$$\frac{1}{C3} = \frac{1}{20\text{pF}} - \frac{1}{113.7\text{pF}} - \frac{1}{113.7\text{pF}}$$
$$\therefore C3 = 30.86 \text{ pF}$$

To finish our problem, we need to find an S-parameter model for the transistor that is closest to our bias condition. Let us assume that we found such a model for the transistor chosen. The negative resistance would look similar to Figure 10.5. In this plot we can see we have around –425 ohms at 20 MHz. This is greater than three times the ESR and we can conclude that we have sufficient gain margin in this design. We can also conclude that the design procedure outlined above will yield excellent working designs. Once the design is synthesized with this procedure, any required changes or optimization can then be done with a software suite like GENESYS.

10.4 Colpitts CC Quick Design Procedure Using a Third Overtone Parallel- or Series-Resonant Crystal

With third overtone crystals, we need to add mode selection; otherwise, the oscillator will always start on the fundamental response. This circuit is shown in Figure 6.22. For the design of the bias, we can use the same procedure as the Colpitts CC fundamental in Section 10.3.2.

Mode selection is accomplished in Figure 6.22 by designing the parallel combination of C_2 and L_1 to "look" capacitive at the third overtone and inductive at the fundamental mode.

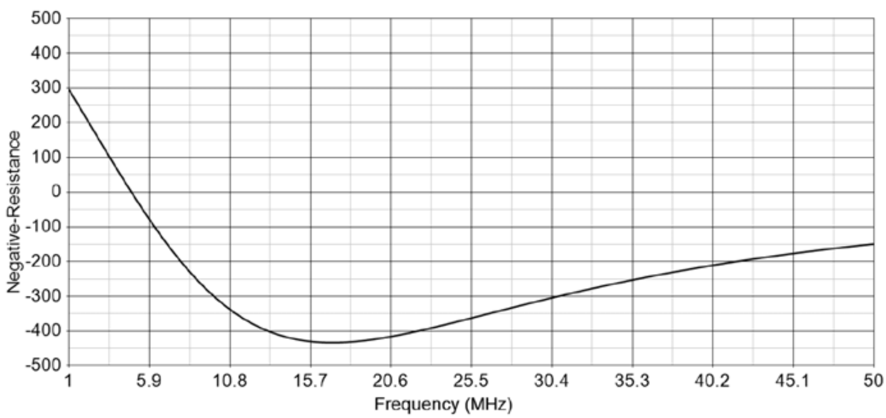

Figure 10.5 Negative-resistance simulation looking into the base of Figure 10.4. In Agilent's GENESYS and using linear simulation, it is the plot of real part of the input impedance, that is, re(Z_{in1}).

10.4.1 Design of the Third Overtone Mode Selection

We will assume that the fundamental response is exactly at $f_0/3$, although we know that this is not true. However, this assumption will not affect the mode selection design.

Start by letting the reactance of C_1 be equal to 70 ohms like before. Now we need to have resonance using the parallel combination of C_2 and L_1, between the fundamental and third overtone response. I prefer setting this mode selection frequency (f_{ms}) at the geometric mean between the fundamental and third overtone response. That is,

$$f_{ms} = \sqrt{f_0 \times \left(f_0/3\right)} = \sqrt{f_0^2/3} \tag{10.14}$$

Because we have two unknowns, we need a second condition to solve the mode selection tank. That other condition is to set the reactance of the tank consisting of C_2 and L_1 to 70 ohms at f_0. Hence, the second condition is

$$\frac{\left(1/2\pi f_0 C_2\right)\left(2\pi f_0 L_1\right)}{1/2\pi f_0 C_2 + 2\pi f_0 L_1} = -j70 \tag{10.15}$$

We can now set up two equations and two unknowns to arrive at the tank values.

10.4.2 Setting a Parallel-Resonant Third Overtone Crystal to Frequency

Setting a parallel-resonant crystal to frequency is the same as in Section 10.3.3 except that now C_2 is a parallel tank. We can even state that the capacitance value of the tank at the oscillating frequency is equal to C_1. However, a more exact solution is

$$C_4 = \frac{1}{1/C_L - 1/C_1 - 1/C_{ms}} \tag{10.16}$$

where C_{ms} is the mode selection tank capacitance at the frequency of oscillation. This is given by

$$C_{ms} = \frac{1}{2\pi f_0 X_{ms}} \tag{10.17}$$

and

$$X_{ms} = \frac{(1/2\pi f_0 C_2)(2\pi f_0 L_1)}{(1/2\pi f_0 C_2) + (2\pi f_0 L_1)} \tag{10.18}$$

