Lab 4. Crystal Oscillator

Modeling the Piezo Electric Quartz Crystal

Most oscillators employed for RF and microwave applications use a resonator to set the frequency of oscillation. It is desirable to use a resonator with the highest possible Q (lowest possible loss). Use of a high Q resonator generally guarantees that the phase of the loop gain will exhibit rapid variation near the frequency where it passes through 0. This means that the frequency of oscillation will be tightly constrained such that environmental changes that tend to alter the phase of the loop gain will not cause significant frequency shifts. In general, both the long-term and short-term stability of the oscillator is improved when the resonator has high Q. Resonators constructed using lumped inductors and capacitors typically have Q's on the order of 100 or so. This is sufficient for some applications, but a much higher Q can be obtained if a quartz crystal is used as an element of the feedback network.

To the circuit engineer the quartz crystal is a two-terminal passive network. The device is an electro-mechanical transducer which converts electric energy to mechanical energy and vice versa. The unit usually consists of a small quartz wafer sandwiched between two metal electrodes. In practice a quartz crystal will exhibit many resonance frequencies. It can be modeled electrically by the equivalent circuit shown in Figure 1.1 at frequencies near one set of resonance frequencies f_s and f_p.

The capacitance C_o is due to the parallel plate capacitor formed by the metal contacts that are used to hold the quartz wafer. The "components" r, L, and C in the equivalent circuit actually represent the effect of the mechanical vibration of the quartz wafer itself, and are referred to as the **motional components** of the model. Typical values for the equivalent circuit elements for a crystal with a fundamental resonance near 5 MHz are:

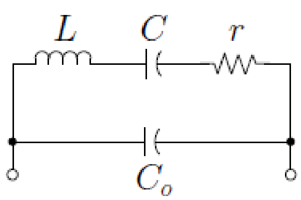

Figure 1.1: Quartz crystal circuit model

L = 0.1H
C= .01pF
r = 5 Ω
Co = 20 pF

The reactance versus frequency characteristic for a crystal with these parameters will have the characteristic shape shown in Figure 1.2.

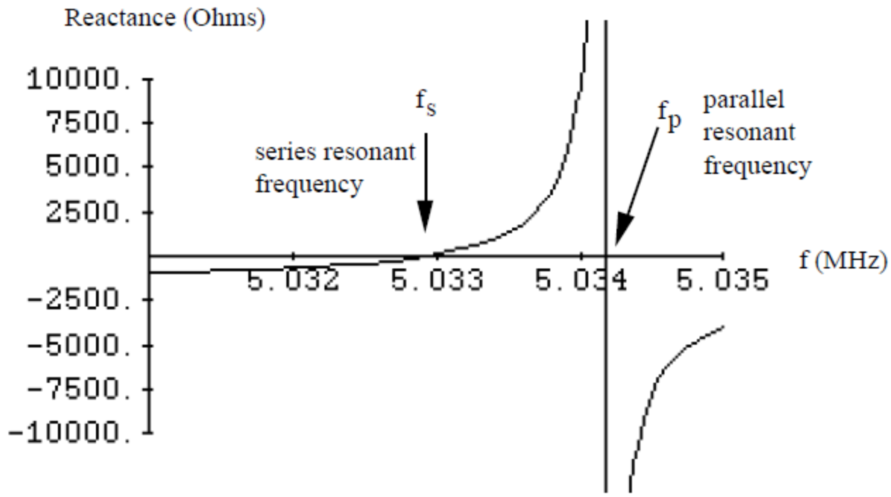

Figure 1.2: Crystal reactance versus frequency

This plot has been clipped and does not show the largest values of the reactance. Notice carefully that the frequency axis covers a range of only 4 kHz. The reactance curve exhibits a series resonance at fs and a parallel resonance at fp. The log of the real part of the crystal impedance is shown in Figure 1.3.

On a larger scale the resonance region on the reactance versus frequency plot would appear only as a small glitch on top of a capacitive reactance curve, e.g., if we plot reactance versus frequency at 50 points between 2 and 8 MHz, the curve would look like Figure 1.4.

