Voltage-Controlled Current Source and Transimpedance Amplifier

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This report explores a voltage-controlled current source (VCCS) using an operational amplifier (op-amp) and an nMOSFET transistor, as well as a transimpedance amplifier (TIA) for photodiode signal conversion. We experimentally determine the system's amplitude response, linearity, and bandwidth, comparing experiment ant theory. A Bode plot analysis is conducted to verify expected low-pass filter behavior. Finally, an optical communication setup is implemented using an Arduino-driven LED and a photodiode receiver.

INTRODUCTION

A voltage-controlled current source is a fundamental circuit for applications requiring precise current control, such as LED brightness modulation. It uses an op-amp to regulate the gate voltage of an nMOSFET, which in turn ensures a stable output current.

The circuit is powered using an Arduino Uno, which supplies a 5V power rail for the op-amp and LED operation [4]. The nMOSFET has three terminals: Gate, Source, and Drain. When the Gate voltage V_{GS} is high enough (above the threshold voltage, which is between 0.8V and 3.0V for the 2N7000 [2]), a conductive channel forms between the Drain and Source, allowing current to flow. The relationship between this output current and the input voltage is governed by the resistor placed in series with the source terminal of the MOSFET.

A transimpedance amplifier (TIA) converts a photocurrent generated by a photodiode into a proportional output voltage. The frequency response of the TIA is determined by the feedback resistor and capacitor, forming a low-pass filter with a characteristic cutoff frequency.

This report presents the experimental validation of both circuits, investigating their amplitude response, linearity, and frequency behavior.

R-1: OP-AMP FEEDBACK AND CURRENT CONTROL

The circuit uses an op-amp and an nMOSFET (2N7000) to create a voltage-controlled current source. A voltage divider generates the reference voltage V_{set}, which sets the desired LED current. The op-amp regulates the MOSFET's gate voltage V_{GS} to ensure that the source voltage follows V_{set}.

Since the MOSFET's drain current flows through the sense resistor (R_{sense}) and the LED, Ohm's Law gives:

$$I_{\text{LED}} = \frac{V_{\text{set}}}{R_{\text{sense}}} \tag{1}$$

This ensures that the LED current is directly proportional to V_{set}. The MOSFET operates in linear mode, acting as a variable resistor controlled by the op-amp. The op-amp continuously adjusts V_{GS} to maintain feedback, keeping the source at V_{set}.

By varying V_{set}, we can precisely control I_{LED}, and in turn the LED brightness.

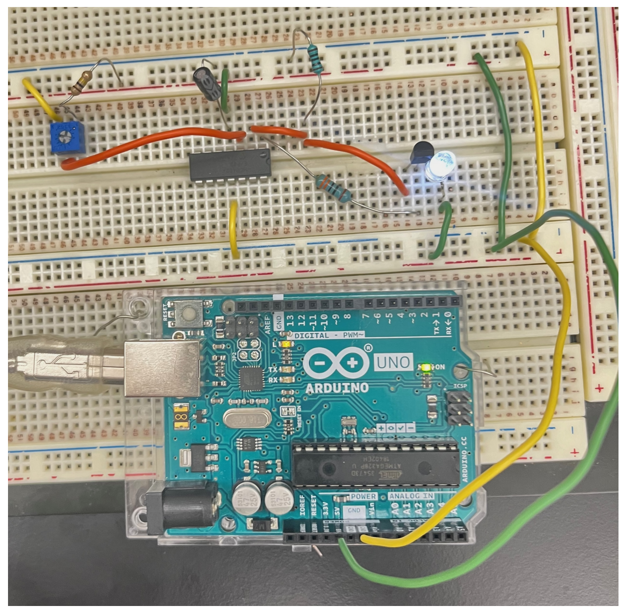

FIG. 1. Breadboard implementation of the op-amp feedback circuit used for current control.

R-2: LINEARITY OF LED CURRENT WITH V_{set}

To analyze the relationship between the LED current I_{LED} and the set voltage V_{set}, we varied V_{set} using the potentiometer from our voltage divider and measured its value using an oscilloscope set to an appropriate scale of 1V/div. The corresponding current I_{LED} was recorded using a multimeter.

Since the sense voltage V_{sense} is given by:

$$V_{\text{sense}} = I_{\text{LED}} R_{\text{sense}} \tag{2}$$

where $R_{\text{sense}} = 99.450 \pm 0.003\,\Omega$ in our circuit, we plotted V_{sense} as a function of V_{set}, as shown in Figure 2.

