Determining the tuning range for TLSI's high frequency VCXOs – T231/T277

Introduction

In the following application note we will explain how to determine the tuning range (sometimes called the "pulling" range) of a Colpitts type VCXO, such as the T231 or T277, and how to adjust the pulling range based on your own application. Three design examples are given to illustrate the feasibility of achieving the desired pulling range. The first example will show how to achieve a larger pulling range (more than ±100 ppm). The second example is for a smaller pulling range (±60 ppm), but still using the same type of varactor diode. The third example shows how using a lower capacitance variation ratio varactor diode can enable you to achieve a smaller pulling range for the VCXO.

Background

TLSI's high frequency VCXO clock generators are ideally suited for a wide range of applications that require the use of fundamental crystals. In addition, some applications may require varying degrees of tuning range control (called pulling range) of the output clock frequency. For example, a typical pulling range of ±100 ppm (which is varactor and crystal dependent) is achieved when using a hyperabrupt varactor diode such as the SMV12xx series from Skyworks™, Inc. A smaller pulling range, say ±50 ppm, can be achieved by using a silicon epitaxial planar diode such as the MA2SVxx series from Panasonic™.

Crystal Equivalent Circuit

Consider a fundamental crystal, such as the 155.52 MHz crystal used in a SONET/SDH application, connected to the T231 VCXO, as shown below in Figure 1.

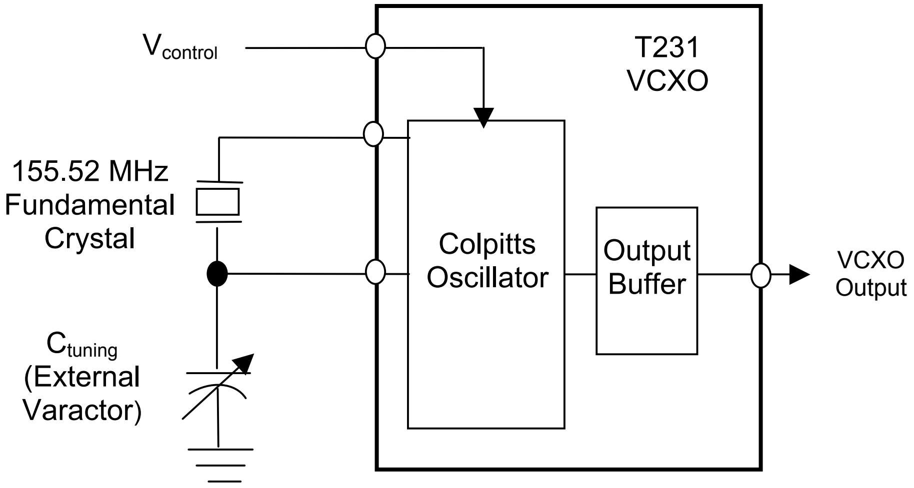

Figure 1. Typical crystal/VCXO connection

The crystal may be modeled with the equivalent circuit as shown below in Figure 2, where:

- C_0 is the crystal's shunt capacitance (primarily from the thickness of the crystal blank)
- C_1 is the crystal's motional capacitance (determined by stiffness of the quartz, the electrode size and the shape and size of the crystal blank)
- C_{tuning} is the total external load capacitance on the crystal and is essentially the capacitance of the varactor diode, which varies with varying control voltage ($V_{control}$)
- L_1 is the crystal's motional inductance (primarily determined by the mass of quartz in motion)
- R_1 is the crystal's series equivalent resistance at its series resonant frequency

