Lab 6:
CMOS Voltage Controlled Amplifier

1. Introduction

The purpose of this design task is to design and construct a Voltage Controlled Amplifier using MOSFET transistors. VCAs have many applications in the areas of communications and signal processing, as they are easily implemented as controllable gain blocks. You can find VCAs in audio mixers, sound cards, amplifiers, wireless devices, and even inside those little voice-activated micro-cassette recorders.

2. Approach

Given the limited timeframe, we have provided you with a fairly simple circuit that functions as a VCA. The circuit is pictured below in Fig. 1.:

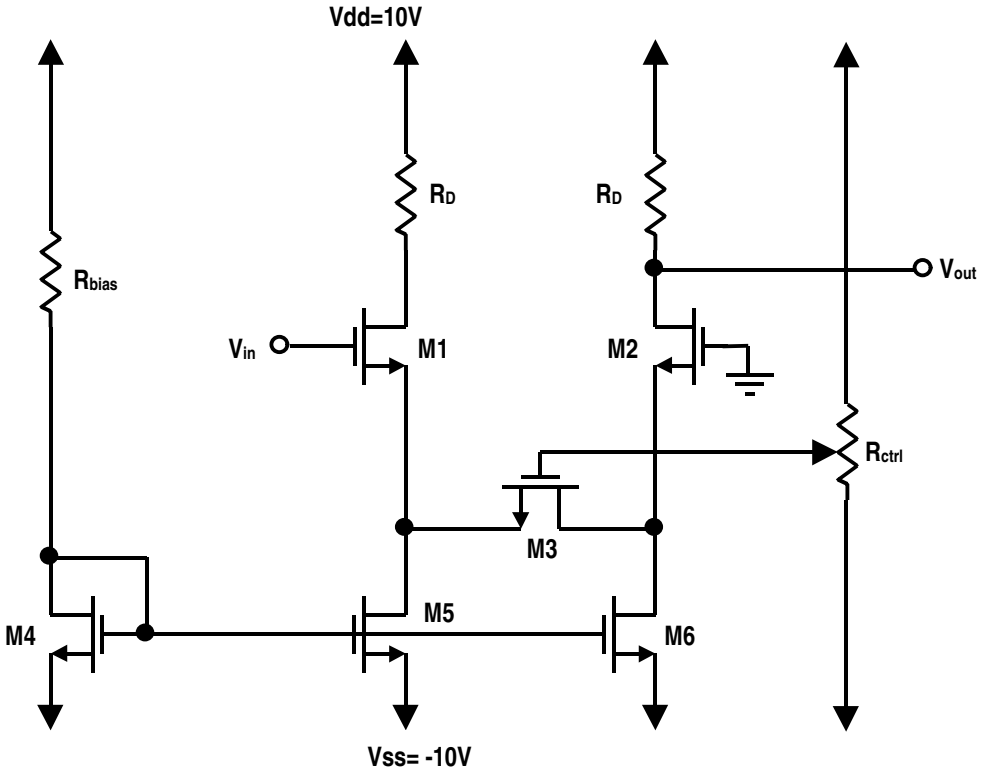

Fig. 1 – VCA Circuit

2.1 Circuit Topology

Generally speaking, this circuit functions as a standard differential pair with one twist… the two 'legs' of the differential pair are joined together by a transistor (**M3**) rather than being directly wired together. This transistor operates in the linear (triode) region rather than saturation, and effectively acts as a 'voltage controlled resistor.' The presence of this device allows us to vary the gain of the differential pair by varying the voltage on the gate of **M3**.

Since **M3** is operating in the linear region as a 'voltage controlled resistor', we can simply replace **M3** with a resistor **R** as shown below in Fig. 2.:

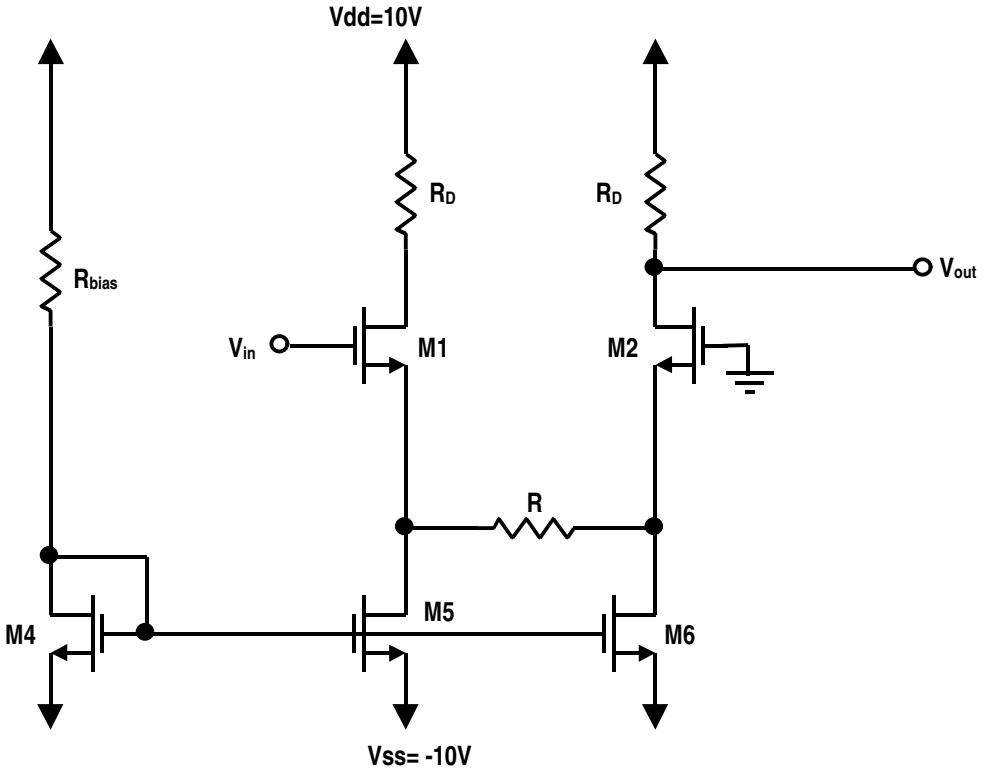

Fig. 2 – Simplified VCA

In order to find the ac gain of this circuit, it is necessary for us to evaluate the small signal model. Since the circuit is symmetrical, we can make the generalization that 'ac ground' occurs in the middle of the resistor **R**, providing us with the following model as shown in Fig. 3.

Since $\mathbf{V_{in}}$ is referenced to ground, the circuit is symmetrical and we can perform a half circuit small signal analysis using the circuit shown in Fig. 4.

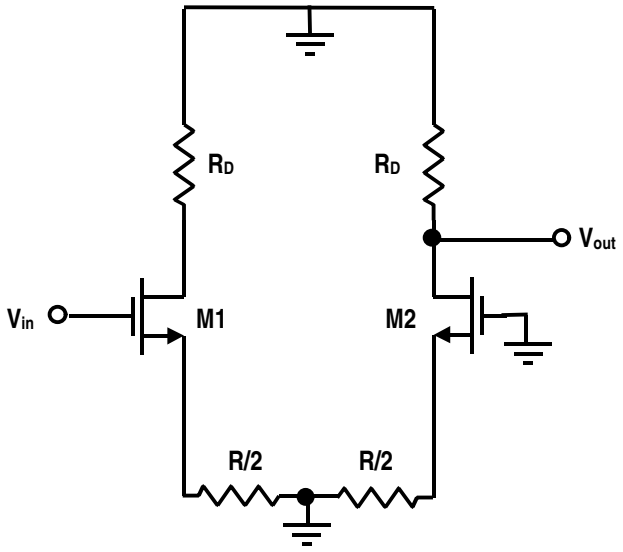

Fig. 3 – AC Analysis Model

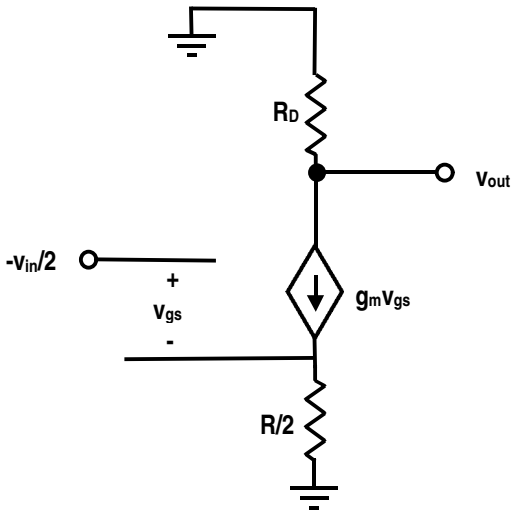

Fig. 4 – Half-Circuit Small Signal Model

By using KCL on Fig. 4, we can derive the voltage gain of the circuit. This comes out to be:

$$\frac{V_{out}}{V_{in}} = \frac{R_D}{R + \frac{2}{g_m}} \qquad \text{(Eqn. 1)}$$

