Design and implementation of a trans-impedance amplifier for a miniaturized saturated absorption spectrometer

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***Abstract*—This paper presents the design, manufacture, and testing of a trans-impedance amplifier for a miniaturized saturated absorption spectrometer. The amplifier has a bandwidth of 32 kHz, a dc gain of 80.3 dB-Ohm, and an output voltage swing of 4.84 V_{pp}. The device can handle an input optical power up to 800 μW, where the photodetection electronics have a Noise Equivalent Power of 0.3 pW/$\sqrt{Hz}$. The circuit board has a size of 27 x 27 mm^2. Signals acquired with our miniaturized device perfectly match those recorded with a commercial table-top optical setup.**

I. Introduction

The trans-impedance amplifier is a building block of several electronic systems. For example, as the analog front-end of many biomedical applications such as 1) cuffless blood pressure monitoring based on photo-plethysmogram, 2) near-infrared spectroscopy, 3) pulse oximetry, or 4) noninvasive blood glucose measuring [1]. Likewise, many of today's communication systems include this block [2]. Moreover, laser sources integrated into miniaturized devices such as atomic clocks, magnetometers, or gyroscopes, are typically locked to an atomic transition to achieve good frequency stability [3]. Most approaches to stabilize a laser source, to an atomic transition, use a saturated absorption spectrometer (SAS) [4]. SAS, like many other laser spectroscopy techniques, requires a trans-impedance amplifier.

[5] introduced a miniaturized SAS setup, where an atomic vapor confined in a novel miniaturized cell containing rubidium atomic vapor was used, and an equally novel spectroscopy setup was developed, both enabling device miniaturization and robustness. Conceived as a measurement instrument, this device should drain as least as possible optical power from the physical system to measure. In consequence the optical power to be detected should be very small, as well as the amplitude of the corresponding electrical signals. Therefore, a small-size low-noise trans-impedance amplifier was required. This paper reports such development.

[5] comprises the amplifier and a heater of the cell as electrical components, and other additional optical components (see Fig. 1). All these components were integrated into a small metal case, so the amplifier circuit had to be: small in its footprint, able to be powered from batteries, and fulfill specific component placement requirements (i.e. photo-diode positioning). Next are listed the main specifications of the circuit.

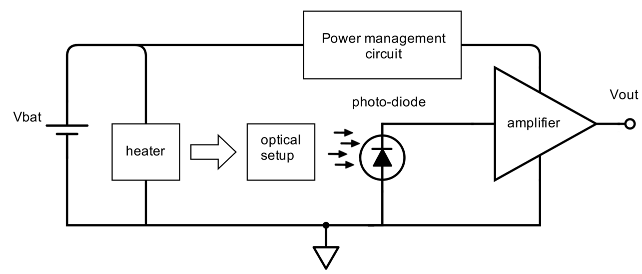

Fig. 1. Miniaturized saturated absorption spectrometer.

- Photosensitive area $\geq$ 0.81 mm^2.
- Wavelength range $\simeq$ 780-800 nm.
- Bandwidth $\simeq$ 30 kHz.
- Responsivity $\geq$ 0.6 A/W.
- Optical power on photo-detector $\leq$ 200 μW.
- Total printed circuit board (PCB) size less than 30 x 30 mm^2.
- Only one power supply to the electronic circuit, including amplifier and heater.

Due to the portable nature of the device, low current consumption was also considered when designing the circuit.

II. Proposed solution

Our solution (see Fig. 2) consists of a photo-diode that converts incident light into current, and a trans-impedance amplifier, that converts this current into voltage [6]. The amplifier's passband gain is given by Eq. 1.

$$V_{OUT} = R_2 I_{D1} \quad (1)$$

where I_{D1} is the reverse current by photo-diode D1.

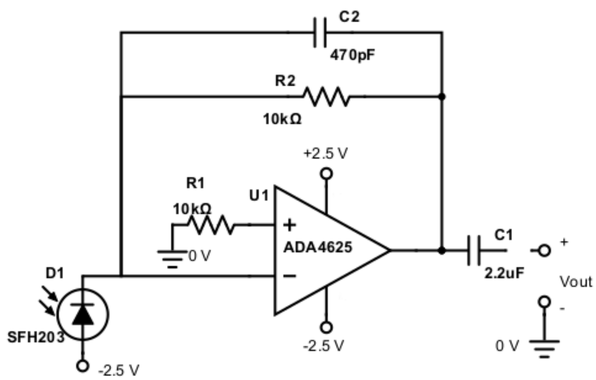

Fig. 2. Amplifier schematic.

