University of Michigan
EECS 311: Electronic Circuits
Fall 2009

LAB 3 – PERPETUAL LED

Issued 10/26/2008
Report due in Lecture 11/9/2008

Introduction

In this lab you will design a stand-alone circuit that is capable of harvesting RF energy from a cell phone and using it to blink an LED. The lab will be designed in two separate stages: 1) design and build a rectifier stage, and 2) design and build an LED switching stage. These stages are illustrated in Figure 1. This is a 2-week lab, the goal for week 1 is to complete the rectifier stage, and week 2 to complete the switching stage and assemble the entire design.

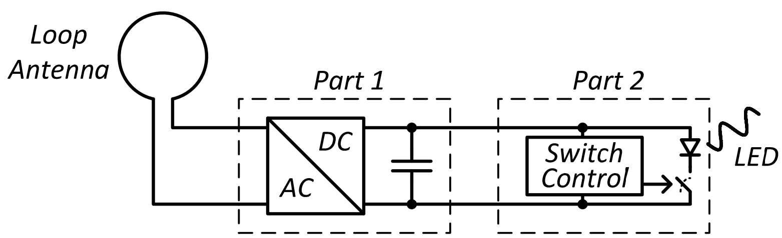


Figure 1. Overview of lab 3.

GSM Cellular Signals (used by AT&T Wireleess, T-Mobile, TracFone)

During a call, your cell phone is transmitting and receiving signal to and from a base station that is usually less than a mile away. A GSM phone (i.e. specifically GPRS/EDGE) uses a type of modulation called GMSK which encodes data on the phase of a sine wave. When you place a call, the phone transmits your voice on a signal with the characteristics shown in Figure 2. The signal sent from the phone will be centered at a frequency around $850MHz$, and will transmit in short, high-power bursts that look like a sine wave, are $570\mu s$ long, and repeat every $4.6ms$.

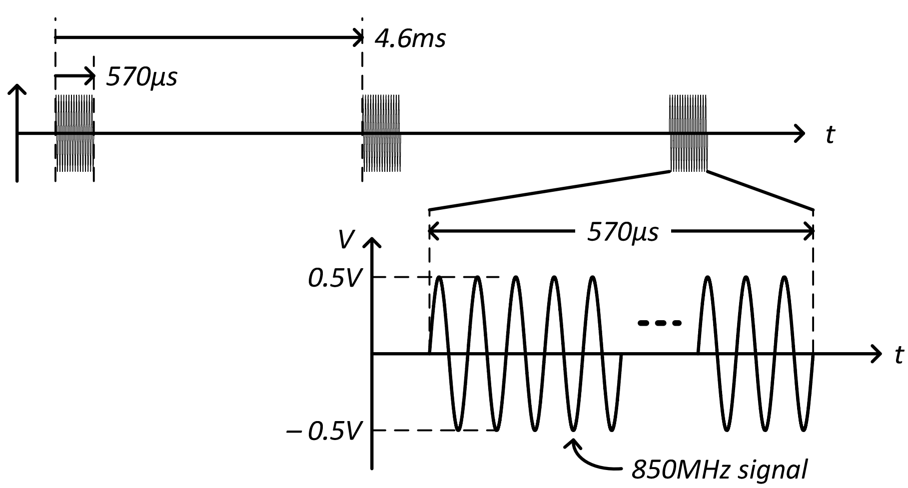


Figure 2. GMSK-modulated signal transmitted from a GSM phone.

Week 1 – Rectifier Stage

This week you will design and build the radio frequency (RF) rectifier stage. This stage will convert a sine wave into a DC signal, boosting the voltage using switched capacitors. The specifications of the rectifier are given in Table 1.

Specification	Value
RF Center Frequency	850MHz
RF Signal Duration	570µs
RF Signal Repetition Rate	4.6ms
RF Source Resistance	300Ω
DC Storage Capacitor	33µF
Rectified DC Voltage	1.7V

Table 1. Rectifier specifications.

Week 1: In-Lab Exercises

L3.1 Build a half-wave rectifier using a 1N7511 Schottky diode from your lab kit, and a 2.2nF ceramic capacitor as the load. Use the signal generator to drive the rectifier with a $20MHz$, $1V_{ppk}$ sine wave (put the generator in high-Z mode). Measure the rectified voltage on the capacitor, and then estimate V_{ON} of the Schottky diode assuming a constant voltage drop model for the diode.

