A Transistor-Controlled FSK Modulator/Transmitter

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Crystal oscillator circuits are best known for their extremely stable operation and low phase noise performance. Crystal oscillators are low cost, with high Q quartz crystals of small size. Several have been discussed in the literature. This article describes an innovative way of using a transistor to modulate the data, removing the hurdle of using varactor diodes, which generally have limited capacitance change.

Basics of quartz crystal

The electrical properties of a quartz crystal can be expressed by the equivalent circuit shown in Figure 1. Two modes of operation are possible: series and parallel resonance. The frequency of oscillation and the related parameters are given by Equations (1), (2) and (3). The lowest crystal impedance exists at the series resonant frequency

$$f_s(\text{series resonance}) = \frac{1}{2\pi\sqrt{(L_1C_1)}} \quad (1)$$

The largest crystal impedance exists at the parallel resonant frequency and can be expressed as

$$f_p(\text{parallel resonance}) = \frac{1}{2\pi\sqrt{(L_1C_{eq})}} \quad (2)$$

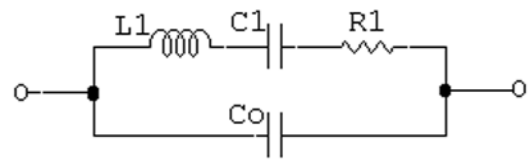
where

$$C_{eq} = \frac{C_1C_0}{(C_1+C_0)}$$

$$Q(\text{quality factor}) = \frac{2\pi f_s L_1}{R_1} = \frac{1}{[2\pi f_s R_1 C_1]} \quad (3)$$

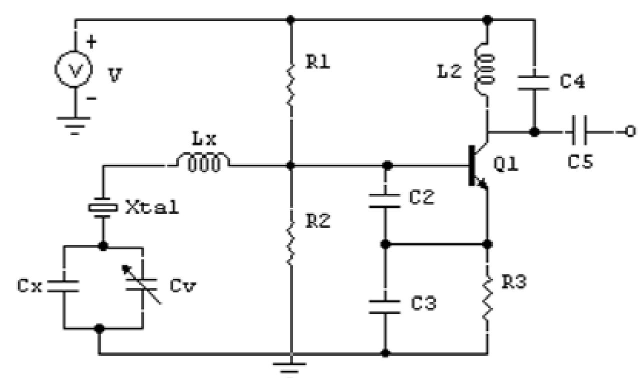
$$M(\text{frequency of merit}) = \frac{1}{[2\pi f_s C_0 R_1]} \quad (4)$$

Crystal calibrated for a parallel mode operation can be used in series mode by using the specified parallel load capacitance in series with the crystal. The frequency of the crystal can be adjusted slightly by adding either a parallel or series trimming capacitor.



Where L_1 = motional inductance
R_1 = series resistance or mechanical losses
C_1 = motional capacitance (~ 1 fF)
C_0 = shunt capacitance (1 – 9 pf)

▲ **Figure 1. Expression of the electrical properties of a quartz crystal.**



▲ **Figure 2. Crystal oscillator circuit as a narrow-band modulator/transmitter.**

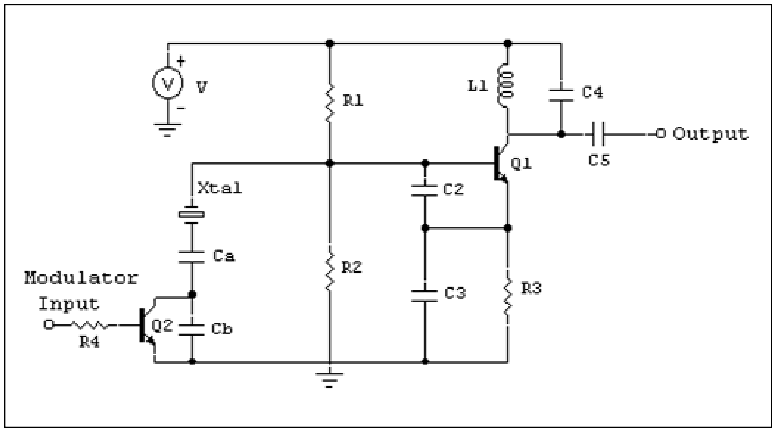
Figure 2 shows the basic oscillator circuit. If the reactance of the crystal (X_e) and the reactance of the circuit (X) satisfy the following relationship, then the oscillation will occur.

$$X_e = -X \quad \text{i.e., } R_e = -R \quad (5)$$

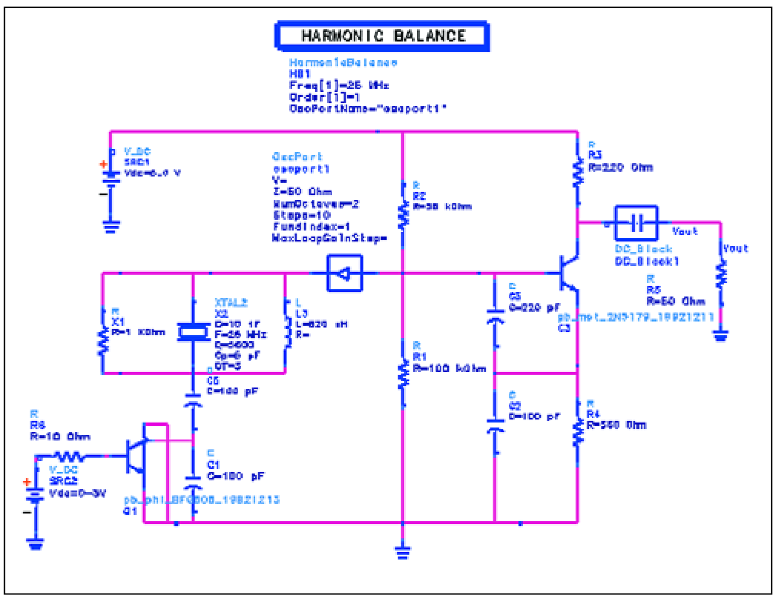
For stable operation,

$$-R > R_e \quad (6)$$

For Figure 1, we obtain



▲ **Figure 3. A circuit with a new way to add value of capacitance that the circuit can accommodate.**



▲ **Figure 4. Circuit simulation sets for HP ADS.**

$$-R = \frac{-g_m}{\left(\omega^2 \times C_2 \times C_3\right)} \qquad (7)$$

where g_m is the mutual conductance and ω is the angular frequency of oscillation of the transistor.

