Low Voltage Operational Amplifier Design for Energy Harvesting Applications

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Introduction

Wireless and embedded systems in remote locations are commonly powered using batteries due to the difficulty of providing a tethered energy infrastructure. However, replacing batteries in these sensors is often difficult and expensive.

There is an increasing need for wireless sensors in applications such as:

- Oceanographic study
- Environmental monitoring
- Military surveillance
- Other remote data acquisition

Harvesting energy from the environment can provide sustainable and durable energy to the sensors.

One method of harvesting energy is through the use of microbial fuel cells (MFC).

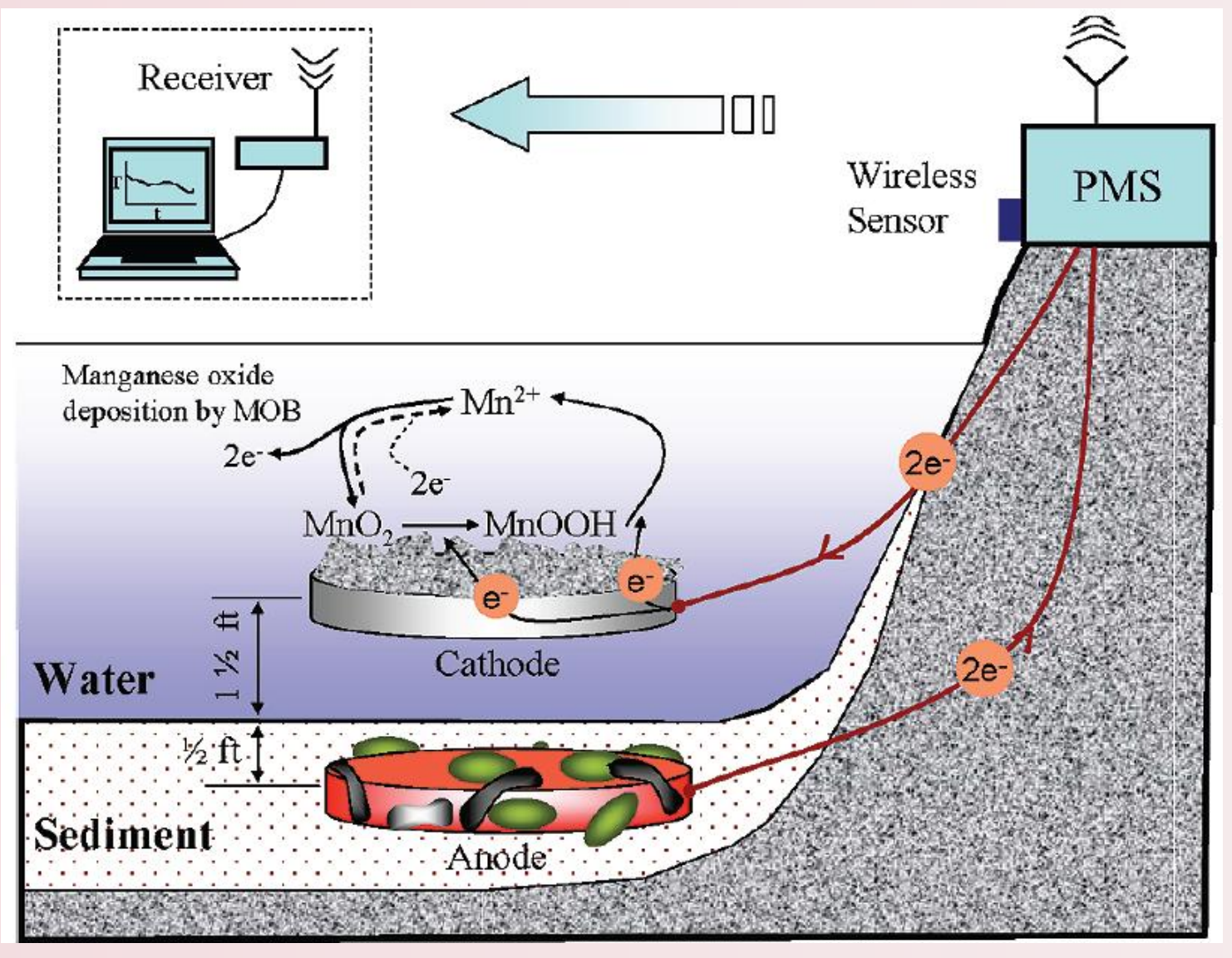

Figure 1. A sediment microbial fuel cell (SMFC) with microbial anode and cathode provides energy for the power management system (PMS). Image from [1].

Background

Power Management System

Amplification of the voltage harvested is a critical step between the MFC and the sensor.

Power management systems (PMS) are used to provide amplification and other regulations of the voltage to the sensor.

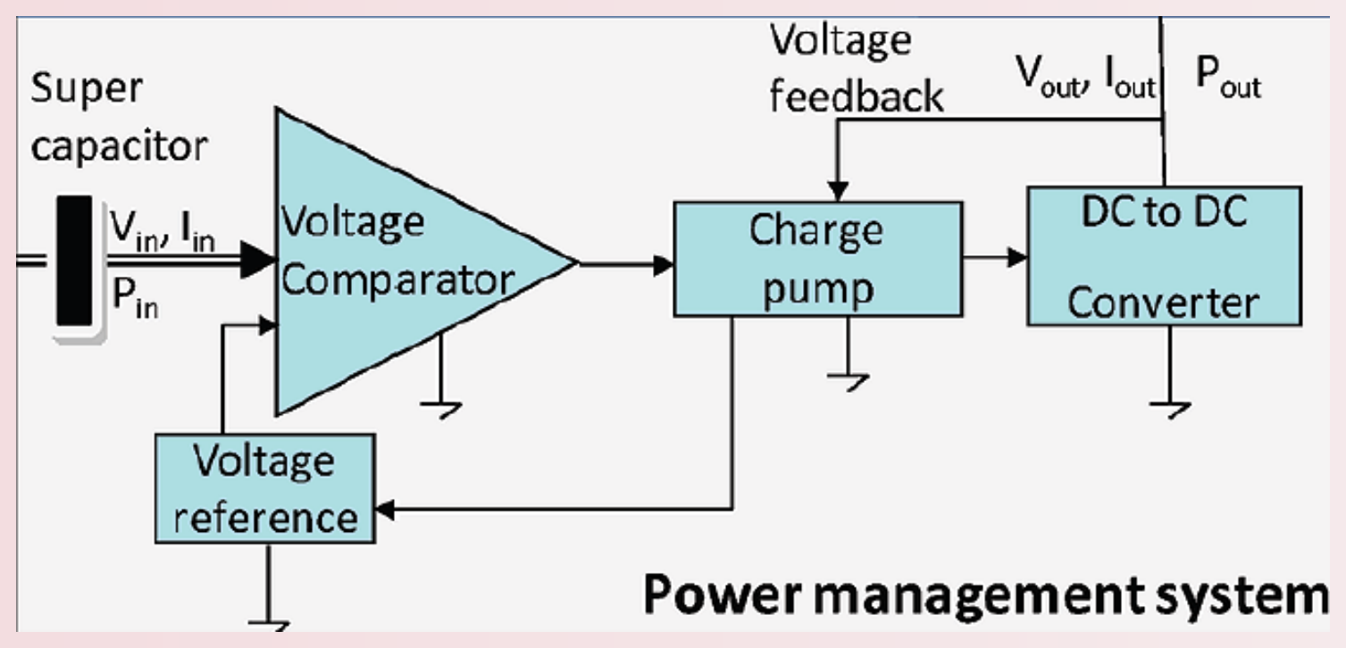

Figure 2. A block diagram of a power management system. Image from [1].

