Project 2

LC Oscillator with Varactor Tuning

Due Date: Friday, October 25, 2019

Background:

An LC oscillator is used in a radio transmitter to generate a carrier signal and in a receiver to tune the radio and convert the received signal to IF or baseband. In early radios, tuning was provided by a variable capacitor mechanically hooked to a knob (often through a pulley arrangement to allow multiple turns of the knob for a single turn of the capacitor). In most newer radios, a voltage controlled oscillator (VCO) is used in conjunction with a “synthesizer” IC which tunes the VCO to a precise frequency.

To keep this project simple, we will design and build a VCO, but not a synthesizer circuit. Instead, we will use a potentiometer to create a variable voltage that adjusts the frequency. We will discuss synthesizers briefly and you can add one later if you like (we have some parts and Arduino firmware for that).

Objective:

The objective of this project is to design, build, and test an LC oscillator suitable for use as an RF source in our FM transmitter that you will assemble and demo for the midterm exam ***and*** later as an LO in our FM broadcast band receiver built and demo’ed for the final exam.

To be used in a classical superheterodyne receiver with an IF frequency of 10.7 MHz, the VCO frequency needs to be above or below the desired station frequency by 10.7 MHz. We will use "low-side injection" where the oscillator frequency is below the desired station's frequency. This will allow us to avoid unintended emissions into the aircraft band, which lies from about 118 MHz to 137 MHz. It will also allow you to generate signals and transmit in the bottom of the FM band, during your midterm demo.

Teamwork:

As before, you should work with your teammate on this project and divide the workload approximately evenly. As in project 1, both teammates should work on and understand the full project - so, like project 1, the work is collaborative - EXCEPT at the writeup stage (See Writeup section on the last page).

Ultimately, as with project 1, two copies of the board will be needed, since each student will need their own for the midterm. As before, we recommend you get one working and then replicate it after that.

Specifications:

- Power consumption of < 40 mW drawn from 5V supply (at 25C).
- Oscillation frequency range suitable for tuning over the FM broadcast band in a ***receiver*** with a 10.7 MHz IF (Tuning range should be a bit greater than +/- 10 MHz to provide some margin on the ends).
- On-board varactor diode and potentiometer for frequency tuning *with clockwise rotation producing higher frequency*.
- Temperature-stable capacitors and on-board voltage regulator for good frequency stability - Frequency drift of less than+/- 10 ppm / ºC and less than 1 kHz per volt of the 5V USB supply variation.
- Output power of > -6 dBm into 50 Ohms.

Circuit topology:

You may use either a common-base(gate) or common-collector(drain) topology. In either case, you should provide a buffer stage, and AC coupling (DC blocking cap) at the final output.

Suggested design procedure:

A suggested design procedure is outlined below. *As in most design activities, component selection in each step may affect previous steps so that some iteration may be needed*.

Step 0: Data Sheet Familiarization

Review the parts available in your kit and study the datasheets. We'll use the 5179 transistors, but also need a voltage regulator and varactor diode - plus a potentiometer.

Step 1: Voltage Regulator Design

Using a three-terminal linear regulator, design a regulated 3.3 V supply to power your oscillator and your tuning potentiometer. This is recommended to meet the frequency drift specification. If not provided, the noise from a USB supply will likely modulate the oscillator frequency excessively.

Step 2: Circuit Selection and Design Bias Circuit

Design bias circuits for your transistor(s) with attention to the power consumption specification. For the oscillator-core BJT, you may want to use a low'ish current to keep the X_{C2} value sufficiently high. But not too low, since it needs to have enough output drive as well. Also, check the regulator data sheet to see how much current it consumes and account for any other users of current. This may limit what you can use in your buffer for example. You may use *typical* values for the regulator current consumption portion. ***Show your calculations, listing the current consumers (regulator, oscillator core, and buffer.***

Step 3: Design Oscillator Core

Select values for the capacitors and inductor of the oscillator core. You should design for a loop gain sufficient to guarantee oscillation. *Also, remember that you must add a varactor for tuning over a fairly large frequency range. Pick your C and L values to allow for this. As stated above, you may need to do an iterative solution in conjunction with the preceeding and following steps*.