10.4.3 Setting a Series-Resonant Third Overtone Crystal to Frequency

If a series-resonant third overtone crystal is used as shown in Figure 6.22, then the oscillator frequency will be wrong. It will actually be high in frequency. Therefore, we need to modify this circuit to bring the frequency back down. This is easily accomplished by adding an inductor in series with the crystal. One may think that just replacing C_4 with an inductor would be sufficient, and in some cases it is. The problem is that inductors come in few standard values and the specific inductance needed may not be available. What we will do is leave C_4 in place and add the inductor in series with it. The combination of the new inductor and C_4 will become a variable inductor. There are many more standard capacitor values that will facilitate fine trimming of the crystal frequency. Figure 10.6 is our new circuit for a third overtone, series-resonant calibrated crystal. C_4 has been renamed as C_s and the new added inductor L_s.

The job of the series combination of L_s and C_s is to resonate out the load capacitance presented to the crystal by series combination of C_1 and the tank consisting of L_1 and C_2. Mathematically the sum of the reactances in series must equal to zero. That is,

$$X_{LS} + X_{CS} + X_{C1} + X_{ms} = 0 \tag{10.19}$$

In practical designs we choose the value of L_s such that it will by itself force the crystal frequency below f_0. Then one uses C_s to fine trim the frequency backup. In some cases, C_s is made up of two or more parallel capacitors to be able to set the frequency within a fraction of a part per million. Off-course, a trimmer capacitor can also be used in its place instead. However, trimmer capacitors tend to be large and very vulnerable to vibration and aqueous cleaning processes.

Problem 10.1

Design a Colpitts CC CLOCK at 100 MHz, with a +5-V supply with output taken from the emitter. The crystal is described as follows: Mode = third overtone, load capacitance = series, R_1 = 60 ohms maximum, C_0 = 3 pF, C_1 = 0.2 fF.

Determine all the component values and prove by simulation that there is no negative resistance at the fundamental response of the crystal.

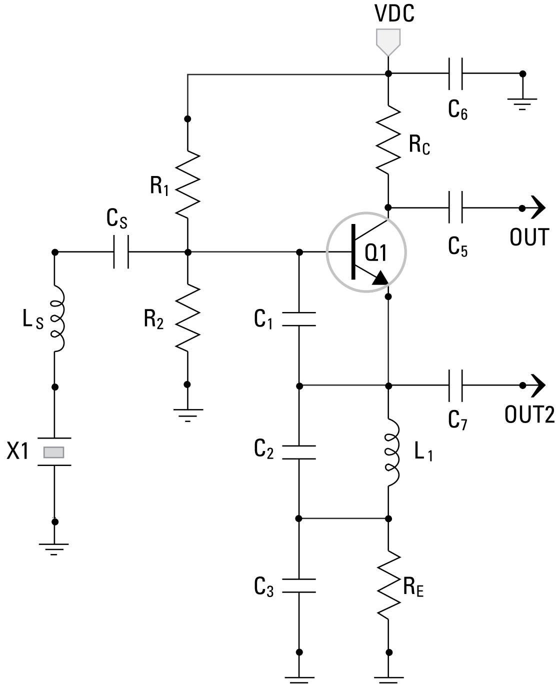

Figure 10.6 Colpitts, third overtone, for series-resonant calibrated crystal. If OUT2 is used, then RC becomes 0 ohms.

Solution:

Because the crystal is series-resonant calibrated, we will choose the circuit of Figure 10.6. The collector resistor will be 0 ohms because we are taking the output from the emitter. Let us choose the identical bias condition as in Problem 10.1. That is: $R_1 = R_2 = 10$ kilo-ohms and $R_E = 330$ ohms. The value of C_1 becomes

$$C_1 = \frac{1}{2\pi(100\text{ MHz})(70)} = 22.7\text{ pF}$$

Let us choose $C_1 = 22$ pF, a standard value. The values of C_2 and L_1 were solved on MathCad using its "solve" function after setting up two equations, two unknowns. The following is that file:

This file solves for L and C of 3rd Overtone mode selection tank

Given the frequency of oscillation:

$$f := 100 \bullet 10^6$$

The tank frequency is then:

$$\text{fms} := \sqrt{\frac{f^2}{3}} \quad \text{fms} = 5.774 \times 10^7$$

Enter the desired tank reactance at f:

$$Z: = -j \bullet 70$$

The C1 split capacitor is:

$$C1 := \frac{1}{2 \cdot \pi \cdot f \cdot Z}$$

$$C1 = 2.274i \times 10^{-11}$$

Below we find the mode selection tank values guess

$$C := 20 \cdot 10^{-12}$$

$$L := 150 \cdot 10^{-9}$$

Given:

$$\frac{1}{2 \cdot \pi \sqrt{L \cdot C}} = \text{fms}$$

$$\frac{\left(\frac{1}{j \cdot 2 \cdot \pi \cdot f \cdot C}\right)((j \cdot 2 \cdot \pi \cdot f \cdot L))}{\frac{1}{j \cdot 2 \cdot \pi \cdot f \cdot C} + j \cdot 2 \cdot \pi \cdot f \cdot L} = Z$$

$$\begin{pmatrix} C \\ L \end{pmatrix} := \text{Find}(C, L)$$

$$C = 3.41 \times 10^{-11}$$

$$L = 2.28 \times 10^{-7}$$

Selecting standard values:

$$L := 220 \cdot 10^{-9}$$

$$C := 33 \cdot 10^{-12}$$

Check:

$$\frac{1}{2\cdot\pi\cdot\sqrt{L\cdot C}} = 5.907\times10^{7}$$

$$\frac{\left(\frac{1}{j\cdot 2\cdot\pi\cdot f\cdot C}\right)\left(\left(j\cdot 2\cdot\pi\cdot f\cdot L\right)\right)}{\frac{1}{j\cdot 2\cdot\pi\cdot f\cdot C}+j\cdot 2\cdot\pi\cdot f\cdot L} = -74.07i$$

From the MathCad file we selected $C_2 = 33$ pF and $L_1 = 220$ nH. Because C_3 and C_6 are bypass capacitors, we choose $C_3 = C_6 = 0.1\ \mu$F.

Now we need to select the values of L_s and C_s such that the crystal "sees" no capacitive load since we have a series-resonant crystal. The load capacitance looking into the base is the series combination of C_1 and the tank capacitance C_{ms}. The reactance of C_{ms} is equal to $-j74$ from the MathCad file. Therefore this capacitance is equal to

$$C_{ms} = \frac{1}{2\pi(100\text{ MHz})(74)} = 21.5\text{ pF}$$

The series combination of 22.7 pF and 21.5 pF is equal to 11.04 pF. The value of L_s then becomes

$$L_S = \frac{\left(1/2\pi(100\text{ MHz})\right)^2}{11.04\text{ pF}} = 229.4\text{ nH}$$

The reactance of L_s is therefore equal to 2π (100 MHz)(229.4 mH) = $+j144.1$. We will choose an inductor with a standard value greater than 229.4 nH and then readjust the reactance with C_s to get us back to $+j144.1$. Let's choose 270 nH for L_s; its new reactance is then = $+j169.6$. This is 22.5 above $+j144.1$. We therefore need C_s to be

$$C_S = \frac{1}{2\pi(100\text{ MHz})(22.5)} = 70.7\text{ pF}$$

The value of 70.7 pF is not a standard but 68 pF is. Our final schematic with values is shown in Figure 10.7.

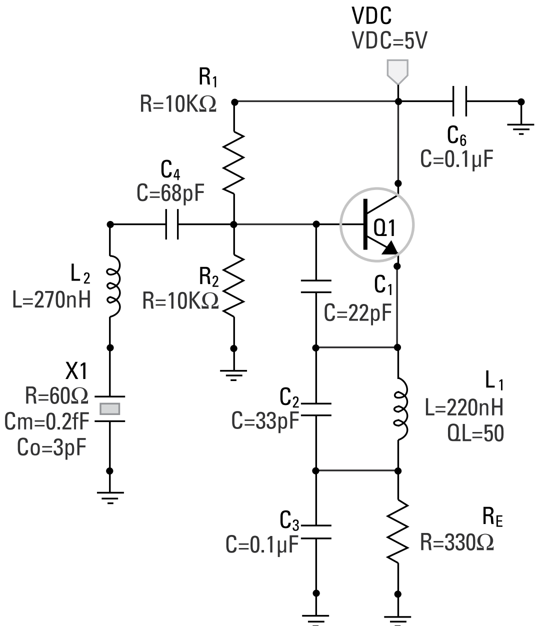

Figure 10.7 Final circuit for Problem 10.2.