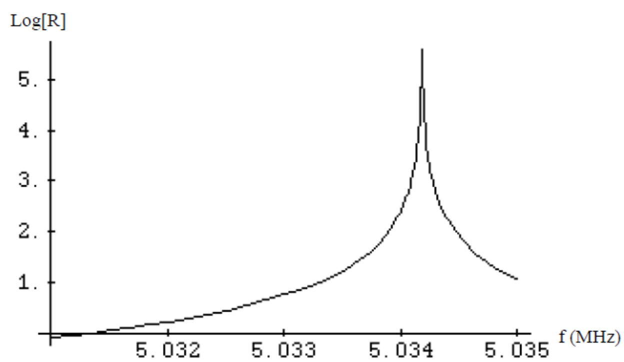

Figure 1.3: Logarithm of crystal resistance

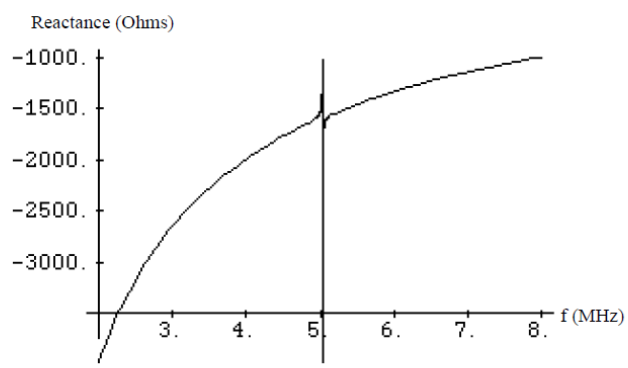

Figure 1.4: Expanded view of crystal reactance versus frequency

For a quartz crystal the parallel resonant frequency will be only a few hundredths of a percent larger than the series resonant frequency. Thus, the frequency range where the crystal looks inductive is very small - on the order of a few kHz for the crystals used in this lab. You should verify (by making use of the fact that $C \ll C_o$) that the ratio of the parallel and series resonant frequencies is well approximated by:

$$\frac{f_p}{f_s} \approx 1 + \frac{1}{2}\frac{C}{C_0} \tag{1.2}$$

In circuits a crystal is usually used to provide either a narrow-band "short circuit" or to act as an inductive reactance with very high Q. Circuit designers often refer to these possibilities as "series- mode" or "parallel mode" operation of a crystal, respectively. These are described below:

- Series resonant mode - the crystal is operated at f_s. Use is made of the fact that the crystal looks almost like a short-circuit at the series resonant frequency.

- Parallel resonant mode - operates between f_s and f_p where the crystal looks inductive. The circuit is designed so that the inductive reactance resonates with an external shunt capaci- tance. Here the crystal can be thought of as an extremely high Q inductor. Manufacturers will specify the external shunt capacitance required to make the crystal resonate at the fre- quency specified on the case. Typical values for the external load capacitance lie in the range 10-40 pF.

On Measuring the Quartz Crystal

It is necessary to use care when using the VNA to measure the impedance of a component such as the Quartz Crystal. Near the resonant frequencies of the crystal the reactance changes very rapidly with frequency. In order to capture this behavior you will need to calibrate the VNA over a narrow range of frequencies centered on the resonant frequency of the XTAL. You will also need to use a slow sweep time so that the measurement dwell time is long compared to the duration of the transient response of the XTAL.

For your 10.245 MHz crystal, you should find that C_o is on the order of 5 pF. The value for the motional capacitance, C, should be very small - on the order of 0.01 pF. The value for L should be on the order of 10 mH. These values for L and C could not be realized using actual capacitors and inductors. For example, a 10 mH Henry inductor would consist of many (tens or hundreds) turns on a coil form, and such a coil would have a parallel resonant frequency well below the desired operating frequency. You should find that r is on the order of 10 Ω. The Q of a quartz crystal is defined in terms of the motional arm of the equivalent circuit, i.e., the series arm consisting of r, L, and C. By definition, the Q of a series resonant circuit is given by:

$$Q = \frac{\omega_s L}{r} = \frac{1}{\omega_s C r} \tag{1.3}$$

The Q of the crystal will typically be on the order of 50,000 or so.

Common Collector Oscillator Design

The heart of the oscillator consists of a single-transistor emitter-follower amplifier in a Colpitts configuration. In order to better understand the design of the oscillator circuit, it's necessary to understand the small-signal mid-frequency model of a BJT transistor given in Appendix A of the Course Notes. A lot of the background information is in Chapter 5 of the Course Notes.

The gain for the oscillator will be provided by a common collector (CC) amplifier (also known as an emitter follower), as shown in Figure 2.1.

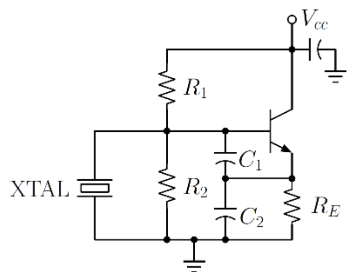

Figure 2.1: Common collector amplifier.