Because MFCs only provide low voltages, all the components in a PMS must be able to operate at low voltages. Optimizing these components to operate at low voltages in turn contributes to the optimization of the PMS as a whole.

Operational Amplifier

One of the components of a DC to DC converter is an operational amplifier (op-amp). Before beginning to optimize an op-amp, design characteristics such as:

- Threshold voltage
- Gain
- Bandwidth
- Slew Rate
- Phase margin
- Unit gain frequency

must be considered.

When dealing with low voltage applications such as MCF powered systems the threshold voltage of the op-amp becomes the most important of these characteristics.

Dealing with this constraint while optimizing the gain and increasing bandwidth circuit performance was the goal of this project.

Theory

The Miller effect accounts for the increase in the equivalent input capacitance of a voltage amplifier due to amplification of the effect of capacitance between the input and output terminals. The input capacitance due to the Miller effect (C_M) is given by:

$$C_M = C(1-A)$$

where *C* is the feedback capacitance and *A* is the gain of the op-amp. Solving for the output voltage gives:

$$v_o = v_i(1 - jwC_M R)$$

where v_o is the output voltage, v_i is the input voltage, *R* is the feedback resistance, and *w* is the frequency. Note that, due to the Miller effect, the output voltage drops off once the frequency is high enough such that:

$$wC_M R \geq 1$$

Therefore, the input and output capacitance of a circuit determines its frequency response.

Methods

The base design used was a folded cascode operational transconductance amplifier presented by Lehmann.

The addition of a capacitor at the output of the op-amp was expected to result in improved bandwidth for the circuit.