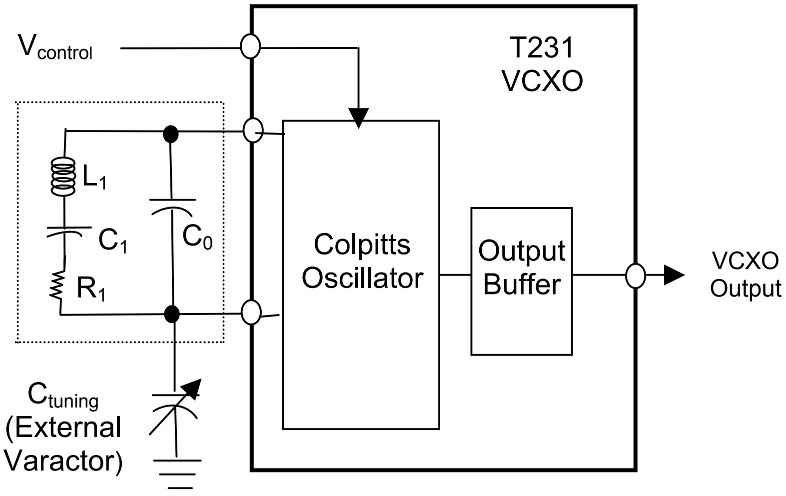

Figure 2. Crystal Equivalent Circuit connected to VCXO

Based on the equivalent circuit shown in Figure 2, the external varactor (C_{tuning}) provides the additional loading capacitance to the crystal circuit which allows it to effectively "pull" its frequency as the capacitance of the varactor is varied by $V_{control}$. The crystal resonant frequency, f_c, can be readily found from the following expression:

$$fc = \frac{1}{2\pi\sqrt{L_1\left(\frac{C_1 x C}{C_1 + C}\right)}} \qquad (1)$$

where $C = C_0 + C_{tuning}$, C_0 is the shunt capacitance which parallels with the additional tuning capacitance, C_{tuning}, C_1 is the motional capacitance of the crystal, and L_1 is the motional inductance. When varying C_{tuning}, it will have a minimum value, $C_{tuning_}$min and a maximum value, $C_{tuning_}$max.

Based on the crystal fundamentals, the frequency tuning range, in ppm, when varying C_{tuning} between C_{tuning}_min and C_{tuning}_max can be expressed as shown below:

$$\Delta f(ppm) = f_{\max}(ppm) - f_{\min}(ppm) \qquad (2)$$

or

$$\Delta f(ppm) = \frac{C_1}{2(Co + C_{tuning}\_\min)} - \frac{C_1}{2(Co + C_{tuning}\_\max)} \qquad (3)$$

Therefore, it can be seen that the tuning range of the T231 depends on the crystal and the external capacitance, which consists of the tuning capacitors, plus parasitic PC board or substrate capacitance.

The parasitic capacitance consists of the PCB pads, PCB layout, interconnect length and spacing, trim and varactor capacitances. Figure 3 shows an equivalent resonant circuit with a 10-pin package. C_{p1} and C_{p2} are the parasitic capacitance (a typical value of 2pF can be used), which is caused by layout and chip bonding pads and component wiring. Adding additional capacitors to these two parasitic capacitances can also be used as trimming capacitance to change the pulling range of the T231. We will illustrate this later. The capacitors, C1 and C2, are part of the input capacitance of the internal Colpitts oscillator.

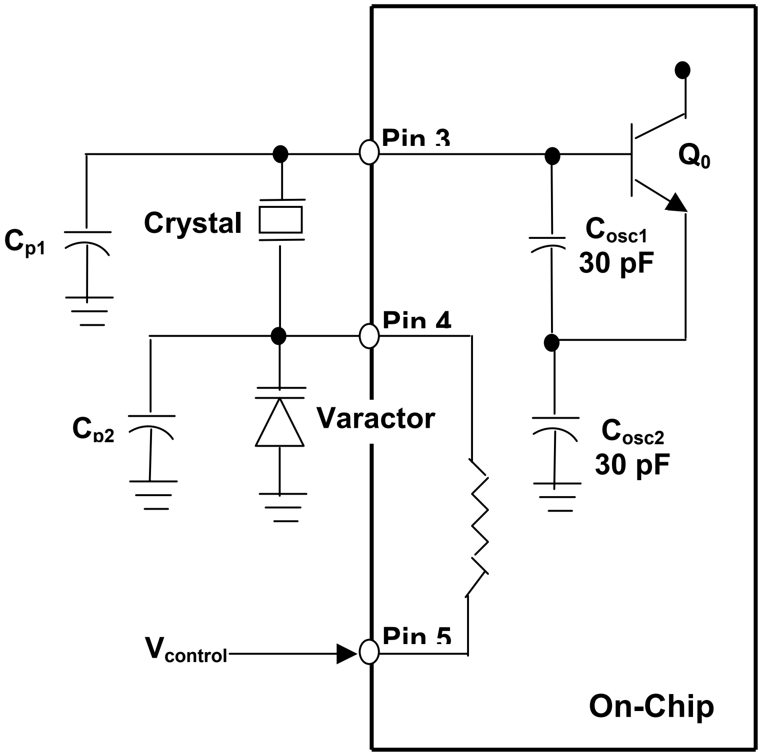

Figure 3. The equivalent resonant circuit considering the on-chip Colpitts circuit, PCB parasitic capacitances and varactor diode.

