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DEVELOPMENT OF A WIDE DYNAMIC RANGE AND HIGH-PRECISION AMMETER FOR BEAMLINE INSTRUMENTATION AT SIRIUS

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Abstract

SIRIUS beamlines require specialized electronic devices to monitor key parameters of the photon beam, such as position and flux, through the detection of extremely low-level electrical currents. Furthermore, experiments conducted in on-the-fly scan mode usually demand fast, high-precision low-level current measurements. To address these requirements, the development of a wide dynamic range ammeter (from 1 pA to 10 mA) has been addressed, based on a logarithmic transimpedance amplifier, eliminating the need for scale switching and featuring high precision and fast response. The proposed device converts the input current into a logarithmic output voltage and offers two operation modes: the logarithmic ammeter and the logarithmic ratiometer, both of which are particularly useful in X-ray spectroscopy experiments. This paper considers an overview of the device as well as its preliminary characterization and results, including logarithmic conformity, bandwidth, and noise.

INTRODUCTION

X-ray beam diagnostics often rely on measuring the photocurrents generated by photodiodes or ionization chamber [1]. During commissioning or experiment preparation, such as beam alignment and focusing, the photocurrent may vary over several orders of magnitude. Conventional ammeters are limited in these conditions, as range switching slows data acquisition and degrades the signal-to-noise ratio [2]. Similarly, synchrotron-based techniques such as X-ray absorption spectroscopy require instrumentation with fast response, wide dynamic range and the capability to compute logarithmic ratios [3]. This work aims to describe a compact logarithmic transimpedance amplifier(Log-TIA) developed to address challenges in experiments and diagnostics on the SIRIUS beamlines.

LOGARITHMIC TRANSIMPEDANCE AMPLIFIER

The proposed device is based on the ADL5304 [4], the State Of The Art Logarithmic Transimpedance Amplifier from Analog Devices, chosen for its capability of producing a logarithmic voltage response to input currents from 1 pA to 10 mA. Moreover, the ADL5304 features high-speed operation, adaptive biasing for photodiode inputs, two current inputs, enabling logarithmic ratio measurements, and a high-precision 100 nA current source for operation as a logarithmic ammeter.

Building upon these features, a logarithmic ammeter/ratiometer was developed, where the operating mode is selected via high-insulation relays controlled by external digital inputs. Furthermore, an auxiliary circuit was implemented to enable current inversion in one of the input channels, thereby extending the measurement capability to negative currents and overcoming a common limitation of conventional logarithmic amplifier.

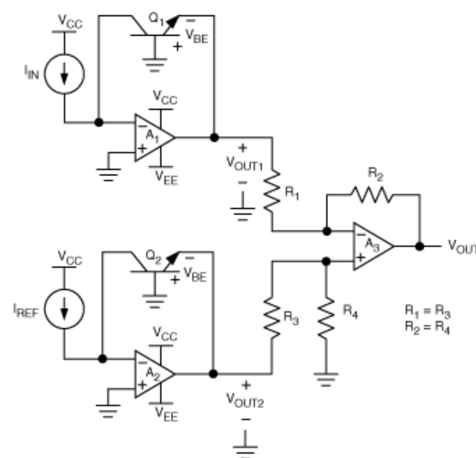

Figure 1: Conventional topology of Log-TIA [5].

Working Principle

The conventional implementation of logarithmic amplifier relies on inserting a bipolar junction transistor into the feedback loop of an operational amplifier [6] as shown in Fig. 1. This circuit exploits the exponential relationship of V_{BE} and I_C shown in Eq. (1).

$$V_{BE} = V_T \log\left(\frac{I_C}{I_S}\right), \tag{1}$$

where V_T is the thermal voltage, equal to 26 mV at $T = 25\,^{\circ}\mathrm{C}$ and increasing with temperature. The saturation current I_S is highly sensitive to temperature and also depends on fabrication processes.

To mitigate these variations in the circuit response, a robust approach is to add a second logarithmic amplifier, where both transistors are matched and kept in thermal equilibrium. The output voltages of the two amplifiers are then subtracted, effectively canceling the influence of I_S, resulting in the fundamental relationship of logarithmic ammeter as shown in Eq. (2).