As the first step in constructing this amplifier, you will need to calculate the appropriate values for the DC bias components R_1, R_2 and R_E. Unlabeled capacitors are bypass and coupling capacitors, respectively, and should have a very low impedance at the intended frequency of oscillation. In particular, a bypass capacitor (a capacitor used to connect a node to ground for AC signals) should have the lowest possible impedance at the operating frequency. A coupling capacitor (a capacitor used to couple one stage to another) need only have an impedance that is small compared to the load impedance that it couples to.

Note that the bypass capacitor shown from Vcc to ground is important, as it is responsible for isolating the oscillator from the wires that connect the circuit to the power supply. Without this capacitor, the wires leading to the power supply and the power supply will all be a part of the circuit at the frequency of oscillation.

DC bias components R_1, R_2 are selected in such a way as to provide bias stability, while not degrading Q of the resonance too much. R_E is the component that sets the quiescent current and, therefore, initial (small-signal) transconductance.

As discussed in the course notes, the base-emitter voltage swing is controlled by the ratio C_1/C_2. It is desirable to keep the base-emitter voltage swing relatively small, which results in the most sinusoidal output voltage. To achieve this, choose C_1 and C_2 such that

$$\frac{C_1}{C_2} \gg 1$$

Additionally, we would like to choose C_1 to be much greater than the input capacitance of the transistor (˜10pF). This will tend to make circuit performance relatively independent of the junction capacitance of the transistor, and mainly dependent on the values of external circuit elements which are under our control. Finally, the sum of C_1 and C_2 determines the precise resonant frequency of the Xtal oscillator, since the approximate series combination of the capacitors appears in parallel with the Xtal.

Procedure: Quartz Crystal

1. Using the technique from Lab 2, measure the reflection from your quartz crystal (you can trim leads to 1 cm). Set start and stop frequencies to 7 and 11 MHz respectively. Calibrate the instrument and take the measurement, saving thedata as in Lab 1. Measure the reactance on the lower end of the measured frequencies (at least 1% lower than the frequency marked on the case) and **determine the package capacitance Co** using :

$$C_o \simeq -\frac{1}{2\pi f X} \tag{1.4}$$

2. Repeat the calibration and measurement for a narrow frequency range (e.g. 10.23 to 10.27 MHz, 6401 pts; also set [Sweep][IF Bandwidth] to 500 Hz and set [Sweep][Sweep Time] to 50 sec.) to focus on the resonant region. **Measure and record fs and fp,** the series and parallel resonant frequencies of the crystal. The crystal impedance will be smallest at the series resonant frequency of the motional arm, fs. At the series resonant frequency of the motional arm, fs, the crystal impedance will be approximately equal to the motional resistance, r. **Record the value of r**. You can use the marker on the Smith chart display format in VNA, and later verify the value in ADS.

3. **Determine C** using the equation 1.2.

4. **Determine L** using the values for C and fs. L and C are series resonant at fs, so that:

$$L = \frac{1}{(2\pi f_s)^2 C} \tag{1.5}$$

5. **Compute the Q** of your crystal using equation 1.3

6. From the reactance plot between the two resonant frequencies, determine the reactance of the crystal at 10.245 MHz, the desired frequency of oscillation. Calculate C_L, the load capacitance that will resonate with the crystal at this frequency.

Procedure: Crystal Oscillator

1. Connect the output to VSA. Adjust the instrument settings to display the 10.x MHz peak and six more harmonics. Record the powers of the fundamental and several more strong harmonics. (Hint: use marker functions). Save the VSA plot.

2. Adjust VSA settings to zoom in on the fundamental frequency. Using the procedure attached at the end of the lab 2 instructions, measure frequency drift and the effect of hand capacitance on frequency.

3. Measure the phase noise of the oscillator using the attached procedure. Note the settings required. Record the value at a given frequency offset. Save the plot.