The pinout of diode is shown in Figure 3.

Figure 3. 1N5711 Schottky diode pinout.

L3.2 A schematic of a 3-stage voltage-boosting rectifier is shown in Figure 4. Sketch the voltages v_A, v_B, and v_C over the first three cycles when v_{RF} is a sine wave with $1V_{ppk}$, assume the diodes are ideal and all caps are discharged at $t = 0$. What are the values of v_A, v_B, and v_C in steady-state ($t = \infty$)?

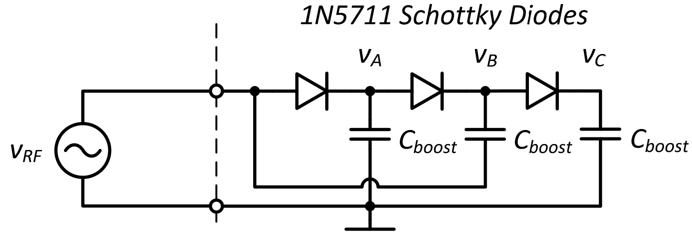


Figure 4. 3-stage voltage-boosting rectifier circuit schematic.

L3.3 Using the V_{ON} measured in L3.1, calculate the minimum number of stages required to generate the value of V_{DD} specified in Table 1 with the multi-stage rectifier shown in Figure 5. Calculate the expected V_{DD} for this number of stages, again using V_{ON} from L3.1. Assume v_{RF} is a sine wave with $1V_{ppk}$. Show your results from L3.1-L3.3 to the GSI.

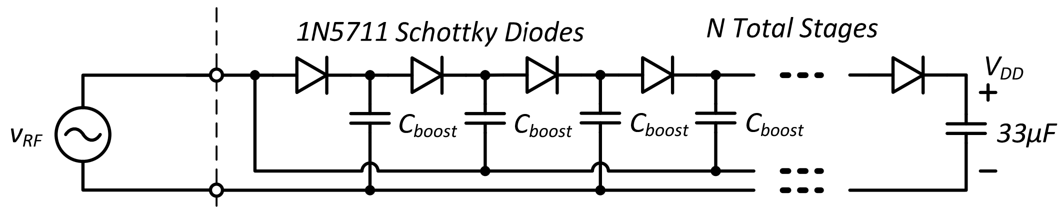


Figure 5. Multi-stage voltage-boosting rectifier circuit schematic.

L3.4 Using the 1n5711 diodes in your kit, build the rectifier shown in Figure 5 with the number of stages you calculated in L3.3. It is recommended you use the small breadboard found in your labkit for this, and minimize the lengths of wires. Measure the steady-state output voltage when a $20MHz$, $1V_{ppk}$ sine wave is applied to the input. Look at V_{DD} on an oscilloscope and measure the peak-to-peak ripple voltage. Finally, measure the time it takes to charge the capacitor from $0V$ to $1.7V$. This can be done by first discharging the $33\mu F$ capacitor with the signal generator off, then enabling the function generator while triggering on V_{DD}. Try different time/div settings on the oscilloscope to capture the entire transient. Have the GSI check you off on this part.

Hint: Trim the leads on your components to keep them short (minimizes parasitic inductance), and try to minimize the number of rows used on your breadboard to build your circuit (minimizes parasitic capacitance).

L3.5 Build a loop antenna, tuned to $850MHz$, using hook-up wire available in the lab. The antenna is a simple circular loop of wire, where the circumference of the loop should equal one wavelength. Calculate the wavelength of an $850MHz$ wave travelling in freespace at the speed of light. When operating at its resonant frequency, this antenna can be modeled by a voltage source with a source impedance of 300Ω as shown in Figure 6.

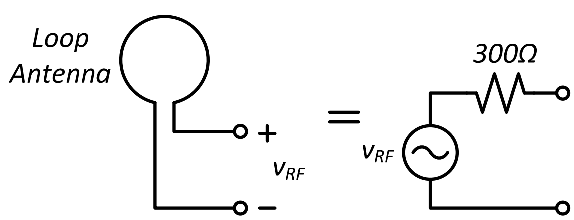


Figure 6. Thevenin equivalent circuit for the loop antenna.