Step 4: Design Varactor Tuning

Add the varactor diode circuit to make your oscillator voltage-controlled and check the lowest and highest frequecies you can achieve. Be sure to use the regulated supply to minimize frequency drift.

Step 5: Buffer and Output Coupling

Design your buffer to produce a low output impedance to deliver the specified level to a 50 Ohm load, while lightly loading the oscillator core. For this part of the design, assume that the peak-to-peak AC oscillation voltage across the base-emitter junction is on the order of to 400 mV. ***You can estimate what the actual amplitude is with simulation, but don't trust the simulation unless you model the Q of the inductor in the tuning circuit (a good assumption is Q is between 30 and 100).***

Simulation:

Check your circuit using Pspice or Agilent ADS in a transient analysis mode and simulate for 100+ cycles or more, as needed for the transients to settle out. Assume a Q of 50 for any inductors, adding a calculated series or parallel R to the inductor to model this. (If it doesn't oscillate at first, try using an ideal inductor to see if the inductor Q is a problem.)

Also, note that you may need to use a STEP-type source for Vcc to produce a disturbance that will get the oscillation started (0r inject a single short current pulse at t=0+ to the LC tank). Otherwise the transient analysis portion of the simulation may just show a flat line. In an actual oscillator, small noise voltages and currents within the circuit start the oscillation, but SPICE does not simulate these effects in transient mode. You can use a pulse source to create a step for Vcc. Set up the pulse to have a rise time of < ½ the period of the oscillator frequency and the width to be greater than the time you simulate. (You can just set the width to 1 second or more...)

Layout:

Plan the layout of your circuit. Remember to use the rules about component placement that you used in building your amplifier, since the core of your oscillator *is* an amplifier. *In particular, keep bypass cap interconnects short. The most critical ones are at the base (for CB configuration), and at the voltage divider where you need a low effective-total Xc value.*

You will need a BNC cable in order to attach to the output of your circuit to the test equipment. Be sure to include a connection point for this new cable in your layout.

Also, you will need to mount the potentiometer to the board. ***Plan ahead for how you want this physically mounted for use in your final receiver !*** This is most easily accomplished by soldering the 3 lugs to pads at the edge of the board and running wires from them to the locations where they connect to your circuit. Then add the knob to make adjustments easier.

Circuit Construction and Measurements:

Construct your circuit and perform/document the measurements detailed below. If you run into problems with your circuit, record them too, together with your solutions.

Measurement 1: "Smoke Test" and Voltage/Power-Consumption Checks

Apply 5V DC to your circuit and check/record/comment-on the regulator output voltage, the oscillator bias voltages, and the total current and power consumption*.

(*Note that your transistor bias voltages may not agree closely with your calculated values, since the presence of a large RF signal in the circuit can interfere with both the bias average DC voltage and the DC voltmeter's measurement.)

Measurement 2: Oscillation Magnitude

Measure the *oscillation* voltage at both the emitter and collector of the oscillator core (or emitter and base if using the CC Colpitts configuration), and at the final buffered output (without a 50 Ohm termination/load). ***Use a high impedance measurement probe*** (e.g. the high-impedance ***active*** RF probe[1]). Recall that these probes attenuate by 10:1, or 20 dB.

Next, connect the output to a 50 Ohm load and measure the output again to determine the effects of loading. Comment on the measured loading effects.

Measurement 3: Amplitude and Tuning Range

Connect your circuit to a spectrum analyzer and measure the frequency of oscillation and the amplitude (in dBm) over the tuning range of your pot. If necessary, adjust your circuit to give acceptable results. Record/graph the frequency and amplitude throughout the range (using a resonable number of points to get good graphs). Your graphs should have voltage on the horizontal axis and two curves - one for frequency and one for amplitude. Use two different Y axes to show this. Why does the amplitude fall-off at low frequencies? Is it still OK relative to the spec ?