Simulating the negative resistance of the Figure 10.7, looking into the base, we obtain Figure 10.8. At 100 MHz we have about –470 ohms, but at the fundamental (around 33.333 MHz) frequency we have more than +800 ohms. These results confirm that the oscillator will not oscillate at the fundamental and that we have sufficient gain at the third overtone (i.e., 100 MHz).

10.5 Transient Analysis of Colpitts CC

We will now perform transient analysis of the Colpitts to examine the steady-state, time-domain waveforms at the emitter and the collector. Our first circuit is shown in Figure 10.9 where the output is being taken from the emitter. To trigger the start of oscillation in the simulator, we have set up three essential techniques in Figure 10.9. First, the supply voltage has been replaced with pulse function as described in the schematic. Second, the crystal is returned to VDC [3] to further facilitate the start of oscillation. Third, we have de-Q the crystal resonator by increasing the motional capacitance by the same factor we have reduced the motional inductance. The ESR remains the same value. The de-Q of the crystal in this way will not affect the steady-state time domain waveform. We do this to speed up the simulation time, which can be very long for crystal oscillators.

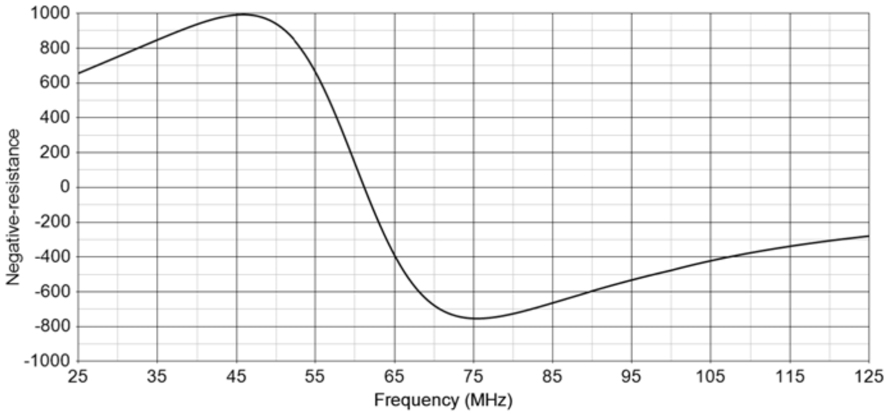

Figure 10.8 Negative-resistance simulation of Figure 10.7.

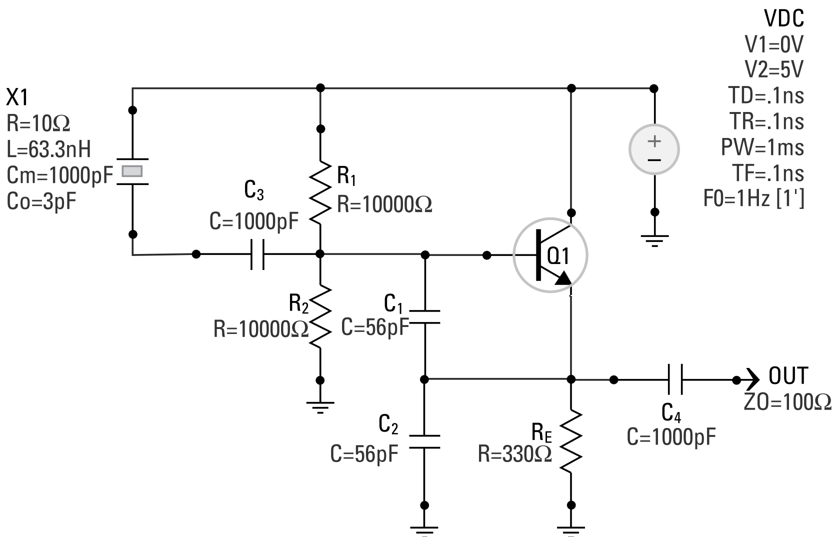

Figure 10.9 The 20-MHz Colpitts CC configured for transient analysis.

Figure 10.10 shows the steady-state time domain output at the emitter of Figure 10.9. This output is "close" to a sinusoidal waveform. The crystal being only one capacitor away is partly responsible for filtering the output at the emitter. Notice the lack of any clipping of this waveform at the emitter. This signal is approximately 1 Vpp.

In Figure 10.11 we have set up the Colpitts to simulate the output at the collector (*Colpitts semi-isolated*). Figure 10.12 shows the simulated output waveform at the collector. It is strikingly different than the emitter waveform. First, it is rich in harmonic content due to the limiting action occurring at the