Form the wire into a circle, and connect both ends of the loop to the positive and negative inputs of your rectifier. Find someone with a GSM cell phone (ideally AT&T, 3G disabled). Ask them to place a call (e.g. to voicemail). Put the phone near the loop antenna while measuring the rectified V_{DD}. Record the highest DC voltage you are able to "harvest" from a cell phone.

Week 2 – Hysteretic LED Switching Circuit

This week you will design and build the stage that controls the turn-on/turn-off of the LED, powered by the rectifier stage. This stage will detect when the rectified DC voltage reaches an upper threshold and then turn on the LED. When the LED is on, it rapidly discharges the storage capacitor. When the DC voltage reaches a lower threshold voltage, the LED is turned off. This operation of switching with two thresholds is called hysteresis. The design specifications are given in Table 2.

Specification	Value
LED Turn-on Voltage	1.7 V
LED Turn-off Voltage	1.5 V
Power at 1.7 V (without LED)	340 μW

Table 2. Hysteretic LED controller specifications.

Week 2: Pre-Lab Exercises

In some pre-lab exercises, you are asked to choose values of resistors. Use only values available in the lab, which can be found at the following website.

http://www.eecs.umich.edu/courses/eecs311/f09/labs.html

P3.1 The circuit used to bias the LED is shown in Figure 7. This circuit has two stable modes of operation: 1) LED on and, 2) LED off. Solve for the base and collector currents in the PNP transistor in both modes of operation when $V_{DD} = 1.7V$. Also, identify the regions of operation of the NPN and PNP in both modes. $|v_{BE,ON}| = 0.6V$ for both the NPN and PNP assuming the CVD model for the B-E juntions. Assume the CVD model for the LED with $v_{ON} = 1.6V$.

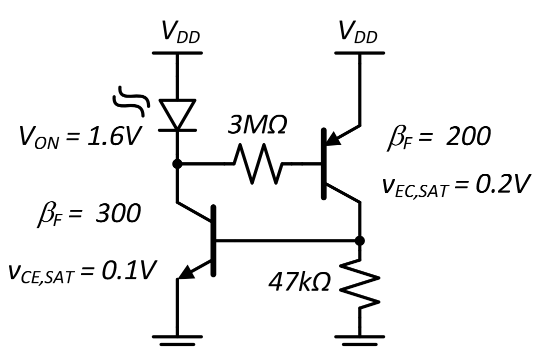


Figure 7. Bi-stable LED circuit.

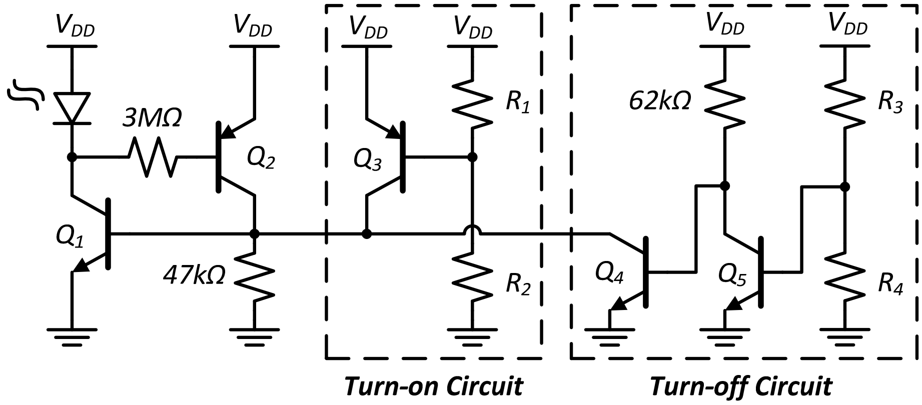


Figure 8. Complete switching circuit.

P3.2 The complete circuit is shown in Figure 8. The bi-stable LED circuit is forced into the "on" mode by driving current onto the $47k\Omega$ resistor with the PNP transistor Q_3. The circuit shown in Figure 9 will be used to detect the turn-on voltage threshold (Table 1). The turn-on voltage of the E-B junction of the PNP is $v_{EB,ON} = 0.55V$. Derive expressions for R_{TH} and V_{TH} in terms of V_{DD}, R_1, and R_2. Determine values for R_1 and R_2 that will turn on the PNP when V_{DD} reaches $1.7V$. Assume $\beta_F = 200$, and the PNP is in the forward active region. Take into account the limit on power consumption given in Table 2 when choosing resistor values.

