

# Modular Analog Current and Voltage Preamplifier System with State Variable Filters and Computer Control Interface

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**Abstract**—We present a versatile modular and variable preamplifier system for frequency-selective measurements of small currents and voltages. The system consists of current and voltage preamplifiers connected to state-variable filters for signal conditioning. These cards are inserted into a 19" mainframe. Via the backplane the modules are connected to a central controller module allowing the control of the amplifier and filter modules via its front-panel controls as well as via a connected computer.

**Index Terms**—preamplifier, analog state-variable filter, micro-controller, low voltage and low current measurements.

## I. INTRODUCTION

MEASURING small currents in the nano- and picoampere range as well as small voltages in the micro- and nanovolt range is challenging. While dc measurements are extremely prone to noise, frequency-selective ac measurements in lock-in technique can significantly increase the dynamic range and detect signals buried under a large noise floor. Feeding the analog measured data into the computer for acquisition and storage makes additional devices necessary. Therefore most available lock-in amplifiers already digitize the signal directly after a first pre-amplification stage and the lock-in task is implemented in a digital-signal-processing (DSP) chip that also acts as the communication interface to the computer (e.g. [1]) instead of analog circuitry for the signal detection. In multi-channel applications, where simultaneous acquisition from different sources is necessary, like Hall measurements, the space needed for the data acquisition equipment, the costs, and the time necessary to communicate with each external device at each data point increase significantly. In such an application it makes sense to use digitizer boards and implement the lock-in technique in computer-based software. With this approach the communication with external equipment can be eliminated, and rack space as well as costs can be reduced. The algorithm for the lock-in detection of signals for multiple simultaneously acquired signals has been implemented for example in LabVIEW [2]. Slightly modifying this software toolkit allows to make full use of the computing power of current parallel hardware architecture in multi-core processors and thus enables for example the use of up to 48 lock-in amplifiers on an Intel

Xeon processor-based eight-core machine [3]. The algorithm can also be implemented in field-programmable gate arrays (FPGA) if a higher level of fault tolerance, determinism, or higher sample throughput is required [4].

This approach already includes two of the four main components of the box-type lock-in amplifiers: the analog-digital conversion and the signal processing. The third component, the communication with the computer, is not necessary as the signal processing is already done in the computer. However, the fourth component, which is the pre-amplification of the signal, is still missing. Therefore pre-amplifiers for small currents and voltages are needed to make use of a software-based lock-in amplifier. Commercial pre-amplifier solutions again have the disadvantage of consuming a lot of rack space due to individual housings and can be a significant cost factor in multi-channel applications. On the other hand often inexpensive and compact, very simple straightforward textbook implementations of differential amplifiers or current-to-voltage converters expose poor noise figures. In addition advanced signal conditioning features of commercial lock-in amplifiers or pre-amplifiers like line frequency filters and variable high-, low-, or band-pass filters for improved signal quality are missing.

Therefore we developed a cost- and space-efficient preamplifier that contains the features found in commercial box devices and combines these advantages with a compact chassis for installation of up to eight preamplifiers in one 19" mainframe together with a module for manual control of all filter parameters from the front panel as well as automated control via a computer interface.

## II. SPECIFICATIONS

The preamplifier and signal conditioning module is also capable to serve in applications beyond the described scenario. This allows us to establish it as a standard module for a variety of experiments. The input stage can either amplify differential or single-ended voltage signals. It can also be switched to current-to-voltage conversion and amplification allowing the same module to be used for voltage and current detection. The input signals can either be dc or ac coupled. The input frequency range has been chosen to range from dc signals to ac signals of up to 8 kHz. This corresponds to the frequency range of the low-temperature transport measurements the module is designed for. But this range can be changed by replacing a small number of capacitors in the circuitry for added flexibility. To remove influences from the grid line filters at 50(60) Hz and 100(120) Hz allow suppression of the base frequency and its first harmonic.