The uncertainties (reported to 1 s.f) were calculated based on the specifications for the multimeter [1] and scope [3] as follows:

$$\Delta I_{\text{LED}} = \pm(0.03\% \times 23.0 \text{ mA} + 0.02\% \times 100 \text{ mA}) = \pm 0.03 \text{ mA}$$

$$\Delta R_{\text{sense}} = \pm(0.002\% \times 99.45\Omega + 0.0010\% \times 100\Omega) = \pm 0.003\Omega$$

$$\Delta V_{\text{set}} = \pm(3\% \times 1.0\text{V/div} + 0.25\% \times 1.0\text{V/div}) = \pm 0.03\text{V}$$

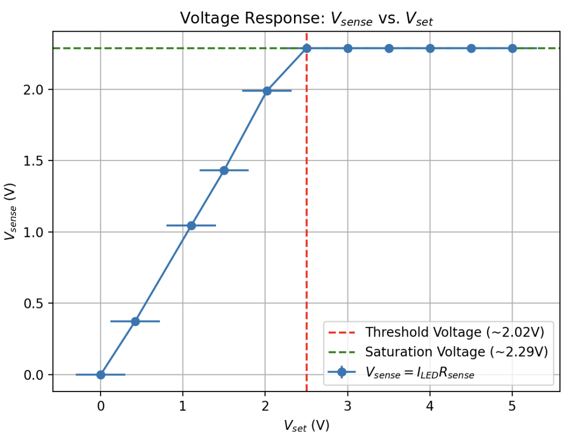

FIG. 2. Measured voltage response of the system, showing V_{sense} as a function of V_{set}.

V_{set} (V) ± 0.3 V	I_{LED} (mA) ± 0.03 mA
0.00	0.00
0.42	3.77
1.10	10.5
1.50	14.4
2.02	20.0
2.50	23.0
3.00	23.0
3.50	23.0
4.00	23.0
4.50	23.0
5.00	23.0

TABLE I. Measured values of V_{set} and corresponding I_{LED}.

From the plot, we observe that V_{sense} (and thus I_{LED}) is approximately linear with V_{set} up to a threshold voltage of about 2.50V. Beyond this point, I_{LED} saturates at around 23 mA, which corresponds to the $\approx 20\,\text{mA}$ rated operating current of the LED. This behavior is expected, as the MOSFET reaches its fully conducting state beyond the threshold voltage.

The results confirm that our circuit operates as a voltage-controlled current source, with a clear transition from the linear region to saturation.

R-3: CIRCUIT PHOTO SHOWING PHOTODIODE, RESISTOR, CAPACITOR, AND OP-AMP

Figure 3 shows the experimental circuit used in this study, highlighting the photodiode, feedback resistor, capacitor, and operational amplifier components used in the transimpedance amplifier setup.

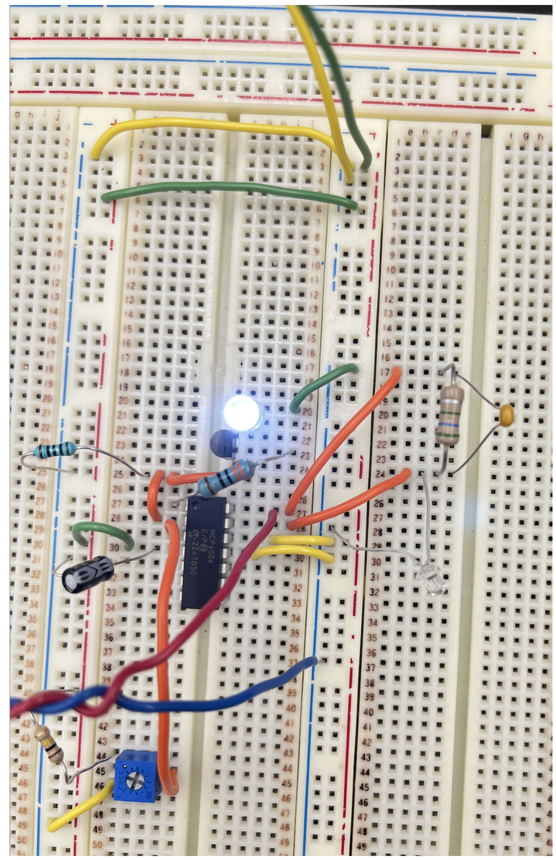

FIG. 3. Breadboard implementation of the transimpedance amplifier circuit. The photodiode, resistor, capacitor, and op-amp are clearly visible.

