SKYWORKS

APPLICATION NOTE

Coaxial Resonators for Voltage-Controlled Oscillator (VCO) Applications

Introduction

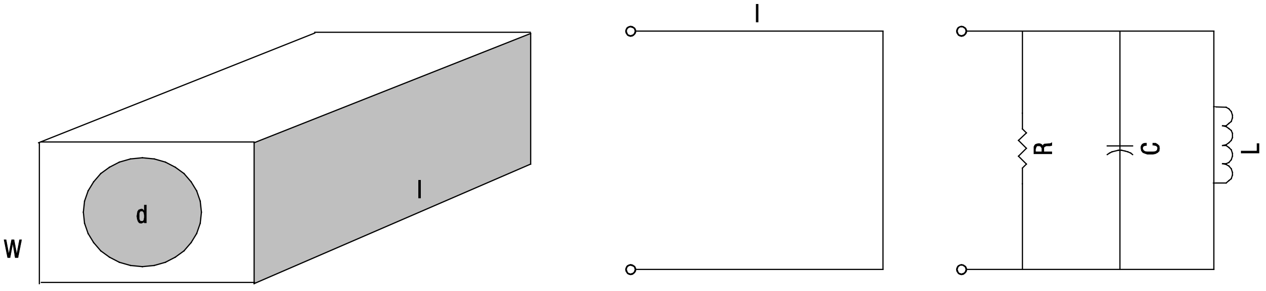
Many engineers choose to design their own Voltage-Controlled Oscillator (VCO) circuits to reduce cost, size, and power consumption. Development of high Quadrature (Q) ceramic coaxial resonators simplifies the VCO design process. When a Skyworks coaxial resonator (transmission line) is the frequency determining element of a VCO, it typically replaces a discrete inductor.

The rugged ceramic resonator has enormous benefits over traditional coils by offering better temperature stability, higher Q, and no microphonics.

This Application Note introduces the design of the Skyworks coaxial resonators, outlines their use in a VCO, and details the method of selecting the correct part.

Coaxial Resonator and Transmission Line Basics

At high frequencies, the distributed inductance and capacitance of a coaxial transmission line is efficient as a circuit element. Short sections of transmission lines with reflecting terminations exhibit inductive reactance when operated below the Self-Resonant Frequency (SRF) of the line, and exhibit capacitance reactance when operated slightly above the SRF. When the SRF is reached, the transmission line may be approximated as shown in Figure 1.



$$L = \frac{8Z_0 l\sqrt{e_r}}{\pi^2 c} \qquad C = \frac{l\sqrt{\varepsilon_r}}{2cZ_0} \qquad R = \frac{4Z_0 Q}{\pi} \qquad Z_0 = \frac{60}{\sqrt{e_r}} \ln\left(1.079\frac{W}{d}\right)$$

Figure 1. Transmission Line Approximation

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Transmission Line as an Inductance

Below resonance, coaxial line elements simulate high Q, temperature-stable, compact inductors. More precisely, shorted coaxial lines exhibit an inductive reactance when used below quarter-wave resonance, and approximate the behavior of an ideal inductance (or “coil”) over a limited frequency range. As the operating frequency (f_0) approaches the SRF of the coaxial line element, the approximation is less valid, as illustrated in Figure 2.

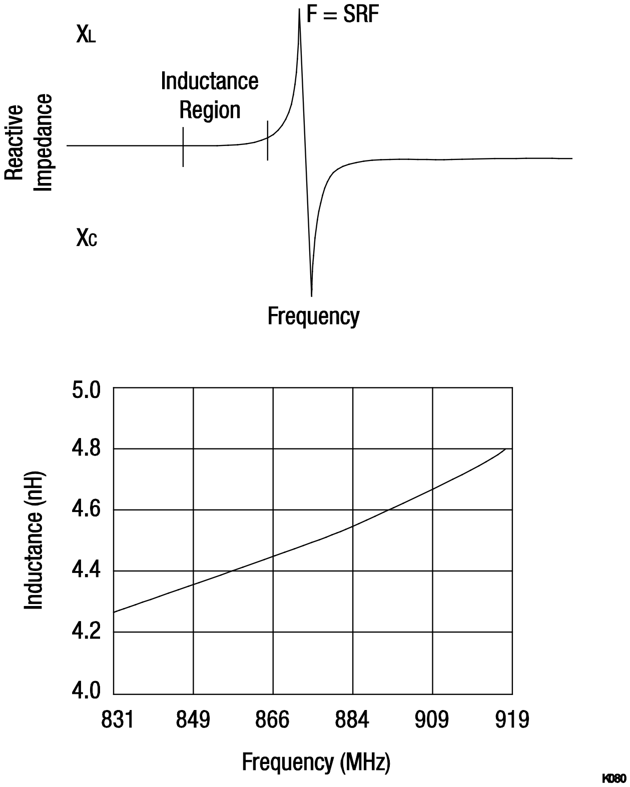

Figure 2. Inductance Region

The following formula may be used to approximate the inductive reactance at the VCO operating frequency (f_0). The coaxial element’s tab inductance appears in series with the coaxial line’s input impedance. An ideal, loss-less transmission line is assumed to simplify the calculations. Minor corrections to the part length may be evident from the prototype circuit performance.