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Any out-of-band noise above 20 kHz is removed by a low-pass filter after the input amplifier. By a matrix combination of two state-variable filters the signal can be high-, low-, and band-pass filtered. Also a notch filter can be formed. The maximum amplification of the signal allows an input of 100 nV to be amplified to the typical full input range of A/D converters in data acquisition cards of 10 V. For currents the minimum amplitude of the input signal that can be amplified to a full 10 V output is 10 pA. These amplifications are achieved by a combination of the input amplifiers, a second amplification stage after removing the out-of-band noise, and a final output amplification. Each of these amplification stages has switchable gain factors. In addition the state-variable filters provide a continuously tunable amplification to fine tune the signal level to perfectly match the input range of the computer-based data-acquisition system.

### III. IMPLEMENTATION

The modular systems consists of the amplifier module itself, a controller module for manual control of the amplifier modules as well as provision of a computer interface, a power supply module, and the mainframe that hosts and interconnects these modules by a backplane. We will now describe the amplifier module in detail.

#### A. Amplifier Module

The amplifier module consists of an input stage to amplify differential and single-ended voltages by two different user-selectable gain factors. It can also be switched to a current-to-voltage converter with three selectable proportional factors. From here the signal is fed to a filtering section, where ac or dc coupling can be selected, out-of-band noise is removed, and notch filters eliminate the base frequency and the first harmonic of the grid. Also additional amplification with four selectable gain factors is provided in this stage. From here the signal is fed into a group of two state-variable filters that are interconnected by a matrix switch. This allows to create of a variety of tunable filter configurations. Also variable gain amplification is provided in this stage to match the output level to the input range of the data-acquisition system. Finally the output stage decouples the signal from the amplification and filtering stages and drives the output to the data-acquisition system. The block diagram of the analog circuit is shown in Fig. 1.

To control the parameters of the analog circuit and for communication with the controller module via the backplane a digital control section on a separate printed circuit board is used. This board also contains the power supply control for the analog and digital components of the module. The block diagram of this control and power supply board is shown in Fig. 2.

1) *Input Stage:* The input stage consists of a differential amplifier for the voltage inputs A and B as well as of a current to voltage converter for the current input I. An analog allows to switch between these two input stages.

a) *Differential Amplifier:* For the differential amplifier a low noise integrated circuit with high common mode rejection and small dc offset is employed. The choice is a Linear

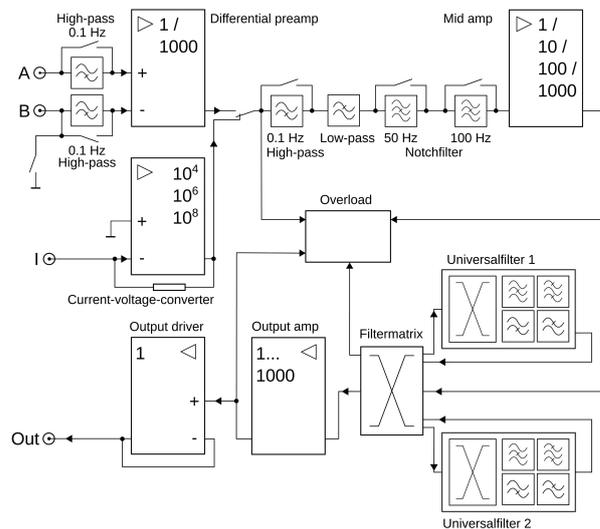


Fig. 1. Block diagram of the analog circuit of the amplifier module. The input signal is connected to port A, B, and/or I. Then the signal is fed either through the differential preamplifier or the current to voltage converter. After that ac or dc coupling is selected, out-of-band noise as well as influences from the grid reduced and second amplification conducted. The third stage consists of two stage-variable filters that are interconnected by a matrix and allow formation of a variety of tunable filter configurations. Right in front of the output driver a continuously variable gain amplification stage allows to match the output level precisely to the input range of the data-acquisition system.