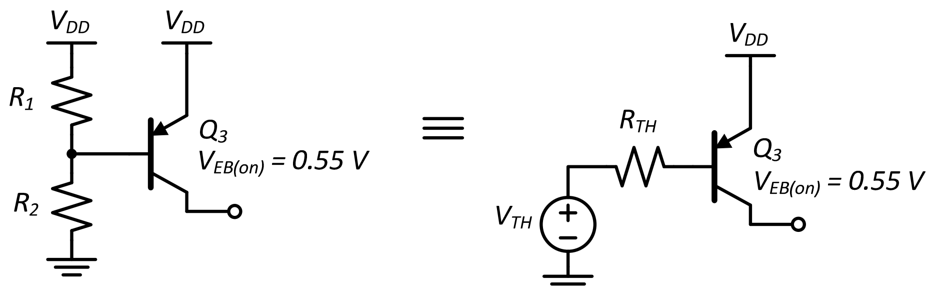


Figure 9. Turn-on threshold detection circuit.

P3.3 The bi-stable LED circuit is forced into the "off" mode by using Q_4 to pull down the base voltage of Q_1 in Figure 8. The circuit shown in Figure 10 will be used to detect when V_{DD} reaches the turn-off voltage threshold (given in Table 2). When V_{DD} drops below the turn-off threshold voltage, Q_5 should go from FAR to the cutoff region. The $62k\Omega$ resistor then supplies base current to turn Q_4 on in FAR. This forces the LED circuit to the off mode by pulling v_{BE} of Q_1 to 0. The turn-on voltage for Q_5 is $v_{BE,ON} = 0.55V$ and $\beta_F = 300$.

Derive expressions for R_{TH} and V_{TH} in terms of V_{DD}, R_3, and R_4. Determine values for R_3 and R_4 that will turn <u>on</u> Q_5 when V_{DD} equals the turn-<u>off</u> voltage. Take into account the specification on power consumption when choosing resistor values.

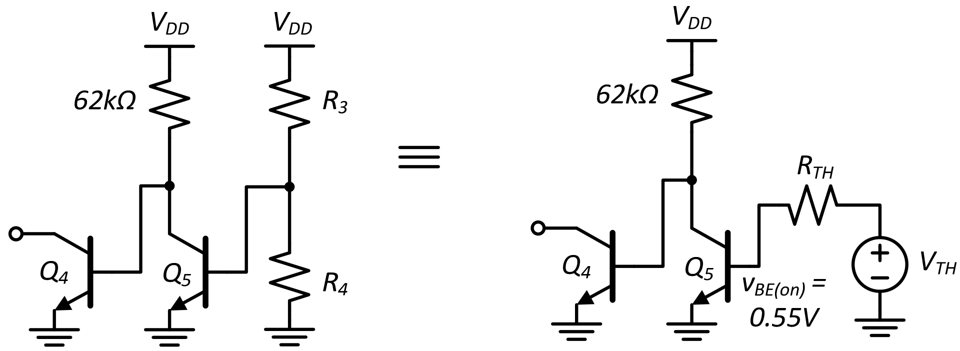


Figure 10. Turn-off threshold detection circuit.

P3.4 Open Cadence and create a new cell in your *lab3* library called *ledcontrol*. Refer to the online Cadence tutorial for help using the NPN/PNP devices.

http://www.eecs.umich.edu/courses/eecs311/f09/tutorials/cadence.html

a) Build the circuit shown in Figure 8, using resistor values found in the previous parts. Use the *lab3_led* component found in the *EECS311Lib* library for the LED. For the NPN devices, use the *AnalogLib > npn* component. Give each *npn* a model name of *2n3904_typical*. For the PNP devices, use the *AnalogLib > pnp* component. Give each *pnp* a model name of *2n3906_typical*. Do not add a voltage source for V_{DD} yet.

b) In your *ledcontrol* schematic, add a piecewise-linear voltage source connected to the V_{DD} pins and ground. This source can be found in *AnalogLib > vpwl*. Within the *vpwl* properties, change the number of pair points to *4*, and enter the pairs given in Table 3.