In the triode region, the equivalent resistance see across the drain-source of **M3** is given by the following:

$$R = \frac{1}{g_m} \cong \frac{1}{2\ (V_{gs} - V_t)} \qquad \text{(Eqn. 2)}$$

Substituting this back into Eqn. 1 yields:

$$\frac{V_{out}}{V_{in}} = \frac{R_D}{\frac{1}{2\ (V_{gs} - V_t)} + \frac{2}{g_m}} \qquad \text{(Eqn. 3)}$$

2.2 Design Procedure

Step 1:

Consider the circuit shown in Fig. 2, but remove **R** from the circuit and replace it with a wire. The circuit is now a standard differential amplifier. Calculate the values for R_{bias} and R_D for this modified circuit to give your circuit the following characteristics:

- I_{bias} through **M4** = 100μA
- Gain = 20dB

Now, construct this circuit on your protoboard. (Remember to replace **R** with a wire!) It is important that you use the proper pinouts on the IC as explained in Appendix A. Apply a 1kHz, 100mV peak-to-peak sinusoidal signal to the gate of **M1**, and verify your circuit is working properly. Record all observations in your lab notebook, and explain any discrepancies.

Step 2:

Now, replace the wire you inserted between the two 'legs' of the differential pair in Step 1 with a 10kΩ pot. Once again, apply a 1kHz, 100mV peak-to-peak sinusoidal signal to the gate of **M1**, and vary the value of the pot. Carefully observe what happens to the gain of the circuit, and verify that it behaves like Eqn. 1 suggests.

Step 3:

Given its location in the circuit, determine the range of the voltage V_{G3} (where the limits of V_{G3} are constrained by the voltage rails) you can apply to the gate of **M3** in order to keep it operating in the linear region. Calculate the equivalent resistance r_{DS3} seen across the transistor for the range of voltages you determined. Replace the 10kΩ pot with the transistor **M3**, and tie its gate to a 10k pot as shown in Fig. 1 to vary the voltage at its gate. Measure the voltage at the gate of **M3** using your oscilloscope or voltmeter, and note any discrepancies between the calculations and actual results. Again, verify that the circuit behaves like Eqn. 3 suggests.

3. Good Analog Design Techniques

In order to have an analog circuit that functions predictably and reliably, good analog design techniques are necessary. Here are some suggestions for making your lab experience less frustrating and more productive:

- If you have an old protoboard, (one that has at one point caught fire, melted, or one that has been corrupted by plugging in digital IC's from 18-240 lab) chances are you will need a new protoboard. Beneath all those little sockets are metal clips, which spread out every time you plug something into them. By the time you have done this several times, they no longer make good contact with wires or IC pins. As a result, you will see strange, noisy waveforms on your oscilloscope, get unpredictable results, or get no results at all. While your protoboard may be ok for the 1's and 0's of digital

IC's, analog components are much more sensitive. Protoboards are available at Tech Electronics.

- Try to keep all signal lines away from power lines, and in general keep all lines a short as possible. Noise can and will find its way into your circuit wherever possible. Long signal paths and power supply lines kept near signal paths are susceptible to noise pickup and coupling.
- Try to keep all your component leads as short as possible. Having wires and components going an inch up into the air and then back into your protoboard will result in noisy and unpredictable performance, especially as you get up into higher frequencies. Clip component leads and wires, and try to get those components flush with the surface of your protoboard. Think about a real circuit board... you don't see components with bent leads an inch up in the air wiggling around!
- Make sure you have a solid ground reference. Without one, your circuit will be 'floating' and will perform miserably or not at all.
- It is unrealistic to put the whole circuit together and expect it to work. Instead, try to build your design in stages, and test it at every step along the way.

Following these general guidelines will not only result in a circuit that works better, but will also make the debugging process much simpler. The extra time spent carefully cutting wires and leads and placing components will save you much more time in debugging later on.

4. Appendices

4.1 Appendix A: Device Characteristics

$V_t = 1.3V$

$\beta = 235\mu A/V^2$

For the best device matching and assurance that the bulk of the transistors is tied to ground, please use the following scheme for wiring up your ICs:

IC #1:		**IC#2:**	
M1:	**Pins 9,10,12**	**M3:**	**Pins 9,10,12**
M2:	**Pins 3,4,5**	**M5:**	**Pins 3,4,5**
M4:	**Pins 6,7,8**	**M6:**	**Pins 6,7,8**

Tie Pin 14 of both ICs to Vdd.

Refer to the datasheet for assignments of gate, drain, and source.

1.2 Appendix B: Parts List

(2) CD4007 CMOS ICs

Resistors, Potentiometers

1.3 Appendix C: Acknowledgements

I would like to thank Dave Guillou and Mariusz Niewczas for their suggestions and ideas.