R-4: OSCILLOSCOPE SCREENSHOTS OF TRANSIMPEDANCE AMPLIFIER OUTPUT

Figure 4 shows the output voltage when the photodiode is fully exposed to ambient light, while Figures 5 and 6 display the output when the photodiode is partially covered and completely pinched, respectively. When the photodiode is fully exposed to ambient light, we observe an output voltage of $V_{pp} = 2.53$ V, which drops to approximately $V_{pp} = 433$ mV when partially covered, which roughly corresponds to a 83% reduction in amplitude. This is expected seeing as the photodiode generates current proportional to the incident intensity of light.

When the photodiode is pinched (i.e. incident intensity is 0), the output does not drop to 0V but instead exhibits noise at a frequency of 59.98 Hz. This aligns well with the lab handout's note that electrical mains noise (50/60Hz) may be observed.

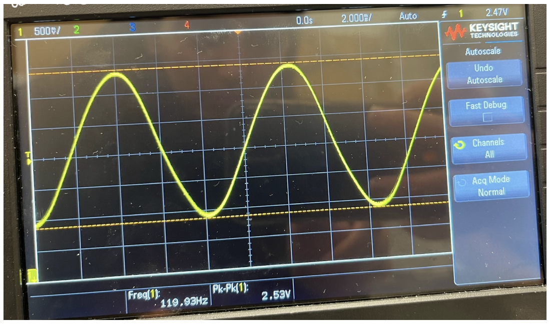

FIG. 4. Scope capture of the output voltage when the photodiode is uncovered.

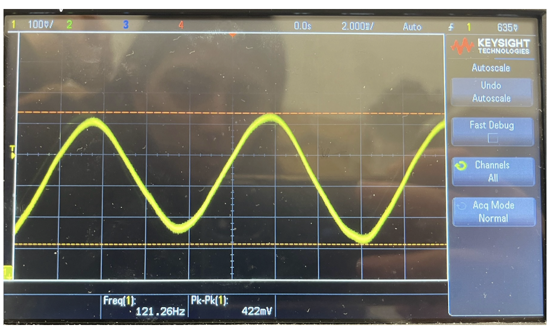

FIG. 5. Scope capture of the output voltage when the photodiode is partially covered.

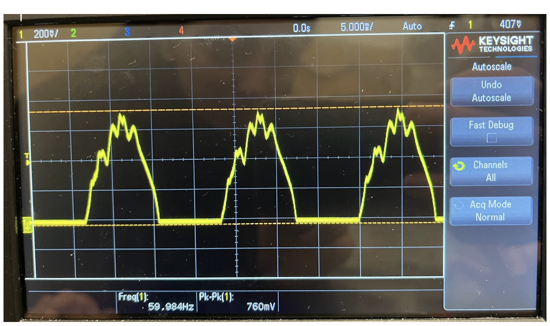

FIG. 6. Scope capture of the output voltage when the photodiode is pinched.

R-5: CIRCUIT PHOTO SHOWING LED AND PHOTODIODE ALIGNMENT

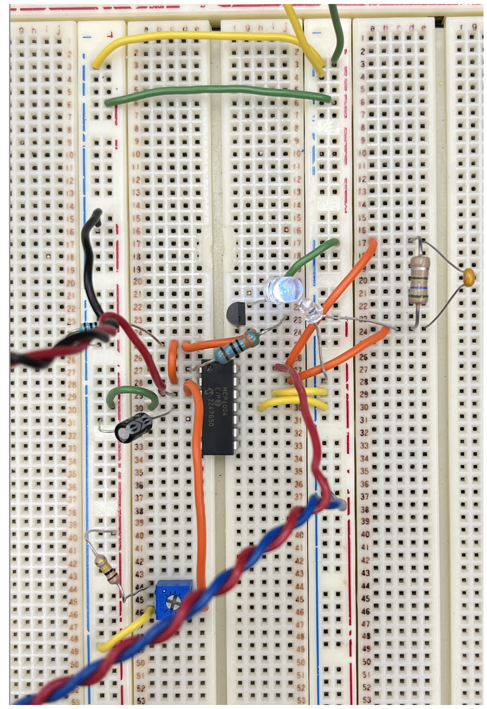

FIG. 7. Breadboard implementation showing the LED and photodiode alignment.

R-6: OSCILLOSCOPE SCREENSHOT OF WAVEGEN INPUT AND PHOTODIODE OUTPUT

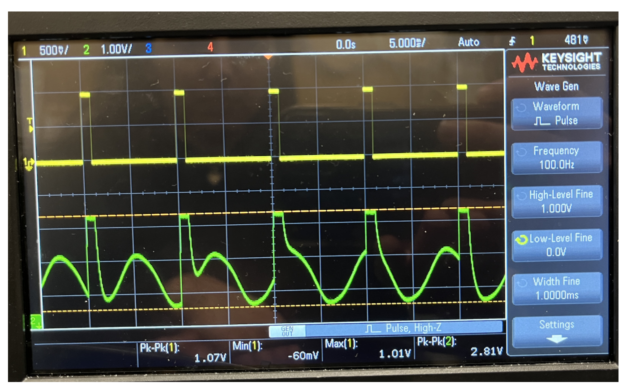

FIG. 8. Oscilloscope capture of the WaveGen input and the photodiode output. The yellow trace represents the WaveGen input, while the green trace represents the photodiode output.