Time	Voltage
0	0
10m	2
20m	2
30m	0

Table 3. Time-voltage pairs for piecewise linear voltage source.

c) Perform a transient simulation of your circuit and determine the values of V_{DD} that turn on and off your LED circuit. Attach a plot of your simulation. Also record the current drawn from the *vpwl* V_{DD} by the circuit when the LED is removed.

Week 2: In-Lab Exercises

As with any large circuit, you will build and test each stage individually before assembling the entire circuit. You'll start by building the switching stage and testing it with a power supply as the DC voltage source. Then you will replace the source with your rectifier stage from Part 1 and try powering the LED with a signal generator and a cell phone.

L3.1 Build the circuit shown in Figure 8 using the component values found in the prelab. For now, wire all V_{DD} pins together and ground pins together, but do not connect them to any supply or to your rectifier circuit from week 1.

L3.2 Connect the DC power supply to your V_{DD} and ground pins. Begin with the power supply set to 0V and slowly increment the voltage until your turn-on circuit turns on the

LED. Detect when the LED turns on by monitoring when the base voltage of Q_1 becomes $v_{BE,ON}$. Once the LED is on, next slowly lower the DC supply voltage and record the value at which your turn-off circuit turns the LED off. Again, monitor the base of Q_1 to detect when the LED is off. Finally, vary the DC voltage from 0 to something over your turn-on voltage several times to make sure the turn-on/turn-off operation is repeatable. Show your circuit to the GSI.

L3.3 Remove the connection to the DC supply and connect the output of your rectifier from Week 1 to the V_{DD} and ground pins. Connect the input of the rectifier to the signal generator. Configure the signal generator as a sine wave, frequency $20MHz$, and high-Z mode. Increase the amplitude of the function generator until the LED just begins to blink. Record the peak-peak voltage required to power your LED.

L3.4 Finally, replace the function generator with the antenna built in Week 1. Use a cell phone to power the rectifier by placing a call and holding your phone very close to the antenna. You may need to try out different positions of the phone to get any rectified voltage. Probe the DC voltage with an oscilloscope while powering the rectifier to verify it is charging and record the peak voltage seen on the rectified V_{DD}.

University of Michigan
EECS 311: Electronic Circuits
Fall 2009

LAB 3 – CHECK-OFF SHEET

NAME: ______________________________________ LAB SECTION: ____________

Have the GSI check you off on the following exercises after you have completed them. Be prepared to answer questions about your circuit or the results.

Exercise .... Date Completed

Week 1:

L3.1-3 Half-wave rectifier, V_{ON}, number of stages ....________________

L3.4 Complete rectifier working ....________________

Week 2:

P3.x Prelab Report Template ....________________

L3.2 Switching stage with DC source ....________________

University of Michigan
EECS 311: Electronic Circuits
Fall 2009

LAB 3 WEEK 1 – REPORT TEMPLATE

NAME: ____ LAB SECTION: ____________

Use the following lab report template to record your measurements. Use the space provided to answer questions.

Lab Report Template

L3.1 Value of V_{ON} for Schottky diode: V_{ON} = _____________

L3.2 Sketch the voltages v_A, v_B, and v_C in the space below for the first 3 cycles of v_{RF}.

What are the values of v_A, v_B, and v_C in steady-state ($t = \infty$):