$$\Delta V_{BE} = V_T \log\left(\frac{I_{C_1}}{I_{C_2}}\right). \tag{2}$$

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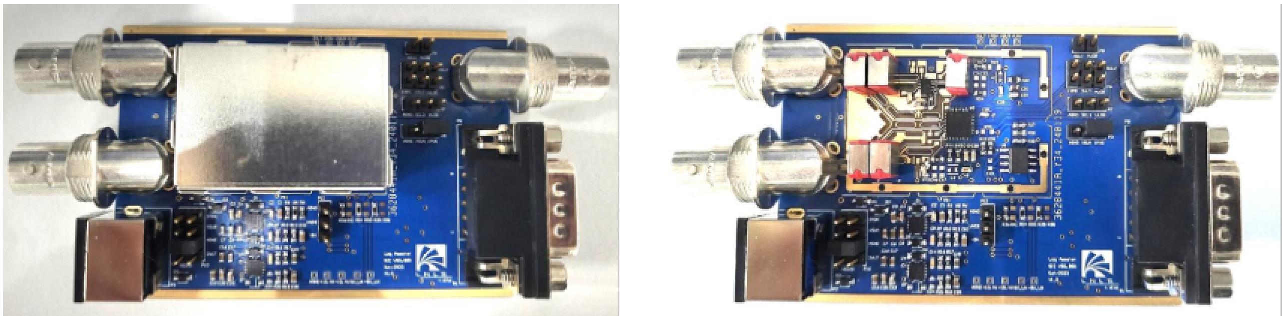

Figure 2: Developed logarithmic ammeter/ratiometer.

Negative Input Current

Due to the presence of a NPN transistor in the feedback loop of the Log-TIA, the input is restricted to sensing positive currents only, which limits its applicability and compatibility with diagnostic tools employed in beamlines. To extend the capability to measure negative input currents, a high-precision current mirror ADL5315 from Analog Devices was employed to invert the input current polarity. For positive input currents, the current bypasses the ADL5315.

The ADL5315 is specified for a current range from 3 nA to 3 mA, with a relative error that is nearly zero within this range. Manufacturer tests, however, demonstrate reliable operation down to 10 pA, where the relative error does not exceed 5 %. Furthermore, the ADL5315 does not significantly degrade the noise performance of the Log-TIA, and its effect on the frequency response is minimal [7].

PCB Design Considerations

Current-input devices are highly susceptible to noise, especially in high-bandwidth applications where filtering cannot be applied. The lowest current levels are easily affected by stray magnetic fields resulting measurement errors. To handle this, the Log-TIA circuitry was separated from the power supply and digital circuitry and enclosed within a high-permeability shield, as shown in Fig. 2.

Another challenge in low-level current measurement circuits is leakage current at the input, which can become a significant source of error. To reduce these effects, all sources of parasitc capacitance in input stage as the solder mask, were removed as shown in Fig. 2. Another approach adopted was to clean the PCB to remove residual flux and dust, which can increase leakage. The board was cleaned with isopropyl alcohol and baked at a low temperature to minimize humidity. Furthermore, the Log-TIA circuitry is surrounded by a guard actively driven by ADL5304, effectively suppressing leakage through the dielectric.

CHARACTERIZATION AND RESULTS

Logarithmic Conformity

To evaluate the logarithmic conformity of the developed ammeter, the characteristic curve was obtained across its entire dynamic range. Input current setpoints, ranging from 1 pA to 1 mA, were generated using a voltage source (Keithley 2280S-32-6) in series with precision resistors (0.1 % tolerance, 50 ppm/°C temperature coefficient). The corresponding output voltages were measured with a precision multimeter (Keysight 34465A). Prior to the measurements, the input current setpoints were calibrated using a high-resolution ammeter (Keysight B2981A) to ensure accuracy. The ammeter was designed to provide a voltage response ranging from -5 V to 5 V over its full dynamic range, as described by Eq. (3).

$$V_{LOG} = \log_{10}\left(\frac{I}{100\,nA}\right). \tag{3}$$

The resulting transfer function is shown in Fig. 3 as the blue curve, demonstrating the highly accurate logarithmic behavior, with a correlation coefficient of 0.9999 and a RMSE of 0.0085. The red curve illustrates the relative deviation of the measured current with respect to the calibration equation. The mean error is 2.45 %, while in the worst case, for an input current of 1 pA the relative error increased to 10 %.

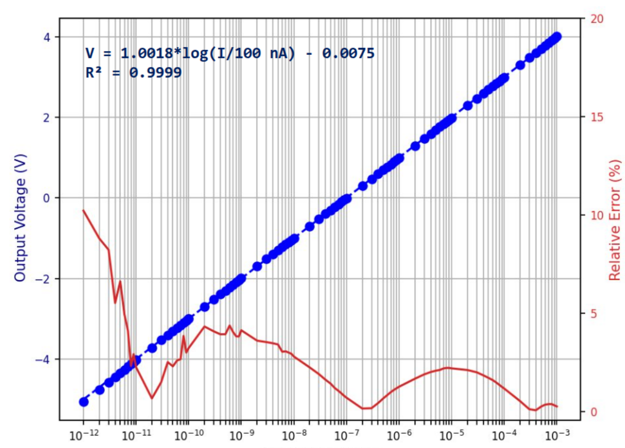

Figure 3: Characteristic curve of logarithmic ammeter.