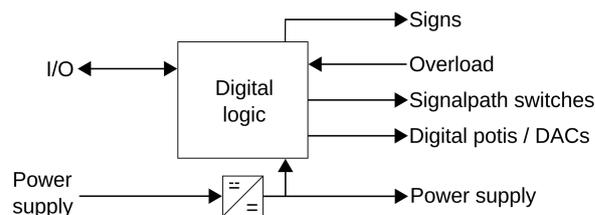


Fig. 2. Block diagram of the control and power supply regulation board. The supply lines from the power supply are received from the backplane connector and are conditioned and converted to the voltages needed on the analog board. A CPLD communicates with the controller module via a SPI protocol over the backplane and controls the switches, potentiometers, and digital-analog converters on the analog board via different protocols.

Technology LT1167 that yields an excellent weighted performance of the above mentioned three criteria for differential amplifiers with a maximum input range of  $\pm 10$  V [5]. The circuit can be found in Fig. 3. Protection against electrostatic discharge and over voltages for the inputs of the differential amplifier is provided by its internal clamp diodes as well as a set of resistors and JFET transistors in the input leads. The transistors here provide small leakage currents and lower noise levels than diodes. Also in the two input leads of the differential amplifier there are high-pass filters with a cutoff frequency of 0.1 Hz that can be switched into the signal path to switch between dc and ac coupling of the input signals. This is done by bi-stable relays. Further relays allow to reference the signals to the ground potential of the amplifier or to keep them floating. For measurements on single-ended signals input B can be connected to ground by another relays. The amplification of the LT1167 differential amplifier is set by a single external resistor. Another relays allows to switch between a  $49.45 \Omega$  resistor network corresponding to a gain of 1000 and open corresponding to a gain of 1. The offset of the differential amplifier can be controlled by a potentiometer

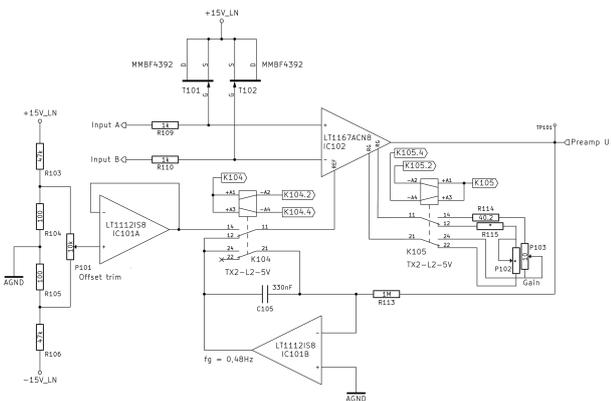


Fig. 3. Differential amplifier in the input stage for ac and dc coupled measurements of differential and single-ended voltage signals

or by an automated offset correction circuit. Here the output voltage of the differential amplifier is fed to an inverting integrator. The output of this integrator is then fed back to the offset correction input of the differential amplifier keeping its output voltage always symmetric around zero.

*b) Current To Voltage Converter:* The current-to-voltage converter consists of a low-noise AD 549 operational amplifier with very low input bias current level [6]. The circuit is shown in Fig. 4. To switch between proportional

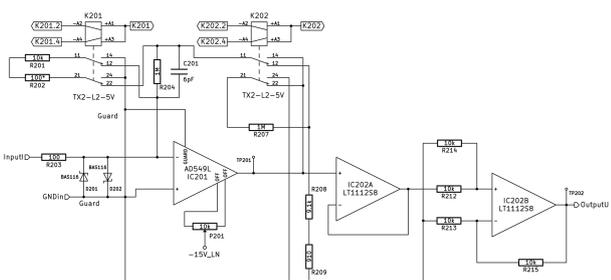


Fig. 4. Current to voltage converter circuit in the input stage.

factors of  $10^4$  V/A and  $10^6$  V/A a bi-stable relays inserts a resistor network of  $10\text{ k}\Omega$  parallel to a  $1\text{ M}\Omega$  resistor in the feedback loop of the operational amplifier. For a higher amplification with a proportional factor of  $10^8$  VA a voltage divider of 1:100 can be inserted at the end of the feedback loop. The input of the amplifier is protected against overload and electrostatic discharge by resistors and diodes in the input lead. For floating measurements the current-to-voltage converter is connected to a voltage follower and an instrumentation amplifier. There is no circuitry to switch between ac and dc coupling in the current input as the large resistors in the high-pass filter would result in large input bias currents. The selection of ac or dc coupling is therefore done in the following filter section.