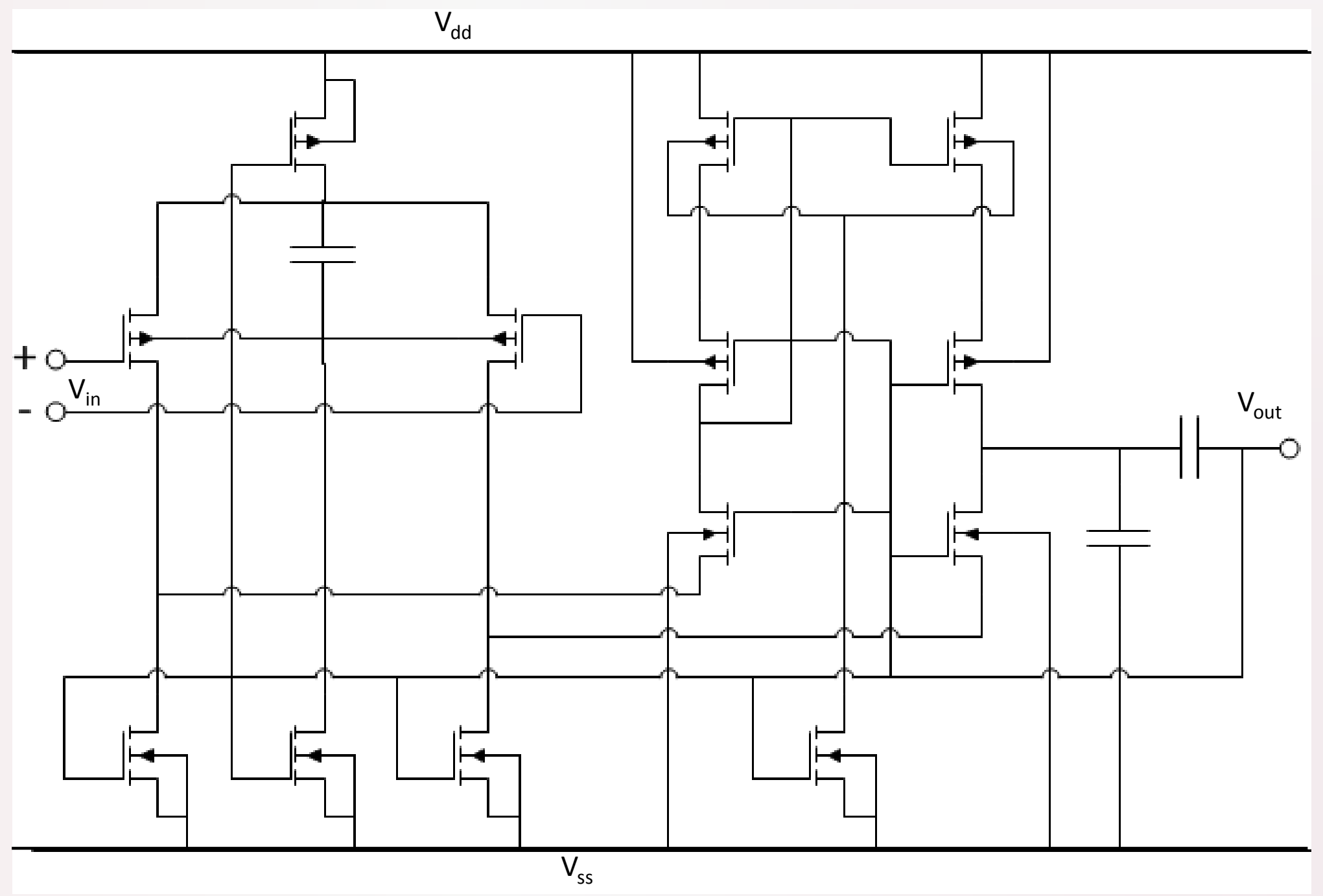

Figure 3. Modified cascode operational transconductance amplifier. Capacitor added before V_{out} to improve frequency response.

Results

Due to the low voltage restrictions of working with MFCs, it is important for the threshold voltage of the op-amp to remain low.

When the gain from the base and modified circuits are overlaid it can be noted that the behavior of the two circuits is identical at low input voltages.