In Figure 3, the V_{control} (pin 5) is used to apply a tuning voltage to the varactor diode to vary its capacitance, results in tuning the output oscillator frequency.

To determine the tuning range of the T231 we need to re-draw the Figure 3 schematic into a simplified form as shown in Figure 4. If using the hyperabrupt type of varactor, SMV1249 for example, from the datasheet we can easily find the capacitances, C_{tuning}_min and C_{tuning}_max , which correspond to V_{control} reaching the maximum and minimum tuning voltages, respectively, for example +4.5V and +0.5V.

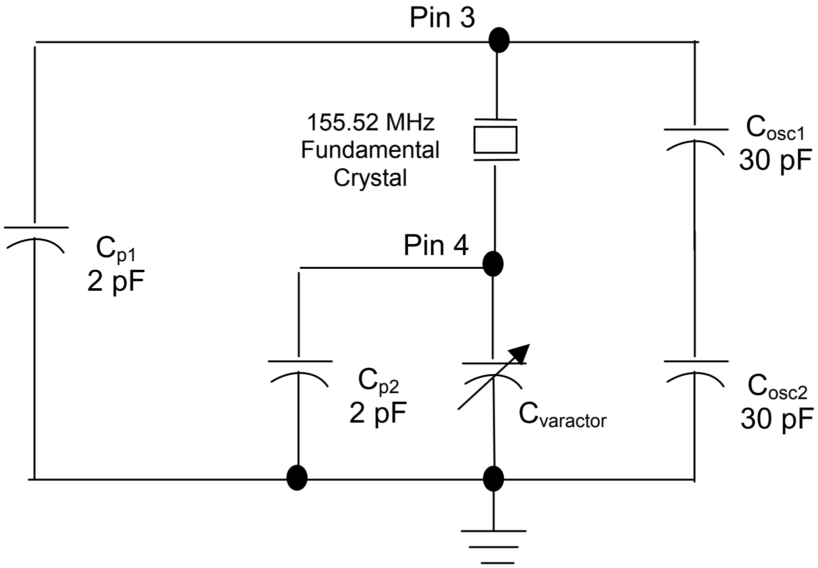

Figure 4. Simplified equivalent resonant circuit of T231 with PCB layout parasitic capacitors, C_{p1} and C_{p2}.

Thus we can calculate total capacitance across the crystal, C_{tuning} from C_{osc1}, C_{osc2}, C_{p1}, C_{p2} and $C_{varactor}$. After calculating C_{tuning} we can use expression (3) above to calculate the tuning range. To illustrate this procedure, let us look at a design example.

EXAMPLE 1: For a typical crystal, the motional capacitance, C_1 =5fF and the shunt capacitance, C_o=4pF. Using a hyperabrupt tuning diode (SMV1249) to achieve as large a tuning range as possible, the typical capacitance can be found from the datasheet as $C_{\max}$ = 25.88pF at 0.5V and $C_{\min}$ = 2.51pF at 4.5V. The varactor diode appears in series with the equivalent 15pF of the internal oscillator capacitances (C_{osc1} and C_{osc2}). Assuming C_{p1}=C_{p2}=2pF (stray board wiring capacitance across both the varactor and the chip terminals), the following calculations determine the pulling range of the oscillator:

$$C_{tuning}\_\min = \frac{(C_{\min} + C_{p2})(15 + C_{p1})}{C_{\min} + C_{p2} + 15 + C_{p1}} = 3.56\,pF \qquad (4)$$

$$C_{tuning}\_\max = \frac{(C_{\max} + C_{p2})(15 + C_{p1})}{C_{\max} + C_{p2} + 15 + C_{p1}} = 10.56\,pF \qquad (5)$$