*2) Preliminary Filtering:* In this section a high-pass filter with a cutoff frequency of 0.16 Hz can be inserted into the signal path to switch between ac and dc coupling. A fourth-order low-pass filter with a cutoff frequency of 20 kHz is permanently in the signal path to efficiently reject out-of-band noise without attenuating the signal in the specified measurement range up to 8 kHz. To reject influences from the grid two notch filters at the base frequency and its first harmonic complement the preliminary filtering stage. These

two notch filters are realized by subtracting the output of a narrow band-pass filters at 50/60 Hz and 100/120 Hz from the original signal. This solution provides very sharp filters with strong suppression of the two frequencies and at the same time affects the phase only in the region between the two frequencies by  $180^\circ$  shift. This circuit is shown in Fig. 5. The amplification stage at the end of this section

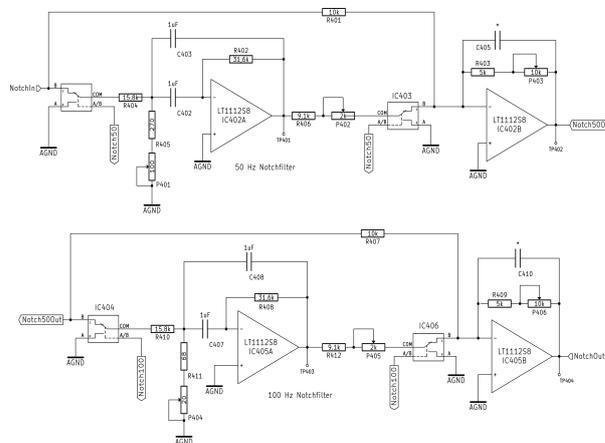


Fig. 5. Preliminary filter stage including switchable ac and dc coupling, 20 kHz out-of-band noise rejection filter, two notch filters for rejection of the grid frequency and its first harmonic, and the user-selectable gain amplifier

allows to select between four different gain factor (1, 10, 100, 1000) by analog switches connecting different combinations of resistors to form the voltage divider in the feedback loop of the instrumentation amplifier as can be seen in the circuit in Fig. 6.

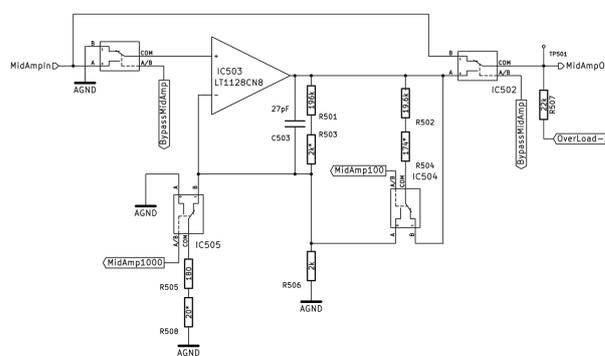


Fig. 6. Switchable gain amplifier at the end of the preliminary filter section.

*3) Universal Filter Matrix:* The main part that makes this module unique compared to traditional preamplifiers is the integrated universal filter matrix section. After the switchable gain amplifier of the preliminary filtering section the signal is fed to two state-variable filters that are interconnected via a matrix allowing different filter types to be created from the two filters.

