Operational Amplifier Design with BJT and MOSFET Devices

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***Abstract*— Operation amplifiers can be designed discretely as well as in an integrated circuit. Using matched transistors of either Metal Oxide Field Effect Transistors or Bipolar Junction Transistors, amplifiers can be made to function as operation amplifiers with upsides that give them an edge over some integrated-circuit designs.**

I. Introduction

Operation amplifiers are a common basic building block for circuit design. Their fundamental operation and mechanics allow for a many different kinds of circuits to be built with them. From active filters, to signal manipulation, to power regulators, Operational amplifiers (Op-amps) are a fundamental part of basic circuit design.

II. Circuit Design – BJT Op-Amp

Operational amplifiers usually follow the same basic block diagram, with a differential input stage, stage(s) to increase the gain, and a low impedance output stage. In integrated-circuit design, resistors are space-consuming and more difficult to make than a transistor, so much of the biasing in an IC is done with transistors. By the use of current mirrors and active loads, you can achieve high gain stages with few to no resistors.

This paper is to demonstrate and validate the design of a multi-stage operational amplifier using discrete components. Matched-pair BJTs can be found in sets of two or more in common ICs, and they are needed to make differential amplifiers or current sources.

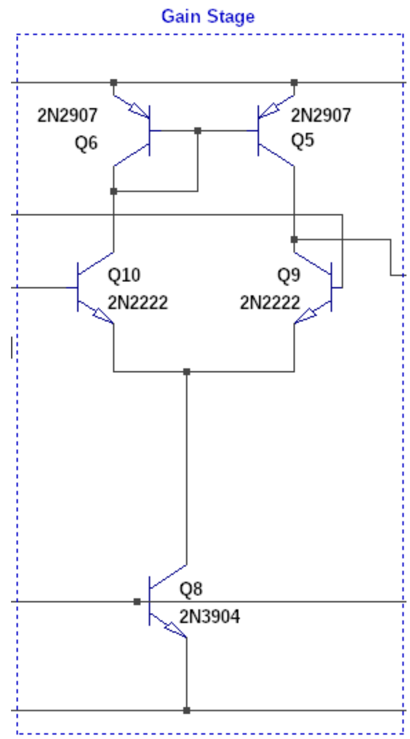
A. Differential Input – First Differential Amplifier

A differential amplifier takes in two signals and amplifies the difference between them by some gain. It has two paths for current to flow and the transistors direct the current to flow more in one path or the other, changing the output voltage accordingly. R14 and R15 were chosen to bring V_{OUT} lower, but to primarily increase the gain – as gain is proportional to the ratio of the collector and emitter resistance.

$$V_{out} = A(V_{in}^{+} - V_{in}^{-}) \tag{II.1}$$

$$\text{Balenced: } A_V = -\frac{R_C}{r_e} \tag{II.2}$$

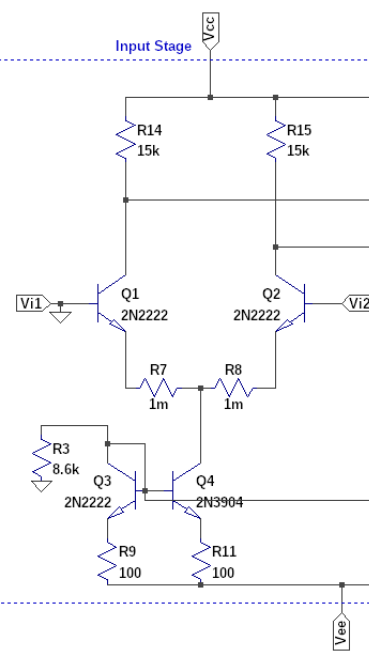
The current mirror is formed by Q3 and Q4, and is programmed for 0.5mA, chosen to provide an easy way to increase the collector resistors R14 and R15 – the quiescent current setting the trade-off of output impedance and gain. R7 and R8 are essentially shorted and would not exist in real circuit – they are only for simulation purposes.



B. Gain Stage – Second Differential Amplifier

The second stage of the Op-Amp is another differential amplifier. Common emitter, or other, amplifiers could be used, but it can be difficult to achieve a high gain using an active load with other types of unbalanced amplifiers. Additionally, by nature of using both outputs of the first amplifier, it's gain is twice what it would be if a single output was taken (single-ended output).