The capacitance C_2 and C_3 can be evaluated for the known values of R, g_m and ω. The biasing resistors can be chosen to provide the desired operating point of the transistor. The capacitors in the circuit together with the motional capacitance of the oscillator will control the pulling range of the circuit.

If the resonance frequency with the load capacitance is f_1, then the difference between f_1 and f_s (frequency pulling) is given by

$$\frac{\Delta f}{f_s} = \frac{f_1 - f_s}{f_s} = \left[\frac{1}{2}\left(\frac{C_0}{C_1}\right)\right] \times \left[\frac{1}{\left(1 + \frac{C_L}{C_0}\right)}\right] \qquad (8)$$

where

$$C_L = \left[\frac{1}{C_2} + \frac{1}{C_3} + \frac{1}{(C_x + C_v)}\right]^{-1} \qquad (9)$$

Introducing an inductor, Lx, can increase this pulling range. The new pulling range is now given by

$$\frac{\Delta f}{f_s} = \frac{f_1 - f_s}{f_s} = \left[\frac{1}{2}\left(\frac{C_0}{C_1}\right)\right]\left[\frac{1}{1 + \frac{C_L}{C_0}\left(\frac{1}{1 - \omega^2 L_x C_L}\right)}\right] \qquad (10)$$

C_v is usually implemented by a varactor diode, which has limited capacitor change.

The circuit in Figure 3 shows a new method of adding value of capacitance that the circuit can accommodate. That is, C_b can be switched on or off by the transistor Q_2. The modulation can now be applied at the input of the transistor, making the oscillator a FSK modulator or low power transmitter.

In Equation 3, the capacitance C_L now becomes

$$C_L = \left[\frac{1}{C_2} + \frac{1}{C_3} + \frac{1}{C_x}\right]^{-1} \qquad (11)$$

where C_x is a function of C_a, C_b and the transistor output capacitance (C_{ce}).

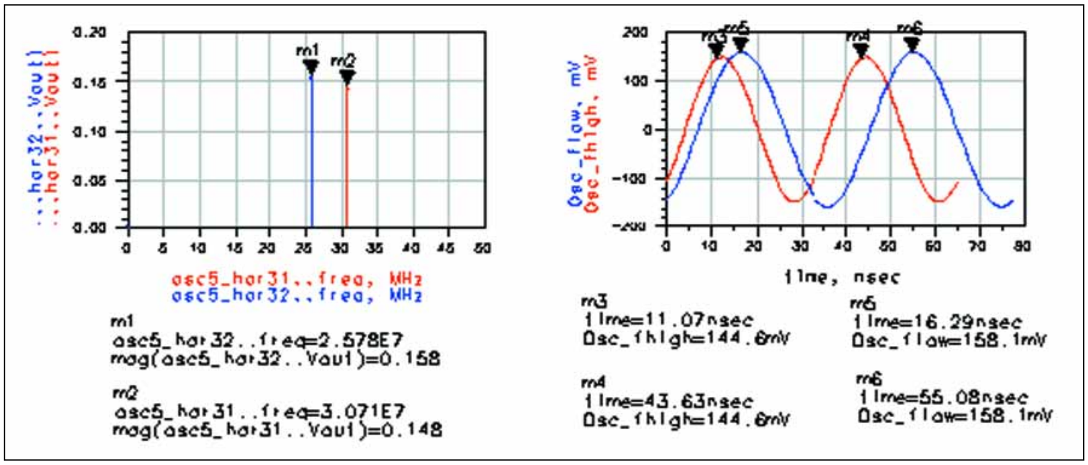
When the transistor Q_2 is fully on,

$$C_x = C_a \qquad (12)$$

When it is off,

$$C_x = \left[\frac{1}{C_a} + \frac{1}{(C_b + C_{ce})}\right]^{-1} = \left[\frac{1}{C_a} + \frac{1}{C_b}\right]^{-1} \text{ if } C_b >> C_{ce} \qquad (13)$$

The frequency shift can be controlled by proper selection of C_a and C_b.



▲ **Figure 5. Simulation results in the frequency domain (left) and time domain (right).**

Simulation and experimental results

Simulation and application verified the above circuit operation. The transistor Q_2 is operating in this circuit as a switch without DC biasing. In the simulation circuit, a coil and a resistance are added in parallel with the crystal to cancel out the shunt capacitance and to avoid abnormal oscillations respectively.

The simulations in Figures 4 and 5 show a frequency deviation of few MHz possible for a FSK modulator. In practice, larger deviation is not possible with the crystal oscillator circuit without compromising the phase noise. Larger deviation reduces the Q value of the crystal and thus increases the phase noise. The oscillator circuit has been verified experimentally with minor adjustments of some of the component values.

Conclusion

This article discussed a simple FSK modulator, or low power transmitter, that uses a transistor in an innovative way to modulate the transmit data. The proposed method allows any value of capacitance to be added to or removed from the crystal branch of the circuit which changes the oscillator frequency. As a result, the use of limited value varactor diodes in this type of circuit is not necessary. ■

Author information

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