Logarithmic Amplifier

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1 Introduction

A logarithmic amplifier (log-amp) gives an output that is the logarithm of the input. The base can be any value of choice. Applications of logarithmic amplifiers include direct analog conversion of values in decibels. For example, the acoustic noise levels are expressed in decibels. Logarithmic amplifiers are also used for extending the dynamic range of circuits.

You have already worked with several op-amp based analog circuits. One common feature of many of these circuits is that the output versus input relationships are governed mainly by the external components connected to the op-amp. Taking this as a lead, for implementation of log-amp we require a component, the terminal characteristics of which include a logarithmic or exponential function. A pn junction diode is such a device. We will use a diode and op-amps, and other components to design, simulate and realise a log-amp. The log-amp in the design presented in subsequent sections would give as output the natural logarithm of the input.

2 Basic Design Concepts

The equation for the terminal characteristics of a pn junction diode in forward bias is

$$I_D = I_S * (e^{V_D/nV_T} - 1) \tag{1}$$

where, I_D is the current through the diode, V_D is the voltage across the diode, I_S is the reverse saturation current, n is the ideality factor of the diode, and V_T is the thermal voltage given by kT/q , where k is the Boltzmann constant, T is the temperature in Kelvin, and q is the elementary charge. We will assume for the time being that I_S and n are constants. The value of V_T at 27°C or 300 K, as you may verify, is 0.026 V. When $V_D >> n * V_T$, say $V_D > n * 100mV$, we may approximate equation (1) as

$$I_D = I_S * e^{V_D/nV_T} \tag{2}$$

and

$$V_D = nV_T * (\ln(I_D) - \ln(I_S)) \tag{3}$$

Equation (3) can be rewritten as

$$\ln(I_D) = V_D/nV_T + \ln(I_S) \tag{4}$$

Equation (3) suggests that a log-amp may be realised by forcing a forward bias current through a pn junction diode, and the voltage across the diode would be linearly related to the logarithm of the current. However the diode voltage would not be true natural logarithm of the input current. It would contain an offset and also a multiplying factor. Moreover we may want to give a voltage input to the amplifier.

3 Development of the Circuit

A voltage can be easily converted to a current using the inverting amplifier configuration. You may please draw the circuit in your note book. The voltage applied to the input resistor is converted to a current, $I = V_{in}/R$, where R is the input resistor connected to the inverting terminal of the amplifier. The same current I is then forced through the device connected between the output of the op-amp and the inverting terminal. The device can as well be a diode. The circuit is given in figure 1.

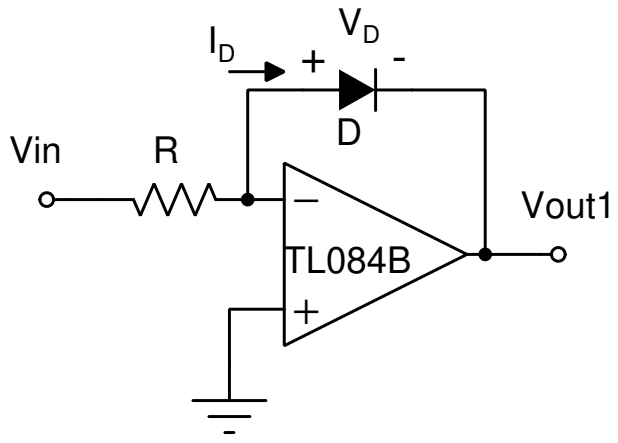

Figure 1: Basic log-amp circuit. For this circuit to function as a log-amp, the polarity of the input voltage should be positive.

$$I_D = V_{in}/R \tag{5}$$

From figure 1,

$$V_{out1} = -V_D \tag{6}$$

Substituting equation (5) in equation (3), and rearranging,

$$V_{out1} = nV_T * (\ln(I_S R) - \ln(V_{in})) \tag{7}$$

Equation (7) can be written in the following form.

$$V_{out1} = a_1 \ln(V_{in}) + a_2 \tag{8}$$

where,

$$a_1 = -nV_T \tag{9}$$
$$a_2 = nV_T \ln(I_S R) \tag{10}$$

Equation (8) tells us that the output of the circuit in figure 1 is the natural logarithm of the input scaled by a factor a_1 and then offset by a_2. We can remove the offset by subtracting a_2 from V_{out1}. The result can then be multiplied by $1/a_1$ using a suitable amplifier, to obtain at the output the true natural logarithm of V_{in}. The complete circuit is shown in figure 2.