*a) State Variable Filter:* The state variable filter is based on [7] and the basic circuit is shown in Fig. 7. We replaced the analog potentiometer that controls the amplification (R2) by an AD5293 10-bit digital potentiometer [8]. This allows amplifications from 0.5 to 1.5 in steps of 0.01. This fine tunable amplification has been chosen to allow perfect matching of the output signal to the input range of the data-acquisition system. To set the Q-factor

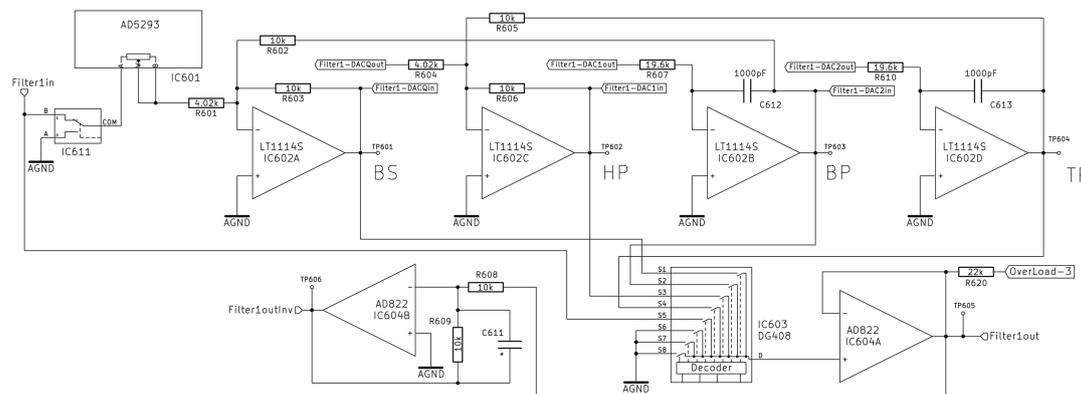


Fig. 8. State variable filter with digitally controllable amplification, Q-factor, and frequency. The additional inverter after the output selector matrix is omitted in the second filter as it is not needed there.

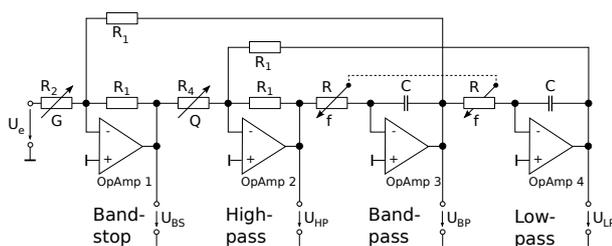


Fig. 7. Basic circuit of a state variable filter [7]

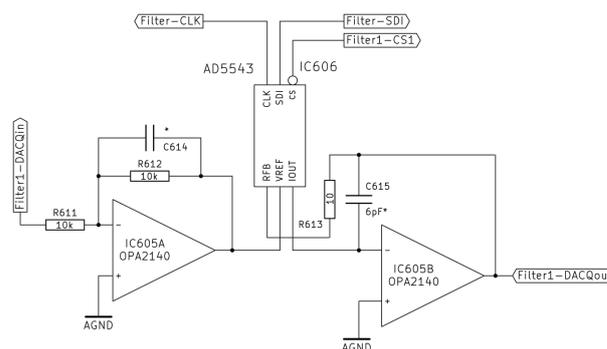


Fig. 9. Circuit for one of the digital-analog converters acting as digitally controllable variable resistors in the state-variable filters.

and the frequency of the filter AD5543 16-bit digital-analog converters replace the potentiometers R and R4 [9]. The Q-factor can thereby precisely be tune between 0.4 and 400. The cut-off / resonance frequency of the filter can be set in steps of 125 mHz from dc to 8120 Hz. This suits the frequency range of our measurements very well. For different applications the frequency range can be adapted by changing just two capacitors. The circuit of the digitally controllable state variable filters is shown in Fig. 8. The digital-analog converters output a current proportional to the reference voltage (i.e. in this case, where they are used as digital potentiometers: the input signal) and the digitally set resistance of the internal resistor network. Therefore the input current has to be inverted converted to a voltage. Our solution with an external current-to-voltage converter has the advantage over digital-analog converters with integrated current-to-voltage converters that the operational amplifier for this task can be chosen from a variety of available components. Thereby a component that matches the requirements of the application – in this case: low noise levels and small offsets – can be employed and higher signal quality than with integrated solutions is achieved. The circuit for the digital-analog converters acting as a digitally controllable resistors is displayed in Fig. 9. The filter outputs four different signals simultaneously: a high-pass, a low-pass, and a band-pass filtered signal as well as a notch-filtered signal. These four signals as well as the original signal are fed to multiplexer allowing the selection of any of these four filtered signals or the original signal as the output of the filter stage. To allow inverted and non-inverted combinations of the two state-variable filters the first filter is also equipped with an inverted output.