v_A = __________ v_B = __________ v_C = __________

L3.3 Minimum number of stages N_{stages} = ______________

Calculated steady-state V_{DD} V_{DD} = ___________

L3.4 Rectifier circuit

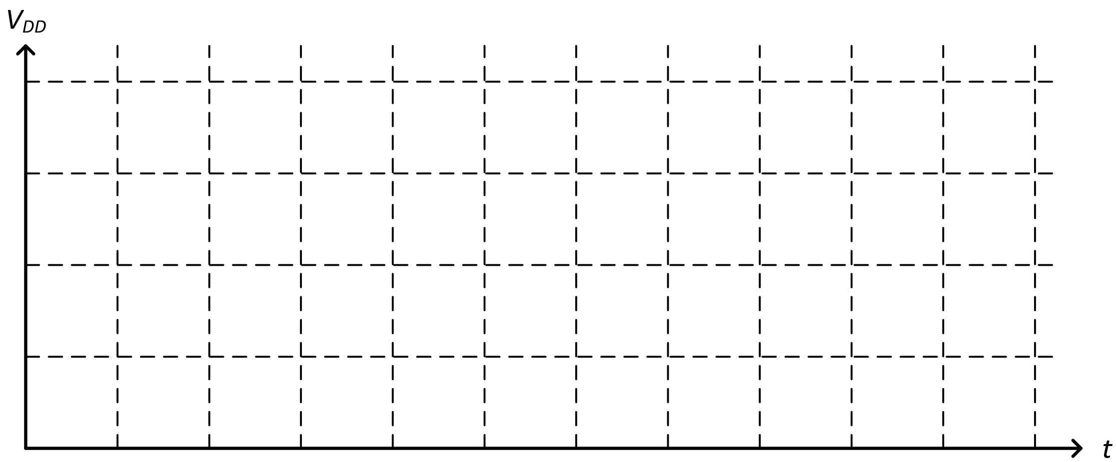
Response of V_{DD} to a $1V_{ppk}$, $20MHz$ input sine wave:

Steady-state value of V_{DD} = _______________

Peak-Peak ripple voltage on V_{DD} = _______________

Time from $0V$ to $1.7V$ = _______________

Sketch the transient response of V_{DD} from $0V$ to $1.7V$:



L3.4 Wavelength at $850MHz$: $\lambda =$ _______________

Highest V_{DD} harvested from a phone: $V_{DD,max}$ = _______________

Service provider of the phone used (e.g. AT&T) = ______________________________

Manufacturer of the phone used (e.g. Samsung) = ______________________________

In the space below, approximate the amplitude of the received RF signal and briefly explain how you arrived at this number. Base your approximation on your measurement of V_{DD} with the function generator source at $1V_{ppk}$, and your measurement of V_{DD} from the cell phone and antenna.

University of Michigan
EECS 311: Electronic Circuits
Fall 2009

LAB 3 WEEK 2 – PRE-LAB REPORT TEMPLATE

NAME: ______________________________________ LAB SECTION: ____________

Pre-Lab Exercises

P3.1 PNP base and collector currents, and regions of operation in two modes:

Off Mode: NPN Region = _____________ PNP Region = _____________

PNP I_B = _____________ PNP I_C = _____________

On Mode: NPN Region = _____________ PNP Region = _____________

PNP I_B = _____________ PNP I_C = _____________

P3.2 **Use only component values available in the 311 lab, listed at** **http://www.eecs.umich.edu/courses/eecs311/f08/labs.html**

R_{TH} = _____________ V_{TH} = _____________

R_1 = _____________ R_2 = _____________

Power in R_1 and R_2 branch at 1.7V = _____________

P3.3 **Use only component values available in the 311 lab, listed at** **http://www.eecs.umich.edu/courses/eecs311/f08/labs.html**

R_{TH} = _____________ V_{TH} = _____________

R_3 = _____________ R_4 = _____________

Power in R_3 and R_4 branch at 1.7V = _____________

P3.4 Piecewise linear simulation in Cadence.

Turn-on voltage = _____________

Turn-off voltage = _____________

Attach a plot of your simulation.

Peak current drawn by circuit without LED = _____________

University of Michigan
EECS 311: Electronic Circuits
Fall 2009

LAB 3 WEEK 2 – REPORT TEMPLATE

NAME: ______________________________________ LAB SECTION: ____________

Use the following lab report template to record your measurements. Use the space provided to answer questions.

Lab Report Template

L3.1 Measured values of resistors used in lab:

$R_1 =$ _______________ $R_2 =$ _______________

$R_3 =$ _______________ $R_4 =$ _______________

$47k\Omega =$ _______________ $62k\Omega =$ _______________ $3M\Omega =$ _______________

L3.2 Switching circuit powered by voltage source.

Turn-on DC voltage = _______________

Turn-off DC voltage = _______________

L3.3 Switching circuit powered by rectifier with $20MHz$ signal generator source.

Peak-peak voltage required to blink LED = _______________