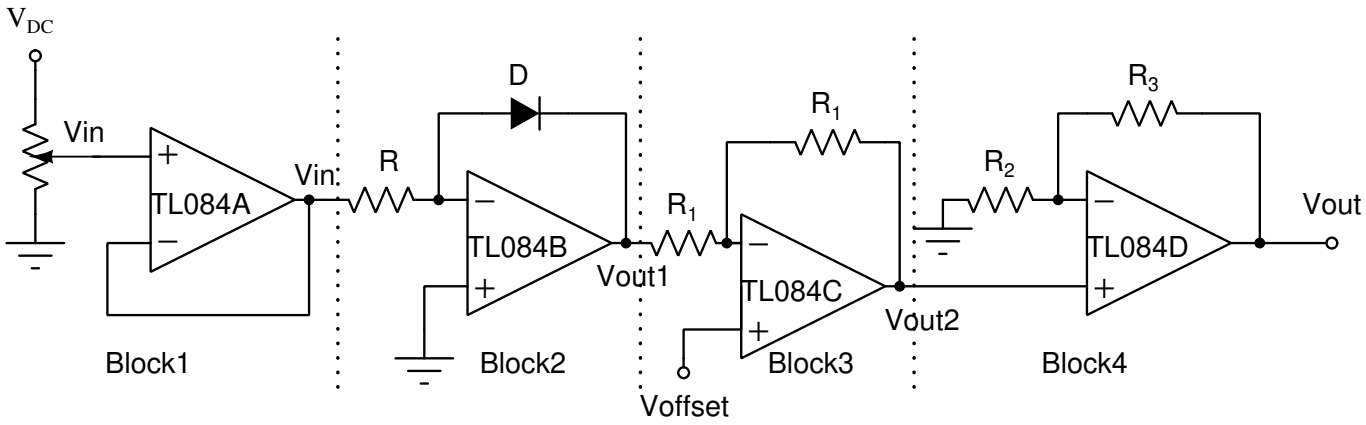

Figure 2: Complete logarithmic amplifier circuit.

The third block is used for removing the offset from V_{out1}.

$$V_{out2} = -V_{out1} + 2V_{offset} \tag{11}$$
$$= -a_1 \ln(V_{in}) - a_2 + 2V_{offset} \tag{12}$$

set $V_{offset} = a_2/2$ in equation (12). So the input to block 4 would be $-a_1 \ln(V_{in})$.

$$V_{out} = -a_1(1 + R_3/R_2) \ln(V_{in}) \tag{13}$$

Choosing $\frac{1}{1+R_3/R_2} = -a_1$, we obtain.

$$V_{out} = \ln(V_{in}) \tag{14}$$

The role of block 1 is to avoid loading the source of V_{in} by block 2.

4 Practical Design Considerations

4.1 Diode Specific Considerations

In section 2, the diode was assumed to be ideal, in the sense that the current through the diode would exponentially increase with the voltage across the diode. We also assumed that the ideality factor, n and the saturation current, I_S are constants. Figure 3 shows the measured current - voltage characteristics of 4 different models of silicon diodes. Please note that $\ln(I_D)$ is plotted as a function of voltage across the diode.

The following observations can be made from figure 3.