Measurement 4: Oscillator Harmonic Spectrum

Set the spectrum analyzer for a wide sweep range. (e.g. 1 MHz to 2 GHz) and photograph or print out the spectrum of your oscillator. Estimate the level of the largest harmonic in dBc ('dB relative to carrier' where 'carrier' is the oscillator power at the fundamental frequency).
Verify there are no significant amplitude non-harmonically related "spurs".

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[1] Unlike the 10M || 15 pF typically assumed for 10:1 scope probes (which is NOT true - its more like 50 Ohms in series with 15 pF at high frequencies), an active probe really does have a high resistance in *parallel* with a small capacitance. Typical values are 100k || 3 pF. This is achieved by placing an amplifier in the probe tip which drives the 50 Ohm coax back to the scope.

Measurement 5: Frequency Drift

Hook the oscillator output to the spectrum analyzer. Set up so that you can observe down to about 1 kHz variations (e.g. using a 10 to 50 kHz bandwidth) Turn the oscillator off for a few minutes and then turn it on, recording the frequency every few seconds for about 1 minute.

Observe and graph how fast the frequency changes and in what direction. Estimate the "drift rate" in kHz/minute at 'startup' from the data. Then let it settle for a while (e.g. 3+ minutes) and estimate the long-term drift rate. Finally, warm up the circuit to about 80C and then record frequencies as it cools back down to room temperature.

Check the frequency shift when the circuit output is loaded and when it is not loaded as well. (You can do this by "sniffing" with an short wire or loop antenna made from a coax with clip-leads at the end.)

Measurement 6: Phase Noise

To assess phase noise, connect your oscillator to the spectrum analyzer and let the frequency stabilize. Our goal is to plot the phase-noise values for frequency offsets from at least 5 kHz to 1 MHz. To allow for this, set the spectrum analyzer to a "Span" of 2 MHz centered on your signal. With the "resolution bandwidth" (RBW) set to 100 kHz, record the oscillator amplitude in dBm and photograph the screen for use in extracting phase noise values later. Then re-center the oscillator spectrum, reduce the span to 200 kHz, and set the RBW to 1 kHz to allow the spectrum to be observed in finer detail. Photograph the result. Take additional "close-in" plots as desired to collect more phase noise information.

In your report, create a graph showing phase noise in "dBc/Hz" versus frequency offset from center. **Use a log frequency scale for delta-f** and plot the phase-noise values for frequency offsets from at least 5 kHz to 1 MHz. As discussed in class, the phase noise in dBc can be found by taking the difference in dB between the power in the spectrum at a certain frequency offset and the total power of the oscillator. To get dBc on a per-Hz basis, note that you must subtract an additional 50 (or 30) dB to account for the 100 kHz (or 1 kHz) bandwidth resolution being used respecitively.

Writeup:

IMPORTANT: One individual writes one section and the second writes the other as specified below. <u>Clearly specify who wrote what.</u>

In your write-up, you must include, <u>**IN THE FOLLOWING ORDER**</u>:

<u>Teammate 2 (the person who wrote up the measurements last time writes up the design this time):</u>

- A photo of your oscillator with decent resolution.
- A complete final schematic diagram ***with all part values shown***. The values must be the actual values used in construction. Be sure to include your inductor dimensions on your diagram.
- A complete AC small-signal diagram of your oscillator showing only components that affect it's frequency of operation.
- Narrative and equations to justify your component value selections. You should understand how the values are calculated and you ***must*** demonstrate this understanding by explaining their selection. However, you should abstract out the detail and iterations you went through, and you may omit the bias circuit design (except for deciding on the current used). <u>Be sure to include your final calculation of tuning range</u> and a discussion of the buffer design you used, and the expected amplitudes.

<u>Teammate 1 (the person who wrote up the design portion last time writes these measurements this time):</u>

- Simulation schematic(s) and plots/discussion of simulated performance
- Descriptions of your measurement ***<u>setups</u>*** plus associated results as specified in the procedures above.
- A summary of how the measurements compared to the specifications and expected performance. If you failed to meet any specifications, discuss possible reasons and solutions.