R-7: AMPLITUDE RESPONSE OF THE SYSTEM

We plotted V_{out} as a function of V_{in} and found a linear response between the threshold voltage and the saturation voltage of the LED. The threshold voltage of approximately 0.56 V corresponds to the minimum input voltage at which the photodiode generates enough photocurrent for the transimpedance amplifier to produce a measurable output. Below this threshold, the photocurrent is too small, and factors like noise dominate.

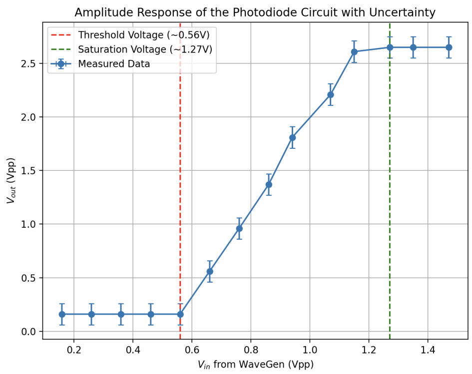

FIG. 9. Amplitude response of the photodiode circuit. The threshold voltage is approximately 0.56V, while the saturation voltage is around 1.27V.

V_{in} (Vpp) ± 0.01 V	V_{out} (Vpp) ± 0.1 mV
0.16	0.16
0.26	0.16
0.36	0.16
0.46	0.16
0.56	0.16
0.66	0.56
0.76	0.96
0.86	1.37
0.94	1.81
1.07	2.21
1.15	2.61
1.27	2.65
1.35	2.65
1.47	2.65

TABLE II. Measured amplitude response of the photodiode circuit. The precise uncertainties for V_{in} and V_{out} are ± 73.25 mV and ± 144.5 mV respectively, but are reported to 1 s.f

The saturation voltage of about 1.27 V represents the point beyond which increases in V_{in} no longer lead to measurable increases in V_{out}, and happens when the photodiode reaches its maximum current output. Since increase in the output voltage is small past $V_{in} = 1.15$V, the true saturation voltage is likely somewhere between 1.15V and 1.27V. Overall, the behavior shown in Figure 9 matches the expected response of a photodiode in a transimpedance amplifier circuit.

R-8: BANDWIDTH MEASUREMENT USING BODE PLOT

We ran the Frequency Response Analysis (FRA) on the oscilloscope, and found the max dB to be just above 13dB, hence the -3dB point just above 10dB. The cursor on the scope has a finite step size so we were only able to extract the 9.78dB point, which occurred at around 549.6Hz.

FIG. 10. Frequency response analysis of the photodiode transimpedance amplifier circuit.

The theoretical cutoff frequency for the circuit, using our component values of $R = (5.79 \pm 9 \times 10^{-4})\,\mathrm{M\Omega}$ and $C = (73.5 \pm 4 \times 10^{-2})\,\mathrm{pF}$, is given by:

$$f_c = \frac{1}{2\pi RC} = \frac{1}{2\pi(5.79 \times 10^6)(73.5 \times 10^{-12})} \approx 374 \pm 2.0 \text{ Hz}. \tag{3}$$

This theoretical f_c deviates slightly from our experimental value of $f_c = 549.6$ Hz, but is on the same order of magnitude, which indicates a reasonable outcome.

Since the measured f_c is in fact *higher* than its predicted value, the deviation cannot be explained by breadboard capacitances and resistances, as f_c is indirectly proportional to these quantities, meaning they would have led to lower f_c measurement instead.

Therefore, a possible explanation for the higher experimental f_c is the limitations in the scope's resolution. As mentioned, we were not able to extract the precise -3dB due to the finite step size when extracting f_c from the FRA interface. In reality, we needed to extract the frequency at just above 10dB, which occurred earlier (i.e., at a lower frequency) in the graph, This may have caused enough of a deviation to explain the discrepancy.

R-9: ARDUINO-BASED LIGHT COMMUNICATION SYSTEM

In this experiment, an Arduino-controlled LED was used to transmit digital signals via light pulses, which were then detected and converted into voltage signals by the photodiode circuit. The photodiode output was processed using a transimpedance amplifier to ensure a measurable response.