Substituting the above values and the other related capacitances into expression (3), the tuning range is:

$$\Delta f\,(ppm) = \frac{C_1}{2(Co + C_{tuning\_}\min)} - \frac{C_1}{2(Co + C_{tuning\_}\max)} \qquad (6)$$

$$\Delta f\,(ppm) = \frac{5x10^{-15}}{2(4x10^{-12} + 3.56x10^{-12})} - \frac{5x10^{-15}}{2(4x10^{-12} + 10.58x10^{-12})} = 159\,ppm$$

The real measured pulling range might be smaller than this calculated result because there will be other parasitic effects to limit the tuning range. For example, in our analysis we did not consider any parasitic resistance and impedance matching issues.

When your application requires a smaller tuning range from the T231, you will have two options. The first option, if you are still using the hyperabrupt varactor diode, is to use the external trim caps C_{trim1} and C_{trim2} added on the PCB board as shown below in Figure 5, together with the parasitic capacitance. As can be seen, then, the pulling range calculation is the same as in **EXAMPLE 1** above.

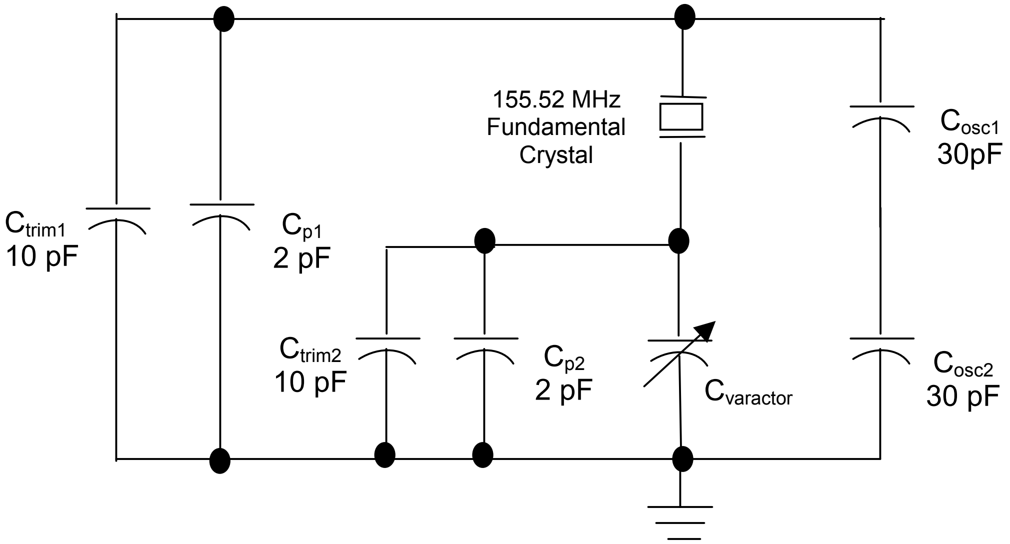

Figure 5. Simplified equivalent resonant circuit of T231 with PCB layout parasitic capacitors and trim capacitors

EXAMPLE 2: Using the same crystal, C_1 =5fF and C_o=4pF and the hyperabrupt tuning diode, SMV1249, the typical capacitance is C_{max} = 25.88pF at 0.5V and C_{min} = 2.51pF at 4.5V, as before. The varactor diode again appears in series with the equivalent 15pF (C_{osc1} and C_{osc2}) internal capacitance. Here, if we assume that we add the 10 pF trim capacitors, C_{trim1} and C_{trim2}, as shown above in Figure 5, we would now have 12 pF of capacitance (10 pF for trim and 2 pF for stray capacitance).

Then, as before:

$$C_{tuning\_}\min = \frac{(2.51+12)(15+12)}{2.51+12+15+12} = 9.438pF \qquad (7)$$

$$C_{tuning\_}\max = \frac{(25.88+12)(15+12)}{25.88+12+15+12} = 15.764pF \qquad (8)$$

Substituting the above values into expression (3):

$$\Delta f(ppm) = \frac{C_1}{2(Co + C_{tuning\_}\min)} - \frac{C_1}{2(Co + C_{tuning\_}\max)}$$

$$\Delta f(ppm) = \frac{5x10^{-15}}{2(4x10^{-12} + 9.438x10^{-12})} - \frac{5x10^{-15}}{2(4x10^{-12} + 15.764x10^{-12})} = 60\,ppm$$

Using the trim capacitors has clearly reduced the pulling range to 60 ppm.