1. As per equation (4) which is the basis for the design of the log-amp, $\ln(I_D)$ versus V_D should be a straight line, if n and I_S are constants. In case of D1, D2 and D3, this is true only over limited ranges of currents. These diodes can be used for making log-amps only over those specific ranges of currents. In case of D4, there seems to be multiple linear segments, each segment with much smaller current ranges than in the case of other diodes. We will

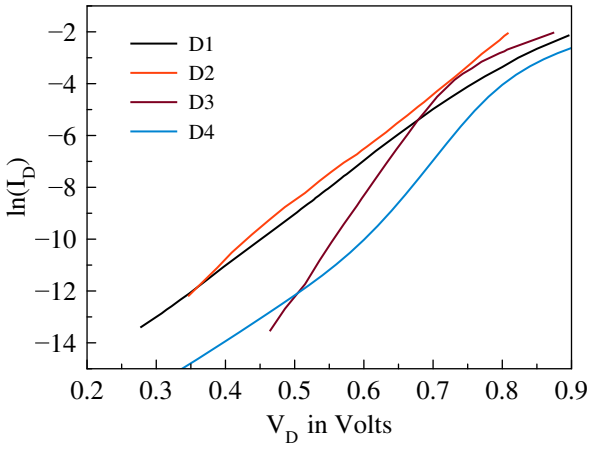

Figure 3: Comparison of the measured current - voltage characteristics of 4 different models of diodes.

not consider diodes like D4 for realisation of log-amps. In fact this diode can be modelled using what is called a 2-diode model. We will not elaborate further on this.

2. By comparing D1 and D3, for current range over which $\ln(I_D)$ versus V_D is linear, you may note that the slopes $(1/nV_T)$ as per equation (4) are not identical. Since V_T is a constant at a given temperature, we may conclude that the ideality factor, n, is different for D1 and D3. The slopes look similar for D1 and D2, indicating that the ideality factors for these two models of diodes are close.

3. The y-intercept of $\ln(I_D)$ versus V_D is $\ln(I_S)$. Hence the saturation current can be estimated from the y-intercept. The saturation currents for different diode models are different.

4. From the above discussion, it is clear that the log-amp design is specific to the model of diode used in the circuit. A circuit designed for D1 would not work with D3, for example.

4.2 Selecting the Input Voltage Range

The $\ln(I_D)$ versus V_D plot for one specific model of diode is shown in figure 4. The open symbols represent the actual measured data. A straight line is fitted to a range of $\ln(I_D)$ highlighted in the figure in maroon colour. The corresponding range of current is I_{D1} to I_{D2}. Using equation (5), the range of input voltage would be from $V_{in1} = I_{D1}/R$ to $V_{in2} = I_{D2}/R$.

If we assume that the maximum input voltage, $V_{in2} = 10V$, then $R = 10/I_{D2}$. Using equation (5), we can also write, $V_{in1} = V_{in2} * I_{D1}/I_{D2}$.

4.3 Extraction of Diode Model Parameters

The diode saturation current, I_S can be calculated from the y-intercept of the linear fit shown in figure 4. Ideality factor, n, can be calculated from the slope of the linear fit shown in figure 4. The SPICE model for the diode can be specified using these parameters as,

.model diode1 D(Is = ? N = ?)

"Is" in the above statement is the saturation current and N is the ideality factor. "?" should be replaced with the values of these parameters estimated from the fitting exercise.

4.4 Choice of Op-Amp

Operational amplifiers require input DC bias currents flowing into the inverting and non-inverting terminals. The input bias current should be much less than I_{D1} for the log-amp to work to specification in the low input voltage range. For example, the input bias current of 741 can be upto 0.5 μA. If $I_{D1} < 5\mu$A, 741 is not a good choice. A precision op-amp with low input bias currents would be a better choice. You may consider TL084 for this experiment.

