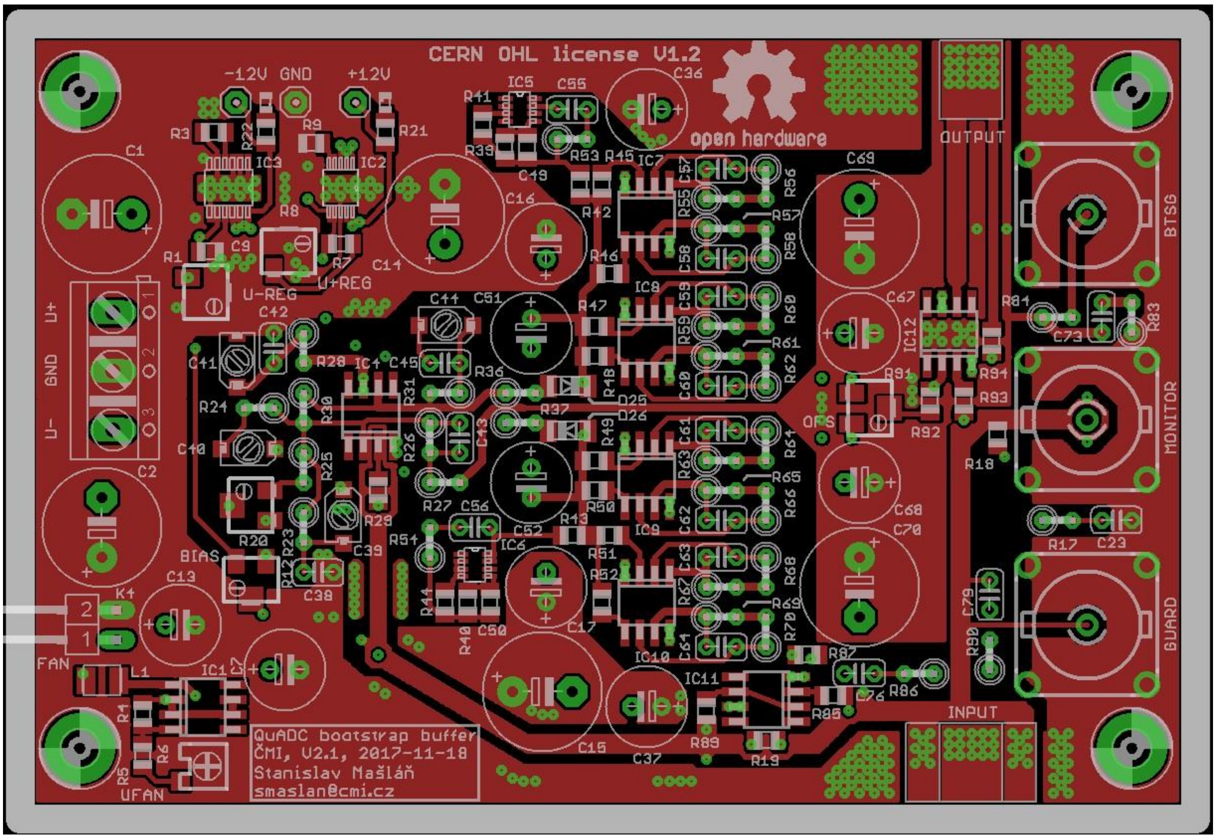

Figure 15 - Assembly - top side.