The second option to reduce the pulling range of the T231 is to use a diode with a low variable capacitance ratio, such as the silicon epitaxial planar diodes, MA2SVxx, instead of the varactor diode. Using this approach there is no need to add the external trimming capacitors. Figure 6, shown below, illustrates the capacitance vs. $V_{control}$ characteristic, comparing the typical hyperabrupt tuning varactor and the silicon epitaxial planar diode.

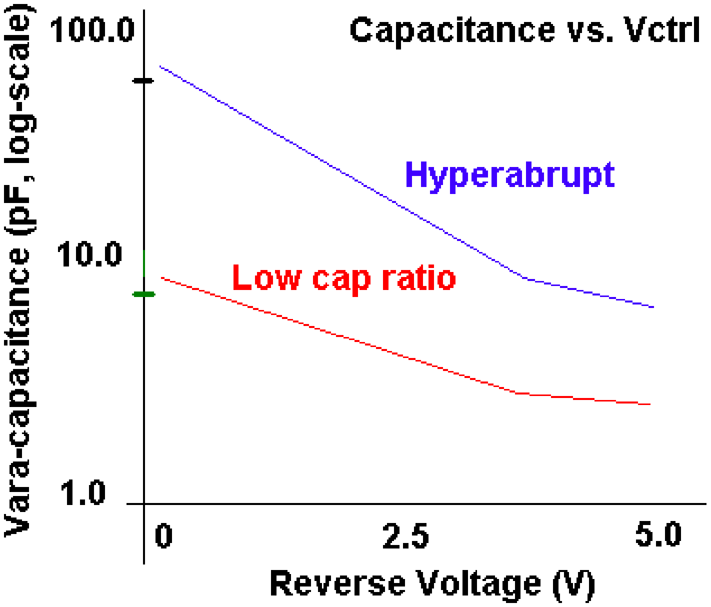

Figure 6. Illustrating the capacitance against $V_{control}$ or the reverse bias voltage between a typical hyperabrupt varactor diode and a silicon epitaxial planar diode.

EXAMPLE 3: Using the same crystal, C_1 =5fF, C_o=4pF and selecting a silicon epitaxial planar diode (the MA2SV02, for example), the diode's typical capacitance is C_{max}= 20.0pF at 1.0V and C_{min}= 9.0pF at 4.0V. As before, the diode is in series with the equivalent 15pF (C_1 and C_2) internal capacitance. Again, assuming the stray capacitances C_{p1} and C_{p2} are 2 pF each, then as before:

$$C_{tuning\_}\min = \frac{(9.0+2)(15+2)}{9.0+2+15+2} = 6.679\,pF \qquad (7)$$

$$C_{tuning\_}\max = \frac{(20.0+2)(15+2)}{20.0+2+15+2} = 9.590\,pF \qquad (8)$$

Substituting the above values into expression (3):

$$\Delta f\,(ppm) = \frac{C_1}{2(Co + C_{tuning\_}\min)} - \frac{C_1}{2(Co + C_{tuning\_}\max)}$$

$$\Delta f\,(ppm) = \frac{5x10^{-15}}{2(4x10^{-12} + 6.679x10^{-12})} - \frac{5x10^{-15}}{2(4x10^{-12} + 9.590x10^{-12})} = 50\,ppm$$

Conclusion

It can be seen from the above analysis and examples, that the T231 VCXO can be used in a wide range of applications where the pulling range of the output frequency needs to be adjusted to suit the application. It is simply a matter of choosing the most optimum layout and selecting the right component s to trim the pulling range appropriately. This analysis and procedure can also be easily applied to the T277 VCXO which also uses a Colpitts oscillator but has a narrower frequency range of operation (8 MHz to 100 MHz) as compared to the T231 (100 MHz to 200 MHz).

Please refer to Application Note AN-106 – "Demo Board for the T231 VCXO" for further information on PCB layout and testing.

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