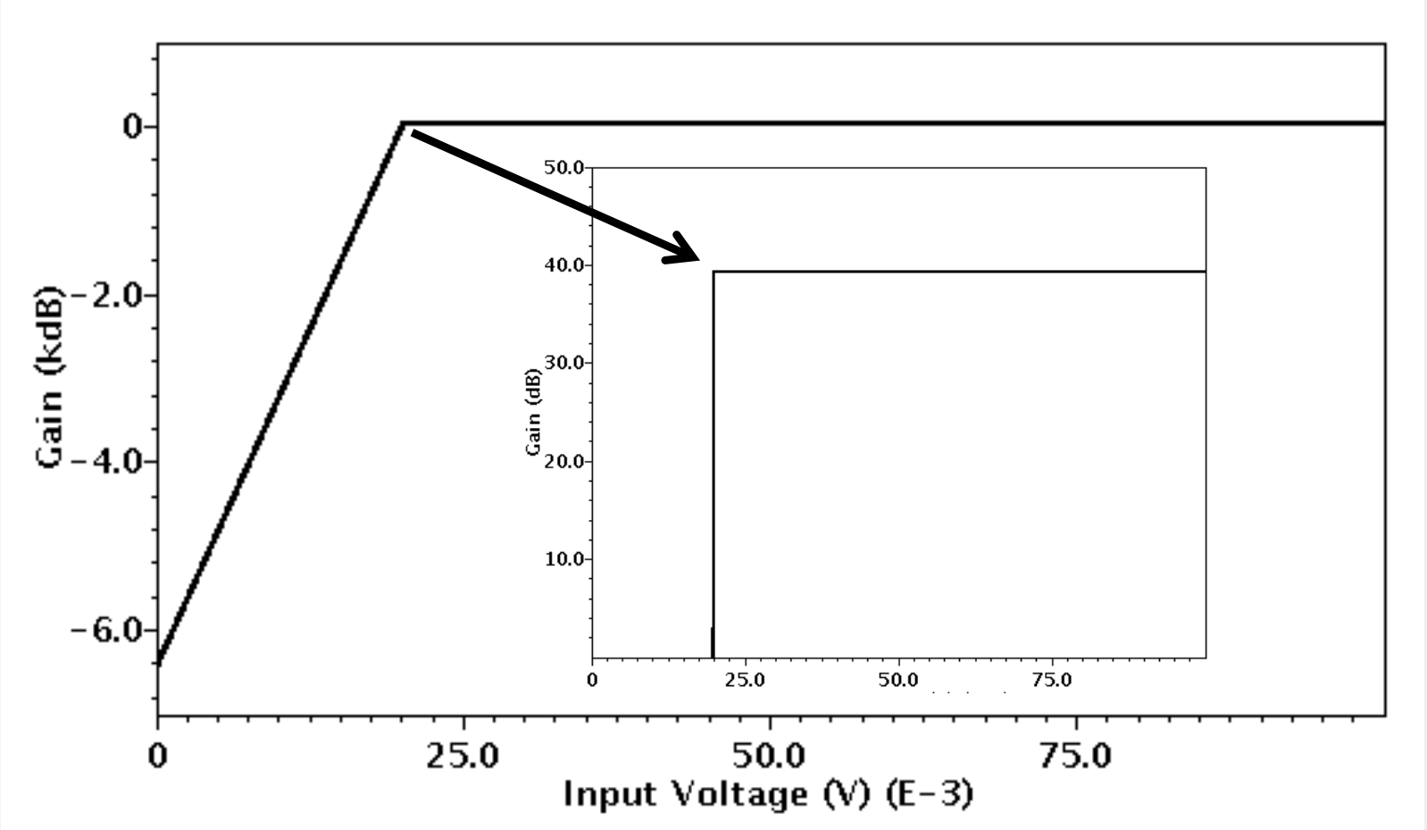

Figure 4. Gain with respect to the input voltage. Overlaid results from base and modified circuits.

In measuring the gain of the op-amp shown in Figure 3 it was found that the gain is relatively constant with respect to the powering voltage.

In the figure show, "powering voltage" refers to the value of V_{in+} where $V_{in-} = -V_{in+}$

Note that the gain of the circuit is constant at 39db.