b) Matrix: The two state-variable filters are connected by a dual 1:4 analog switch multiplexer that allows the

creation of different filter combinations. The circuit is shown in Fig. 10. This section also includes a high-pass filter to remove any dc offset acquired in the state variable filters. An offset correction inside the filters is hard to achieve as manual potentiometers could only be set for one given status of the digital-analog converters that are the main offset source. Therefore the offset correction after the filter represents the most efficient way to obtain a pure ac signal. If a dc measurement is conducted a digital potentiometer in the final impedance converter can be used to tune the offset corresponding to the settings of the potentiometers and digital-analog converters according to a calibration table. The matrix allows the combinations of the two state-variable filters shown in Fig. 11. By setting appropriate filter param-

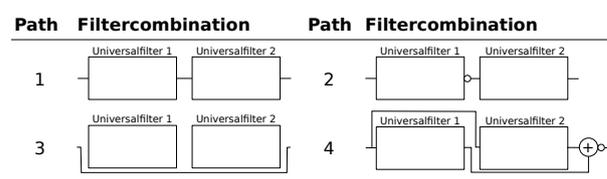


Fig. 11. Overview of the possible combinations of the two state-variable filters by the interconnection matrix.

ters and choosing the corresponding interconnection from the matrix (configuration 1) it is possible to create for example narrow band-pass filter of fourth order by cascading both filters with the same resonance frequency. For application requiring a certain bandwidth of signals but at the same time good suppression of any out-of-band noise the two filters

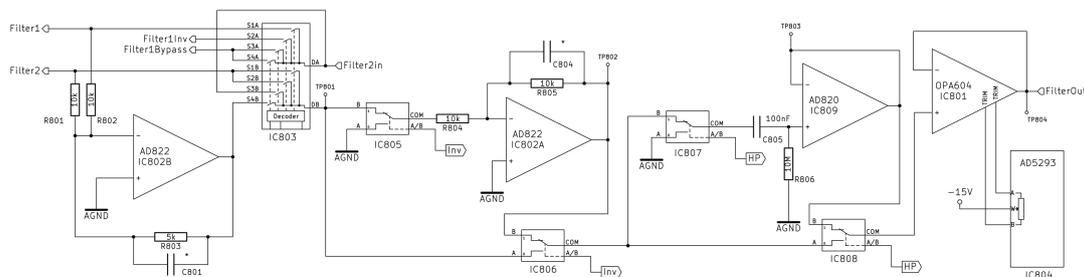


Fig. 10. Matrix circuit connecting the two state-variable filters by a dual 1:4 multiplexer and providing additional offset adjustment.

can also be configured as a cascade of one high- and one low-pass. For detection of a base frequency and at the same time one of the harmonics the two filters can be configured as band-pass filters at the corresponding frequencies and by summing the signals (matrix configuration 4) the combined output is created. If the filter shall be disabled the whole section can be bypassed in matrix configuration 3.

4) *Output Stage:* In the final stage the signal can be amplified by a variable digitally selectable gain factor in an instrumentation amplifier. The gain is set by the ratio of a fix resistor and a digital potentiometer allowing gain factors of 2-102 or 11-1011. To switch between the two different ranges an analog switch can insert another resistor in parallel to the fixed resistor of the gain determining circuit. To obtain amplifications of 1 this amplifier is set to 2 and the amplification of the state-variable filters is set to 0.5. A voltage follower with an output driver creates the output of the circuit and feeds the signal to the output plug of the amplifier. The output impedance is 50 Ω and the maximum current that the output can provide is 250 mA.