Given that the maximum optical power is 200 μW, and the responsivity is 0.6 A/W, then the maximum I_{D1} will be 120 μA. Therefore, the value of the feedback resistor R_2 was set to 10 kΩ, to provide a gain of 80 dB-Ohm. In this case, the amplifier output voltage swing has to be equal or greater than 1.2 V. Resistor R_1, of the same value of R_2, was placed on the operational amplifier's non-inverting input to decrease the effect of the bias current. To ensure circuit stability, and to set the system's bandwidth, a feedback capacitor C_2 was put in parallel with the feedback resistor. The value of C_2 can be obtained from Eq. 2.

$$f_{-3dB} = \frac{1}{2\pi R_2 C_2} \tag{2}$$

where R_2 is the feedback resistor's value, and f_{-3dB} is the system's cutoff frequency.

Two additional components were included in the circuit. Firstly, a voltage regulator to reduce power supply interference and ripple, and allow for a wider power supply voltage range. Secondly, a virtual ground generator or "rail-splitter" that provides a positive and negative supply voltage, and a virtual ground in the middle point of these supplies sources.

Given the low power of the optical signals to be detected by the photo-diode, electromagnetic filters were used, to lessen electromagnetic interference beyond the circuit's cutoff frequency.

A. System components

The SFH203 photo-diode from Osram was chosen, as its responsitivity, photosensitive area, and wavelength match those listed in Section II. Through-hole packaging was chosen because the leads could be used to set the height of the photo-diode, and thus adjust it to the device's mechanical design.

The ADA4625 operational amplifier from Analog Devices was adopted. It was chosen for its low noise, low offset voltage, and low input bias current.

In order to supply the operational amplifier with both a positive and negative voltage rail, a virtual ground generator was used (TLE2426 Rail Splitter from Texas Instruments). This chip can generate a virtual ground whose value is always equal to one half of the input voltage, and it can range from 4 V to 40 V while sinking and sourcing up to 20 mA.

The Microchip MCP1801 voltage regulator was chosen due to its low dropout voltage, high power supply rejection ratio (PSRR), and input voltage range of up to 10 V.

The schematic of the amplifier is presented in Fig. 2, and the schematic of the power-management circuit, which includes voltage regulation, noise filtering, and voltage rail splitting, is presented in Fig. 3.

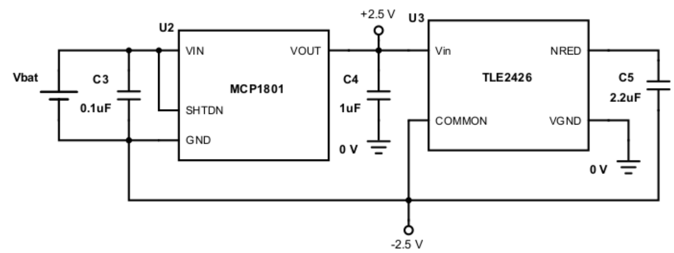

Fig. 3. Power-management circuit.

B. PCB layout

The final PCB is 27 x 27 mm^2 with a 3 x 3 mm^2 keep-out area in the corners, to avoid contact from the PCB ground plane to the metal of the case. The photo-diode was located on the bottom side of the PCB according to the mechanical design specification (see Section II-C). The final board layout can be seen in Fig. 4.

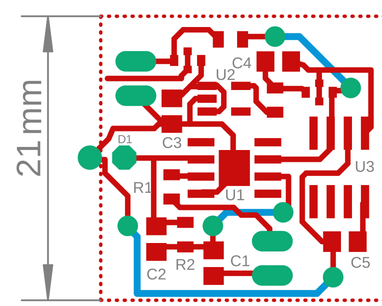

Fig. 4. PCB layout (top view): top layer in red, bottom layer in blue, pads and vias in green.

C. Mechanical design of the case

The optical setup used in this device, and reported in [5], has the advantage that it does not require any alignment to obtain a spectrum signal similar to the one obtained in a carefully aligned SAS. Therefore the mechanical setup does not have stringent requirements in machining precision. The light is delivered to the device through a polarizing maintaining optical fiber, and is collimated by a fiber coupler fixed to the device. The device container (shown in Fig. 5) was machined to hold in place a polarizing beam-splitter, the cell in its heater, and the PCB, onto which the photo-detector was soldered. Other optical components like a quarter-wave-plate and a retro-reflecting element, that are simply glued to the container, do not require careful positioning.

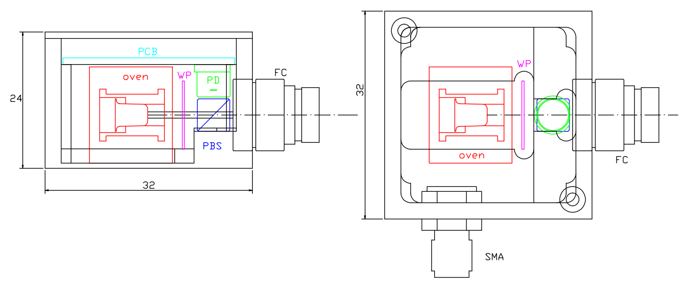

Fig. 5. Case mechanical design: top view (right) and side view (left). Different components are marked in colour: fiber coupler (FC) in black, polarized beam-splitter (PBS) in blue, quarter-wave-plate (WP) in pink, photo-diode (PD) in green, PCB in light-blue, SMA connector in black, and the heater in red.