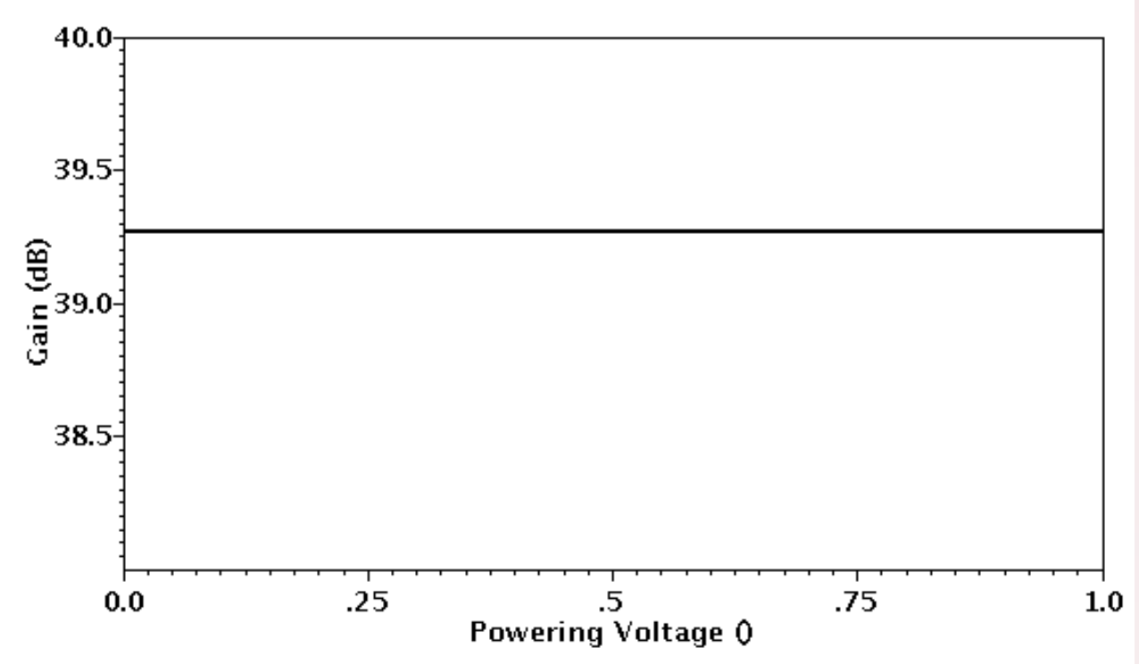

Figure 5. Gain of the circuit with respect to the powering voltage.

In Figure 6 two graphs of output voltage with respect to frequency are shown. The solid line corresponds to the base circuit, and the dashed line refers to the modified circuit in Figure 3.

Note that the output voltage for the second circuit is significantly higher at high frequencies.

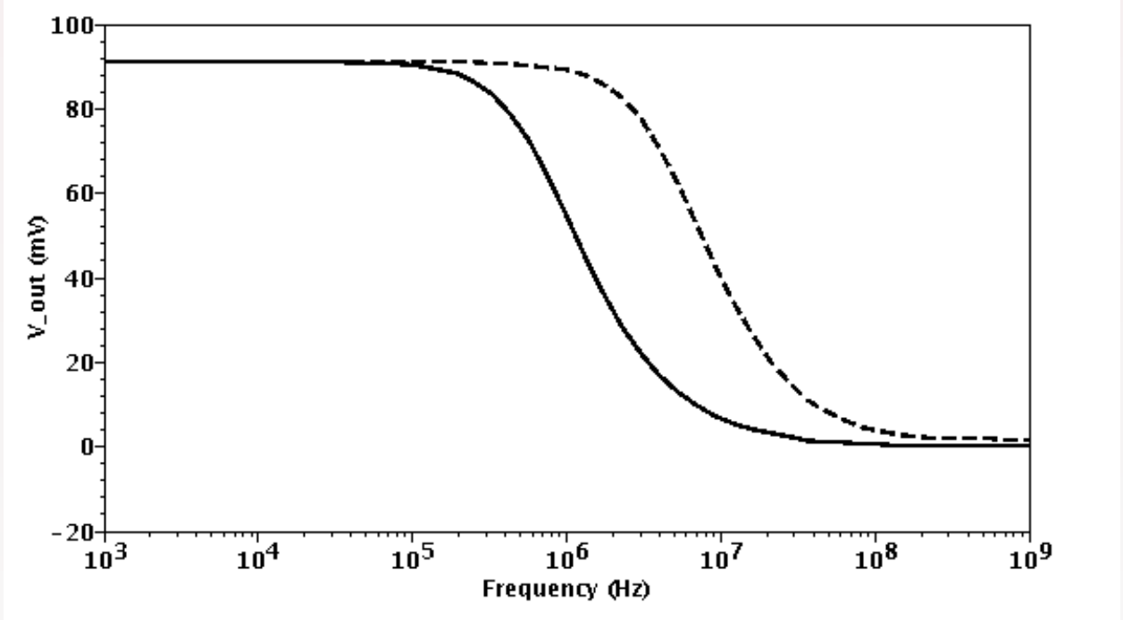

Figure 6. Output voltage with respect to frequency.

Translating this result to gain shows that the improved circuit, the results of which are again shown by the dashed line, has a much higher gain at high frequencies.