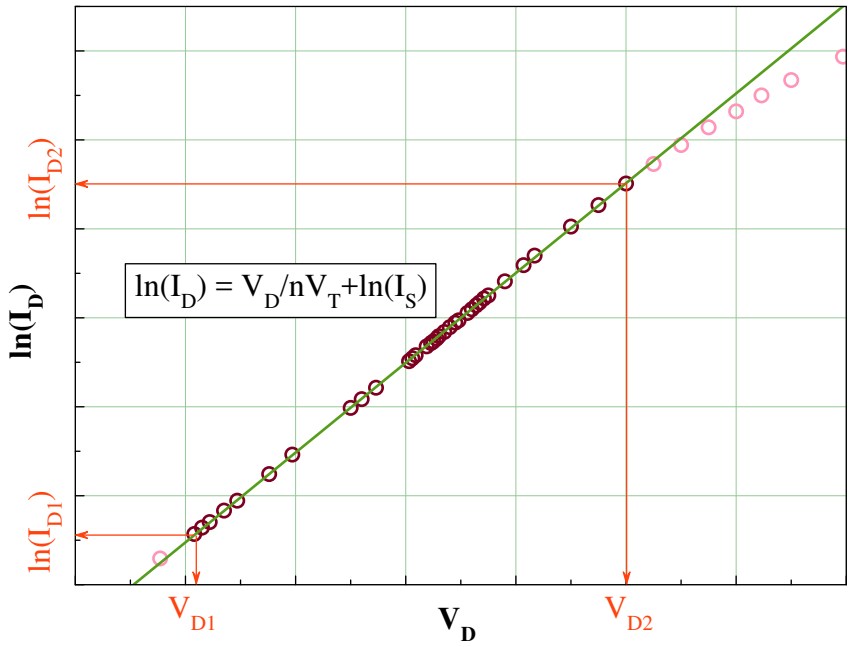

Figure 4: Current - voltage characteristics of a specific model of diode. The open symbols represent the actual measured data. The straight line represent a linear fit to $\ln(I_D)$ versus V_D data. Equation (4) is valid only over the current range I_{D1} to I_{D2}.

5 Experiment

After carefully reading this document you are expected to conduct the experiment. You would be provided the measured I_D versus V_D data for a diode suitable for log-amp implementation. The experiment would involve the following steps, which should be executed and should be carefully documented.

1. You would be provided a text file containing the measured current - voltage characteristics of a diode suitable for implementing log-amps. Plot $\ln(I_D)$ versus V_D. Use open markers (no line) as shown in figure 4 for plotting the experimental data.

2. In the above plot, manually identify the range over which $\ln(I_D)$ is a linear function of V_D. This can be done by manually drawing a line passing through the linear segment of the plot identified by visual inspection. Determine the linear fit using two sufficiently far spaced data points falling on the manually drawn straight line. Calculate I_S and n. (Recommendation: If you know how to use the curve fitting functions of the plotting software you are using, use it.)

3. Determine the range of diode currents over which the log-amp can be operated. Determine the value of R.

4. Write down the expression for V_{out1}.

5. Determine the values of V_{offset}, R_1, R_2, and R_3.

6. Create a SPICE model file for the diode.

7. Verify and fine tune the design using SPICE simulations. Create a plot containing the ideal expected V_{out} versus V_{in} (a line plot is recommended), and the data obtained from SPICE simulations (a scatter plot with open markers is recommended). The ideal expected plot would be a straight line passing through zero and would have slope of 1. Any deviation of the results of simulation (easily identified if the plots are made as recommended) calls for fine tuning of the design.

8. Assemble and test the circuit. The circuit should be tested by varying the input voltage over the designed range and documenting the output voltage. Create a plot containing the ideal expected V_{out} versus V_{in} (a line plot is recommended), and the data obtained from the hardware (a scatter plot with open markers is recommended). If any deviations are seen, fine tune the implementation to obtain results as close to ideal as possible.

9. Suppose that you would like to obtain $\log_{10}(V_{in})$ as the output. What changes are needed in the circuit to achieve this? Would the change lead to any additional constraints on the specifications of the circuit?

10. Document prepared with the above details should be submitted to your TA/RA for evaluation.