Bandwidth

The bandwidth of a Log-TIA has two determinant factors, the junction capacitances and the effective emitter resistance,

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r_e in feedback loop transistors. These elements form a low-pass filter, with a cutoff frequency that can be approximated by Eq. (4).

$$f_{-3dB} = \frac{I_C}{2\pi V_T C_J}, \tag{4}$$

where C_J denotes the effective junction capacitance. The equation indicates a proportionality between bandwidth and the transistor collector current I_C.

To characterize the frequency response of the developed ammeter, a vector network analyzer (Keysight E5061B) was used to measure the S_{21} scattering parameter over a frequency range from 5 Hz to 50 MHz. The bandwidth was determined indirectly by normalizing the S_{21} parameter and applying the -3 dB criterion. To evaluate the maximum frequency response performance, all filtering capacitances were removed.

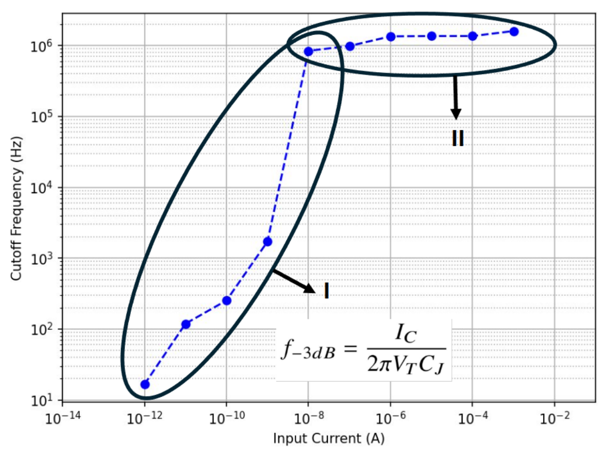

Figure 4: Cutoff frequency of the Log-TIA.

Figure 4 shows the cutoff frequency in the full dynamic range of the ammeter. The highlighted region I corresponds to input currents from 1 pA to 10 nA, where the behavior is governed by Eq. (4). In region II, for input currents above 10 nA, the cutoff frequency reaches a maximum value constrained by the gain–bandwidth product of the output-stage op-amp.

Noise

The noise is primarily determinated by shot noise, which depends on I_C. At low input currents, the output noise increases due the high small-signal gain.

To optimize low-frequency measurements, additional filtering was applied, and the device was characterized in logarithmic ratiometer mode, using the same signal on both inputs. The output noise voltage was measured with a 32-bit sigma-delta ADC (AD7177, Analog Devices).

Figure 5 shows the noise spectral density of Log-TIA for different values for input currents. For input currents above 10 µA, the noise is mainly limited by the input noise propagated to the output. For input currents below 1 µA, the noise increases as the current decreases. Table 1 shows the RMS noise over a range of input currents from 10 pA to 1 mA.

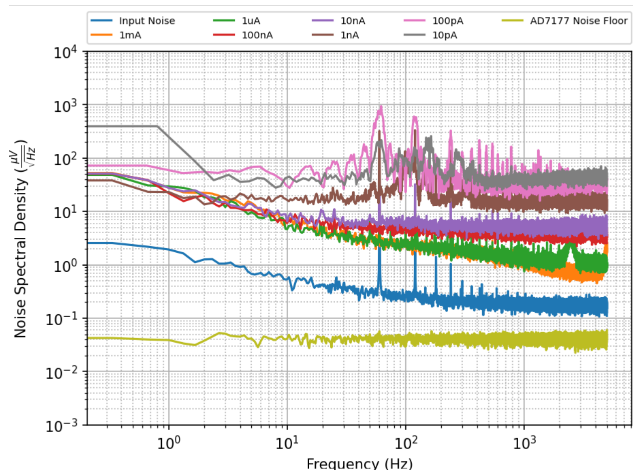

Figure 5: Noise spectral density for proposed log ammeter circuitry.

Table 1: 0.5 Hz to 5 kHz RMS Noise

Input Current	RMS Noise	Input Current	RMS Noise
10 pA	8.11 mV	100 nA	290.36 µV
100 pA	4.27 mV	1 µA	146.96 µV
1 nA	1.35 mV	10 µA	114.54 µV
10 nA	392.28 µV	100 µA	110.98 µV
		1 mA	112.77 µV

CONCLUSIONS

A wide dynamic range ammeter is proposed in this work to monitor key parameters and improve the experimental setup in the SIRIUS beamlines. It is based on a state-of-the-art logarithmic transimpedance amplifier that eliminates the need for scale switching and computes the logarithmic ratio directly in analog hardware. The characterization procedures demonstrate highly accurate logarithmic behavior across the entire dynamic range, a wide frequency response with a 1 MHz bandwidth for input currents above 10 nA, and low noise. For input currents above 10 µA, the RMS noise remains around 110 µV within a 0.5 Hz–5 kHz bandwidth, while for currents below 1 µA, the noise increases reaching 8.11 mV RMS at 10 pA. Further measurements will be conducted demonstrate its applicability to real experimental in a SIRIUS beamline, with one candidate being the XMCD experiment at the EMA beamline.

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