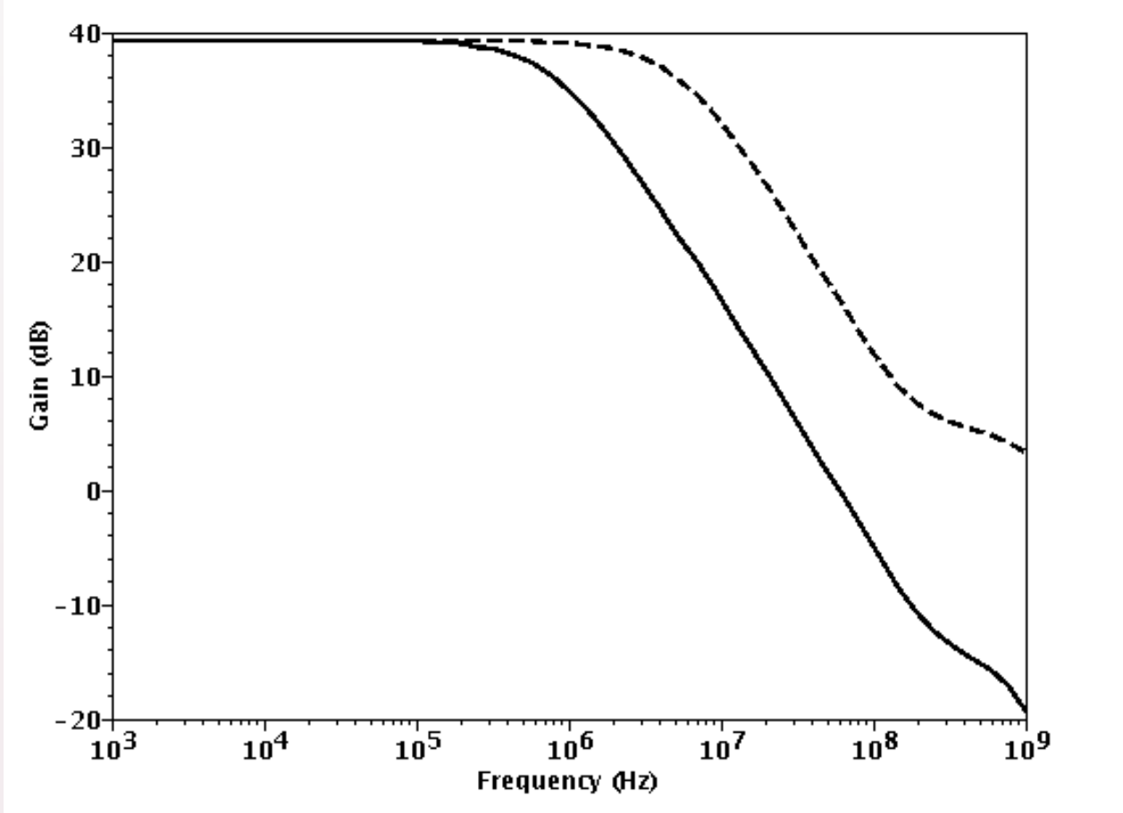

Figure 7. Gain of the circuit with respect to frequency.

Conclusions

By adding a capacitor at the output of the op-amp, thereby increasing the capacitance of the circuit, the bandwidth of the op-amp was greatly improved.

The threshold voltage of the circuit remained unaffected by the added capacitor, allowing the circuit to function at the same initial low voltages.

Throughout this study the goal was to improve the performance of the op-amp while maintaining a low powering voltage. By combining ideas from various sources, this goal was achieved.

References and Acknowledgements

1. Conrad Donovan et al.,"Batteryless, Wireless Sensor Powered by a Sediment Microbial Fuel Cell" Environ. Sci. Technol. 2008, vol. 42, pg 8591-8596
2. Torsten Lehmann, Marco Cassia, "1-V Power Supply CMOS Cascode Amplifier" IEEE Journal of Solid-State Circuits, 2001, vol. 36
3. Benjamin J. Blalock et al., "Designing 1-V Op Amps Using Standard Digital CMOS Technology" IEEE Transactions on Circuits and Systems, 1998, vol. 45

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