$$A_d \approx \frac{r_{o4}||r_{o2}}{2(r_e + R_E)} \tag{II.3}$$



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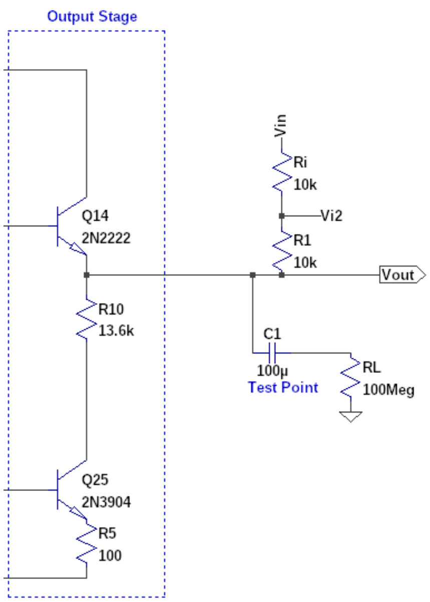
$$\text{With load: } A_D \approx \frac{r_{o4}||r_{o2}||R_L}{2(r_e + R_E)} \quad \text{(II.4)}$$

Where r_{o4} is for Q5 in this case, and r_{o2} is for Q9. The input resistance of the output-stage should be the emitter resistance as seen through the base.

C. *Emitter-Follower – Output Stage*

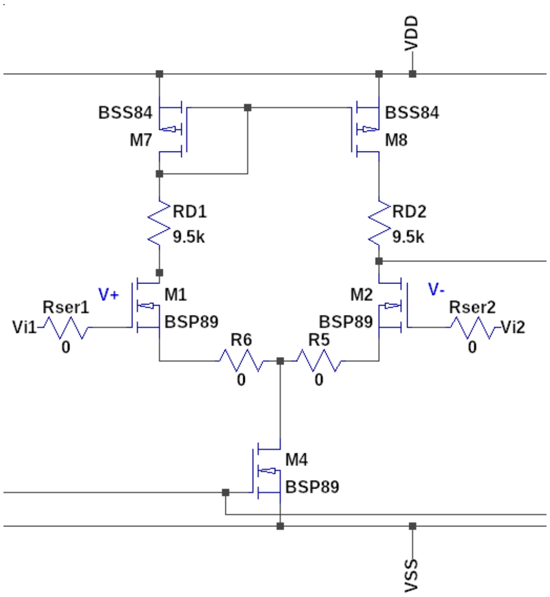


The purpose of this stage is to provide a current gain, a lower output impedance than the gain stage provides. The emitter resistance will affect the input impedance of the Common-Collector stage (CC), and thus also affect the gain of the gain stage. R10 was chosen as 13.6k to drop roughly 7V, to somewhat center the output and also provide a high input impedance to the final stage.

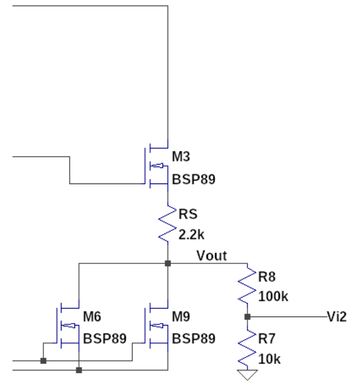
III. Circuit Design - MOSFET Op-Amp

MOSFETs are also a three-terminal amplifier device, the primary difference being that they are better modeled as voltage-controlled current-sources rather than current-controlled-current-sources.

A. *Differential Input Stage*



B. *Output Stage*



M6 and M9 function as the constant current sink underneath the output MOSFET, M3. They were doubled up to have a greater voltage drop over RS, so that RS could be half as large as otherwise needed to bring the output closer to 0V.

IV. Results

MOSFET Op-Amp

Input Bias Current	0
Input Offset Current	3.1nA
Input Offset Voltage	1.9uV
Bandwidth	2.5kHz
Slew Rate	0.56V/uS

BJT Op-Amp

	LTSpice	Calculated
Input Bias Current	1.21uA	----
Input Offset Current	0.17uA	----
Input Offset Voltage	39mV	----
Bandwidth	906kHz	----
Slew Rate	1.61V/uS	----
Input Resistance	190kOhm	220kOhm
Output Resistance	236Ohm	----
Differential Gain	4965V/V	----
CMRR		

V. Discussion

LM741 - Properties

Input Bias Current	80nA
Input Offset Current	20nA
Input Offset Voltage	1mV
Bandwidth	1.5MHz
Slew Rate	0.5V/uS

Both the BJT and MOSFET op-amp designs successfully operated in an inverting or non-inverting Op-Amp configuration – the BJT design had a much better bandwidth and slew-rate but was much more complex and difficult to build. The MOSFET design is great for a simple way of having very high input impedance, and a mix of the two designs might turn out very successful.

VI. CONCLUSION

In conclusion, operation amplifiers can be designed discretely as well as packaged in an integrated circuit. The degrees of which you can control the outcome of the design change drastically when using discrete components – but upsides such as being able to use resistors or other large components can give an edge to discrete op-amp designs where chips like the LM741 cannot compete.

VII. APPENDIX