Procedure: Building the Colpitts Stage

1. Select the through-hole components for the Colpitts oscillator.
   Use instructor input and advice

2. Build the Colpitts circuit on the prototyping board, without the crystal
   Note: Keep the circuit compact with short ground connections
   Ask for soldering help or instruction if needed

3. Connect to 12 V power (don't forget the bypass/decoupling capacitor)

4. Check base and emitter DC voltages of the circuit

5. Connect the crystal to the Colpitts circuit

6. Capacitively couple a series output R (300-500 Ω) to the circuit output

7. Check for oscillation using VSA (ask about a proper connection)

8. If the main peak power is too low in power – troubleshoot

9. Demonstrate the oscillation to your instructor

10. If approved, record spectrum, accurately measure f_peak, drift

11. Calculate THD. Observe and record the scope waveform.

12. Ask instructor about possible improvements

Measurements for Oscillator Characterization

- Measure the output power (in dBm) and frequency of the fundamental harmonic. Compare this to what you observed on the oscilloscope.
- Record the frequencies and output powers of the first seven harmonics. Estimate the total harmonic distortion (THD) from the output spectrum. Use the first five harmonics to estimate THD. THD (in percent) can be calculated as follows:

$$\text{THD (percent)} = \frac{total\ power\ of\ all\ harmonics\ above\ fundamental}{total\ output\ power\ of\ signal} \times 1$$

- How stable is the output at the fundamental frequency (i.e. is there any frequency drift over time)? Quantify this drift by setting up the delta marker:
  - **[Peak Search]**→[More]→[Continuous Peak Search]
  - Adjust the span and RBW. Observe for one minute and record the largest frequency drift. How susceptible is the output frequency to stray capacitance (e.g. hand capacitance)?

- Measure the phase-noise spectral density of the oscillator at an offset of 1 kHz from the carrier. For an explanation of Phase Noise, see Chapter 5 of the text, or, even better, read an Agilent application note. Essentially, phase noise is caused by random processes which make the frequency of your oscillator change like $f_{inst} = f_0 + \frac{1}{2\pi}\frac{d\phi}{dt}$. Phase noise can be combatted by using a phase-locked loop (a feedback technique) and a narrow output filter (as seen on the function generators).

– Use the following procedure to set up the VSA to perform a phase demodulation and spectral analysis of the resulting demodulated phase waveform. Your TA may tell you that this measurement has not had all of the kinks completely worked out.

– [Mode] → [Phase Noise]

– [Meas.] → [Log Plot]

– Use [Auto-Tune] to tune in to your fundamental frequency

– Set [Tracking] → [Span] to 20 kHz

– Print out graph of phase variance vs. frequency offset. · Measure the phase variance at a 1 kHz offset. For the XTAL oscillator, you may notice that the phase variance at a 1 kHz offset is in the noise floor. To accurately measure phase variance for the XTAL oscillator, set your span to 1 kHz and your RBW to 10Hz. This will show a zoomed-in picture of the phase variance for a frequency offset of 0 to 500Hz. Print out this graph if necessary.

Report Guidelines

1. Brief description of the lab (2 pts)
2. Description of the Xtal and model (2 pts)
3. Diagram of the setup for Xtal measurement (2 pts)
4. Description of calibration and Xtal measurement (2 pts)

5. Show ADS model for the measured Xtal (2 pts)
6. Explain how the component values were obtained (4 pts)
7. Include narrow scan R and X plots for data and model (3 pts)
8. Include wide scan reactance plots plots for data and model (3 pts)
   (data and model plots should appear on the same axes, well-marked)

9. Include a picture of the measured PCB/SMD oscillator (2 pts)
10. Provide the spectrum or table of 5-7 peaks (3 pts)
11. Calculate the THD, show calculation (2 pts)
12. Describe the drift measurement and VSA settings (2 pts)
13. Give the peak frequency and drift with and w/o hand (3 pts)

14. Include a diagram of the Colpitts oscillator, include load voltage divider (4 pts)
15. Explain the roles of R1, R2, RE (2 pts)
16. Explain what sets the lower and upper bounds on of R1, R2, RE (2 pts)
17. Explain the roles of C1, C2 (2 pts)
18. Explain what sets the lower and upper bounds on of C1, C2 (2 pts)
19. Include the values chosen for the initial construction (2 pts)
20. Describe any necessary troubleshooting and changes (2 pts)
21. Provide the spectrum or table of 5-7 peaks (3 pts)
22. Calculate the THD, show calculation (2 pts)
23. Use output voltage divider to estimate RF power output (2 pts)
24. Give the accurate peak frequency (down to 10 Hz precision) (2 pts)
25. Measure drift with and w/o hand (2 pts)
26. Include a picture of your completed Colpitts (front and back) (3 pts)

27. One paragraph reflections from each lab partner (include name). (3 pts)

General report formatting, organization, clarity. (5 pts)

Total: 70 pts

Expected length of report is 6-9 pages, depending on graph format, line spacing, etc.