Figure 11 shows the breadboard implementation of the circuit, including the Arduino, LED transmitter, photodiode, and transimpedance amplifier. This setup allowed us to analyze how optical signals can be converted into electrical signals and used for communication.

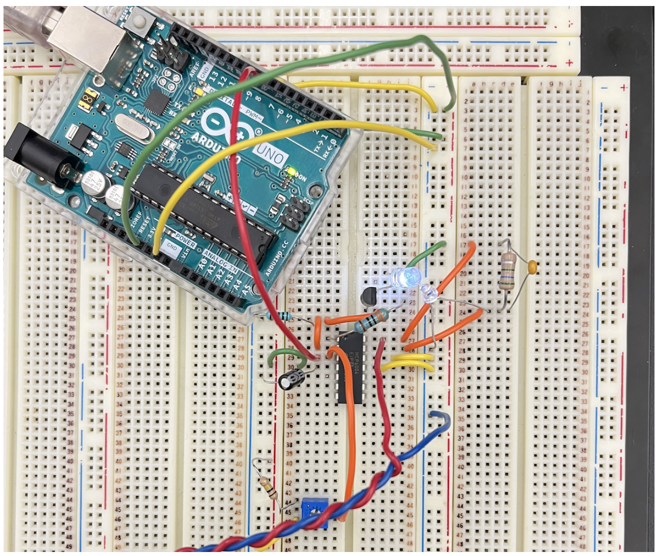

FIG. 11. Breadboard implementation of the optical communication system, showing the LED transmitter, photodiode receiver, and transimpedance amplifier.

R-10: OSCILLOSCOPE CAPTURE OF PRIME NUMBER TRANSMISSION

Figure 12 shows the oscilloscope screenshots of the received signal. Each burst of pulses corresponds to a different prime number, with increasing numbers of pulses as the sequence progresses. The prime number corresponding to the signal may easily be identified by counting the number of voltage peaks grouped together in each scope capture. These represent the LED being blinking—turning on and off rapidly—as instructed by the Arduino code.

Overall, the signal was successfully detected by the photodiode and processed by the transimpedance amplifier. A video of the results has been uploaded to Quercus for a better display of the results.

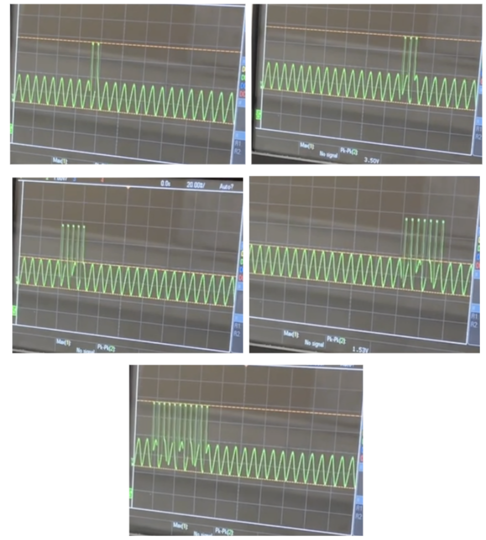

FIG. 12. Sequential images showing the oscilloscope capture of prime number transmission.

CONCLUSION

We successfully demonstrated the operation of a VCCS using an op-amp and nMOSFET, as well as a transimpedance amplifier for photodiode signal conversion. We observed the expected linear relationship between V_{set} and I_{LED} up to saturation, and found the measured system bandwidth to be in reasonable agreement with theory. Overall, the study highlights the effectiveness of these circuits for precise current control and optical signal processing.

Acknowledgements

These experiments were performed with Sanai Nezafat.

[1] Keysight Technologies, *34461A Digital Multimeter Datasheet*, `https://www.keysight.com/ca/en/assets/7018-06411/data-sheets/34461A.pdf`, 2025. [Accessed: Mar. 4, 2025].

[2] Supertex Inc., *2N7000 N-Channel Enhancement-Mode MOSFET Datasheet*, `https://www.farnell.com/datasheets/2337817.pdf`, 2025. [Accessed: Mar. 5, 2025].

[3] Keysight Technologies, *InfiniiVision 1000 X-Series Oscilloscopes Data Sheet*, `https://www.keysight.com/ca/en/assets/7018-06411/data-sheets/5992-3484.pdf`, 2019. [Accessed: Mar. 5, 2025].

[4] Arduino, *Uno Rev3 SMD Specifications*, `https://docs.arduino.cc/hardware/uno-rev3-smd/`, 2025. [Accessed: Mar. 4, 2025].