D. Power consumption

Table I presents a worst-case estimation of the power consumption of the device, considering a supply voltage of 6 V. The total power consumption of the device is 375 mW where the heater represents more than 93 %.

TABLE I
POWER CONSUMPTION (MAXIMUM)

Component	Model	Power consumption	
Voltage Regulator	MCP1801	4.2 mW	1.1 %
Rail Splitter	TLE2426	0.9 mW	0.2 %
Operational Amplifier	ADA4625	19.5 mW	5.2 %
Photo-diode	SFH203	0.3 mW	0.1 %
Heater	-	350.0 mW	93.4 %

III. RESULTS

A. Testbench results

A custom-designed board to perform the frequency response characterization of the amplifier was developed. In this board, an HP 3245-A Universal Source replaces the photo-diode, a Tektronix PS280 provides a dc supply voltage of 6 V (the minimum value supported by the power-management circuit), and a Tektronix TDS1001B digital oscilloscope acquires the output voltage (see Fig. 6). Testbench measurements were made with a peak-to-peak input current of 120 μA and a frequency ranging from 10 Hz to 100 kHz.

Fig. 7 presents simulations results of the amplifier's frequency response along with experimental measurements. As can be observed, the measured performance of the amplifier is very similar to the expected one. The cutoff frequency is 32 kHz, and the simulated one is 34 kHz. The dc gain value is 80.3 dB-Ohm, almost equal to the expected value of 80 dB-Ohm. Finally, the obtained output voltage swing was 4.84 V peak-to-peak, slightly lower than the theoretical value of 5 V,

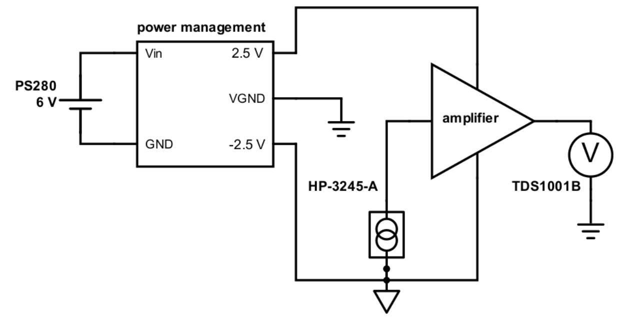

Fig. 6. Experimental setup.

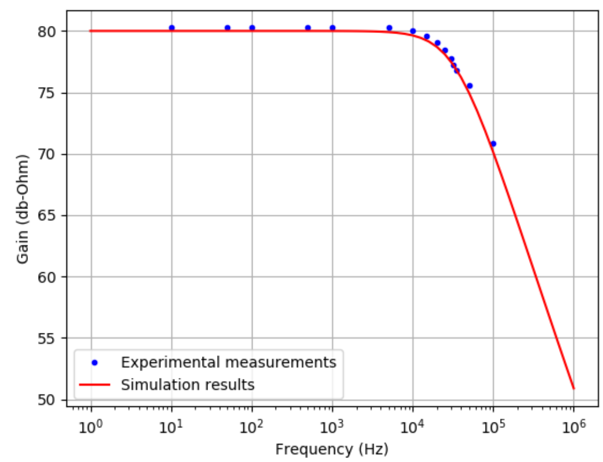

Fig. 7. Frequency response of the amplifier.

but large enough to accommodate an input optical power of 200 μW.

The achieved output voltage swing can accommodate an input optical power of up to 800 μW. On the other hand, the measured Noise Equivalent Power (NEP) of photodetection electronics is 0.3 pW/$\sqrt{Hz}$.

B. Experimental results

The completed system can be observed in Figs. 8 and 9. Fig. 10 shows the SAS spectrum measured directly at the oscilloscope. The lower blue trace shows the saturated absorption spectrum in the ^{85}Rb(5S$_{1/2}$ (F=3) $\rightarrow$ 5P$_{1/2}$ (F=2,3)) transition from our device, while the upper yellow trace shows a reference signal from an optimized table-top setup (the device spectrum appears as a frequency derivative due to the output capacity used to eliminate an offset (see Fig. 2). Both spectra show the same resonances widths as well as a similar signal-to-noise ratio.