5) *Digital Control:* The pre-amplifier and filter modules is controlled by a CPLD. The analog switches used in the different stages are controlled by switching their digital input from 0 V to 3 V. These signals are provided directly from the digital outputs of the CPLD. For the bi-stable relays short pulses of 5 V with higher power are needed. The power is provided by driver-ICs that receive the pulses from a mono flop connected to the CPLD. The digital potentiometers and the digital-analog converters are controlled via the serial SPI protocol. The protocol is provided by the controller module and is handed on the the devices by the CPLD. As both types of receiving chips (potentiometers and digital-analog converters) use different variants of the SPI-protocol with respect to the Clock Phase (CPHA) the protocol setting are changed in the controller module depending on the type of the receiving component. The overload control circuits report their status to digital I/O ports of the CPLD. They are connected to pull-up resistors to keep them in a high state until the overload detection pulls the port down to the low state.

The communication with the controller module is also realized via a SPI-based bus-system over the backplane connector. Multiple modules can be connected to the same controller module. To distinctively communicate with a single amplifier each module is equipped with a chip-select line that allows the activation of communication input of the module.

6) *Power Supply:* The different parts of the module need different power supplies: the operational and differential amplifiers are supplied with ±15 V. The relays are controlled

with +5 V and the digital potentiometers, digital-analog converters as well as the CPLD are supplied with +3.3 V. These four voltages are generated from the ±18 V and +8 V input voltages. The ±15 V voltages are provided by feeding the ±18 V through voltage regulators. For the differential amplifier and the current-to-voltage converter in the input stage a separate ±15 V supply with additional stabilization and filtering is employed. The +5 V supply is generated by a voltage regulator from the +8 V input and the +3.3 V supply is generated by another cascaded voltage regulator form the +5 V supply.

#### B. Controller, Power Supply, and Mainframe

Multiple preamplifier modules can be integrated in one 19" rack housing. The modules are connected to a backplane acting as a power supply and data and control distribution. Besides a common data and control bus using the SPI protocol, each slot is assigned a distinct digital module select line to allow individual module selection. They all share the same power supply lines for ±18 V and +8 V. The power supply module can be chosen to be a single power supply or a redundant module to higher fault tolerance. In addition a battery module is in preparation. This module will consist of two independent, redundant battery supplies for the preamplifiers. While one module is charged and disconnected from the preamplifiers the other one is disconnected from the mains and powers the preamplifiers. By this power supply scheme we are able to ensure continuous operation in contrast to common battery powered systems that have limited run times due to the battery capacity limitations. At the same time we can make use of the advantage of significantly reduced noise in battery powered operation due to the disconnection from the mains supply.

The different preamplifier modules in one rack are all controlled by a micro-controller driven control module in the left-most slot. This module provides a LCD-Display to show the system status as well as to navigate through and change the settings of the preamplifiers. The user input is done via a turn-and-push button and system settings are stored in non-volatile memory to save the settings also, when the system is powered down. Besides this local manual control the controller module also features a USB-connection to a host computer. Here, more convenient control of the preamplifier settings as well as status monitoring is available through a collection of LabVIEW procedures.

#### IV. CIRCUIT BOARD DESIGN

The module consist of two separate printed circuit boards: one for the analog circuit and one for the digital controller.

The latter one also contains the power supply conditioning. This guarantees farthest possible separation of the analog lines from the digital signal paths that could introduce noise. To further reduce the influence of the digital lines on the analog signals the digital protocol has been chosen in such a way that digital signals are only present while a change in the settings is executed. After that all digital signals on the analog board are shut down. In addition all analog signals are routed on one side of the double layer board. The power supply and digital lines are routed on the backside. A similar separation is done for the digital board: Here the digital signals are routed on one side and the power supplies are on the other side.

For shielding purposes all free areas on the boards are filled with grounded guard plates. Special attention has been paid to put guard shielding around the input current-to-voltage converter and its input line following the guidelines in [6]. The two boards mounted on each other are then inserted into a shield cassette that allows mounting in a 19" mainframe. It provides openings for the backplane connector on the back as well as for the BNC connectors on the front for the two differential voltage inputs, the current input as well as the output of the amplifier. There are also outlets for status LEDs.

## V. PERFORMANCE

By choosing extreme low-noise components we reach calculated input noise levels of  $9.6 \text{ nV}/\sqrt{\text{Hz}}$  at a bandwidth of 12 kHz for the differential preamplifier with a gain of 1000. This corresponds to a noise voltage of 1.1 mV at the amplifiers output and is more than a factor of two better than the noise voltage of the previously used commercial lock-in amplifier [1]. With a current input noise of  $134 \text{ fA}/\sqrt{\text{Hz}}$  at 1 kHz for a proportional gain of  $10^6 \text{ V/A}$  we reach the same noise level as [1]. The plots of amplitude and phase versus frequency in Fig. 12 show the almost linear frequency response of the preamplifier in the low-frequency regime with the two sharp and deep notch filters at 50 Hz and 100 Hz inserted into the signal path. In Fig. 13 one of

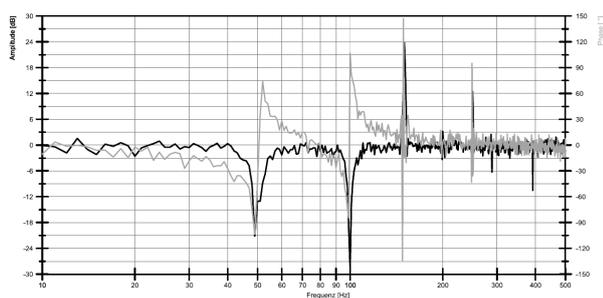


Fig. 12. Frequency response of the preamplifier with the two notch filters inserted into the signal path for a single-ended input voltage of 100 nV and a total gain of  $10^5$ .

the universal state-variable filters has been inserted into the signal path with a center frequency of 1 kHz and a Q-factor of 25. At the same time the overall gain has been increased to  $10^7$  corresponding to an output voltage of 1 V for the unchanged single-ended input voltage of 100 nV.

## VI. CONCLUSION

We developed a universal preamplifier module for a wide variety of applications in measurements of small currents

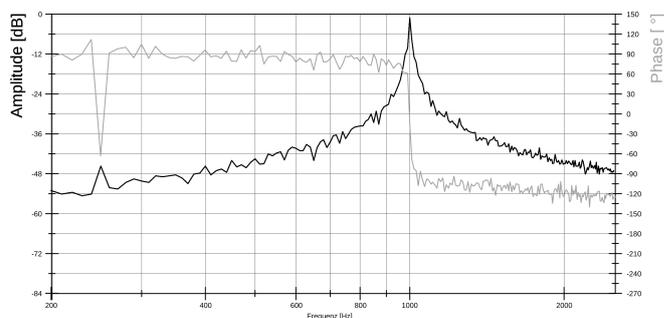


Fig. 13. Frequency response of the preamplifier with one state-variable filter configured as a narrow band pass at 1 kHz with a Q factor of 25.

and voltages. The module exhibits excellent noise figures comparable to or better than typical industrial products. Due to its flexibility allowing single-ended and differential voltage signals as well as currents as input the same module can be used in different situations leading to standardization in the laboratory. The versatile signal conditioning features including line filters and, most importantly, the matrix of two state-variable filters, allow very small signals to be fed to commonly used data-acquisition systems that rely on analog-digital conversion of  $\pm 10 \text{ V}$  signals with maximum usage of their input range. The ability to combine several modules in one rack enclosure supports multi-channel applications that become more and more important in experiments that become more and more complex. At the same time the flexible choice of the number of modules and the central chassis, power supply, and controller module help to reduce the costs for experimental setups significantly. The ease of control via either the central controller module's front panel or a PC via a standardized LabVIEW driver allows convenient integration in existing measurement setups.

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