C. Comparison with prior work

Table II compares the performance of our design with some prior designs. The width of the spectra, characterized by the Full Width Half Maximum (FWHM), evaluates how

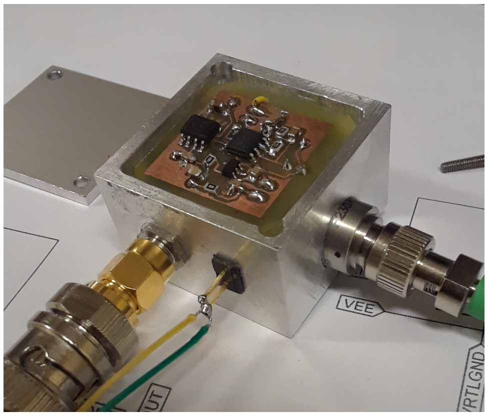

Fig. 8. Miniaturized saturated absorption spectrometer (open view).

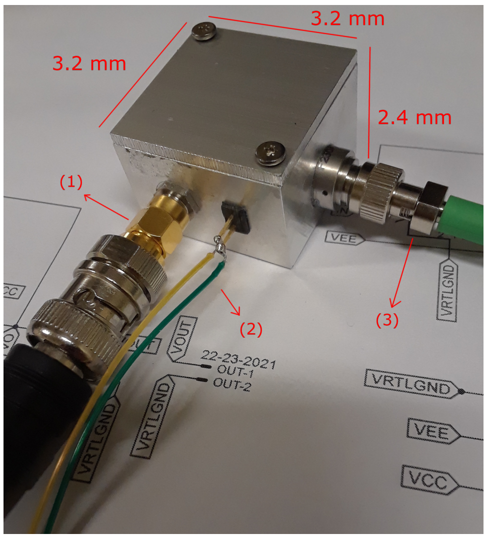

Fig. 9. Miniaturized saturated absorption spectrometer (closed view). The output to the oscilloscope (1), the power supply connector (2), and the input laser source (3) are highlighted in the figure.

good the system is. The lower its value, the less spreading is introduced by various unwanted mechanisms. This width should be compared to the natural width of 6 MHz. Therefore, our system obtains a performance similar to [7] occupying a much smaller volume. On the other hand, there are solutions such as [8] that achieve smaller volumes for the optics setup but having broader resonances.

TABLE II
STATE-OF-THE-ART COMPARISON

	[7]	[8]	Table-top setup	This work
Device volume (cm^3)	146	0.1	-	25
Volume of the atomic vapor cell (cm^3)	2.0	0.006	50	0.1
Cell temperature (^oC)	-	45	25	80
Atomic resonance FWHM (MHz)	20^+	35^*	20	20^*

* with a light intensity of 3 mW/cm^2
\+ with a light intensity of less than 3 mW/cm^2

Fig. 10. Frequency spectrum from the reported setup (lower blue trace) and a reference spectrum (upper yellow trace) shown directly in an oscilloscope.

IV. CONCLUSIONS

We successfully designed, manufactured, and tested a 27 x 27 mm^2 PCB that comprises a low-noise amplifier along with a power-management circuit, for a miniaturized saturated absorption spectrometer.

Signals recorded with our miniaturized device perfectly match those acquired with a commercial table-top optical setup.

Experimental results show that the amplifier has a bandwidth of 32 kHz, a dc gain of 80 dB-Ohm, and an output voltage swing of 4.84 V_{pp}. The device can handle an input optical power of up to 800 μW, where the photodetection electronics have a Noise Equivalent Power of 0.3 pW/$\sqrt{Hz}$, and the electronic circuit power consumption represents less than 7 % of the overall power consumption.

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REFERENCES

[1] A. Atef, M. Atef, E. E. M. Khaled, and M. Abbas, “CMOS transimpedance amplifiers for biomedical applications: A comparative study,” *IEEE Circuits and Systems Magazine*, vol. 20, no. 1, pp. 12–31, 2020.
[2] B. Razavi, “The transimpedance amplifier [a circuit for all seasons],” *IEEE Solid-State Circuits Magazine*, vol. 11, no. 1, pp. 10–97, 2019.
[3] J. Kitching, “Chip-scale atomic devices,” *Applied Physics Reviews*, vol. 5, no. 3, p. 031302, 2018.
[4] W. Demtröder, *Laser spectroscopy*. Springer, 2015.
[5] K. Sosa, J. Oreggioni, and H. Failache, “Miniaturized saturated absorption spectrometer,” *Review of Scientific Instruments*, vol. 91, no. 8, p. 083101, 2020.
[6] J. Graeme, *Photodiode amplifiers: op amp solutions*. McGraw-Hill, Inc., 1995.
[7] C. Affolderbach and G. Mileti, “A compact laser head with high-frequency stability for rb atomic clocks and optical instrumentation,” *Review of scientific instruments*, vol. 76, no. 7, p. 073108, 2005.
[8] S. A. Knappe, H. G. Robinson, and L. Hollberg, “Microfabricated saturated absorption laser spectrometer,” *Opt. Express*, vol. 15, no. 10, pp. 6293–6299, May 2007.