The preferred inductive reactance at the operating frequency can be approximated [3] as follows:

$Z_{INPUT} = X_L = Z_0 \tan(\Theta) \qquad 0 \geq \lambda \geq \lambda/4$

where:

Z_{INPUT} = Impedance at the coaxial line terminals (Ω)

Z_0 = Coaxial line characteristic impedance (Ω)

$\Theta = \frac{2\pi\ell}{\lambda_G}$ Coaxial electrical length (radians)

ℓ = Coaxial line physical length (inches)

$\lambda_G = \frac{11803}{f_0 \sqrt{\varepsilon_R}}$ Wavelength in the dielectric at f_0 (inches)

VCO Basics

A varactor diode is the most widely used method to vary the operating frequency of an oscillator. Because a shorted transmission line looks inductive when operated below the SRF of the line, a varactor can tune the circuit, as shown in the Figure 3.

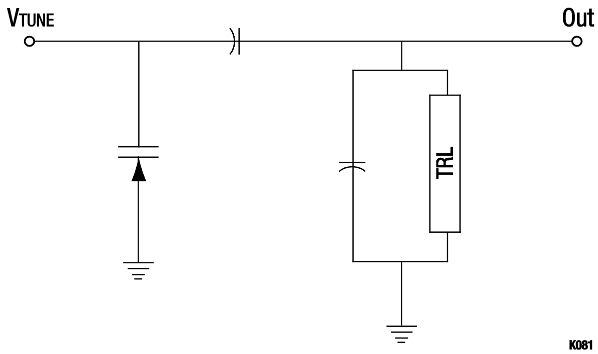

Figure 3. Transmission Line in Varactor Tuned Resonant Circuit

Typical VCO Circuit using a Skyworks Resonator

The circuit in Figure 4 shows typical DC biasing and load circuits added to the VCO circuit [4]. The major frequency determining components are: D1, C2, TRL, C3, and C8. The tuning range of the VCO is determined by the C2 varactor coupling capacitor. As the value of C2 is increased, the tuning range increases at the expense of circuit Q [5].

Important: Component parasitics are significant at these operating frequencies, and should be estimated and included if computer modeling is used [6].

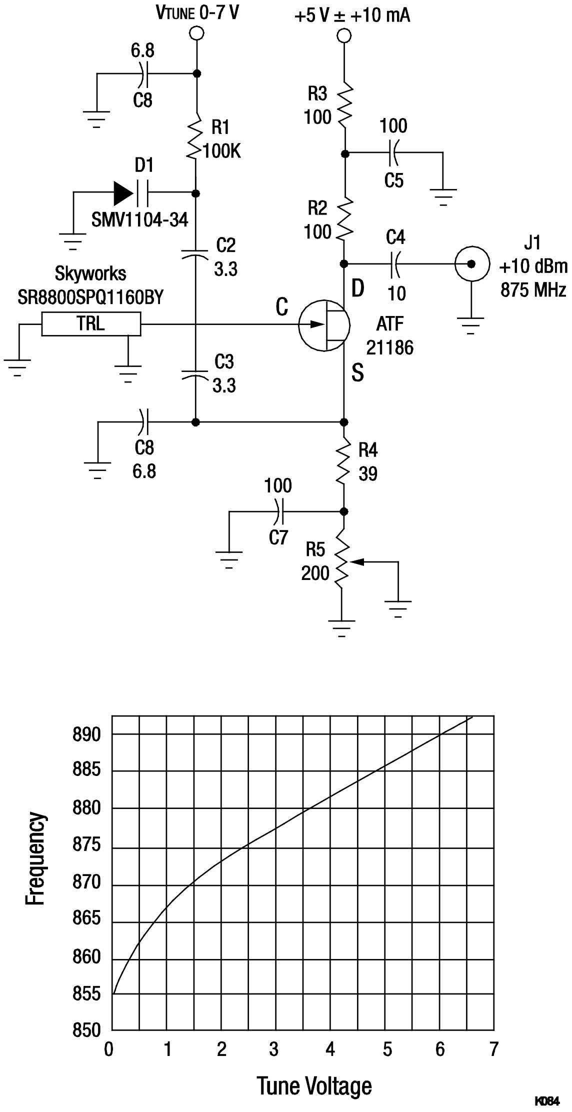

Figure 4. Typical DC Biasing and Load Circuits

Selecting the Correct Skyworks Part

Select a Skyworks coaxial resonator that has a higher SRF than the operating frequency of the VCO. The designer may refer to Skyworks *COAX Program Application Note (202665)* for frequency, material, and size guidelines. The following sections also provide steps on how to specify the proper Skyworks part.

1. Determine a preferred inductance or circuit impedance (Z_{INPUT}).
2. Choose an operating frequency.
3. Select an initial profile and material from Table 1.
4. Calculate the length of the part using the following formula:

$$\iota = \frac{\lambda_G}{2\pi} \tan^{-1}\left(\frac{Z_{INPUT}}{Z_0}\right) \text{inches}$$

Z_0 and λ_G can be obtained from Tables 1 and 2.

5. Choose the final profile.

Table 1. Coaxial Line Properties vs Profile and Material

Profile	Material Type				Tab Inductors
	1000	2000	8800	9000	
HP	25.3 Ω	18.1 Ω	13.1 Ω	8.6 Ω	1.8 nH
EP	22.5 Ω	16.1 Ω	11.7 Ω	7.7 Ω	1.0 nH
SP	18.3 Ω	13.1 Ω	9.5 Ω	6.3 Ω	1.0 nH
LS	18.4 Ω	13.1 Ω	9.5 Ω	6.3 Ω	0.9 nH
LP	27.4 Ω	19.6 Ω	14.2 Ω	9.4 Ω	1.0 nH
SP	25.7 Ω	18.4 Ω	13.3 Ω	8.8 Ω	0.6 nH
SM	18.4 Ω	13.1 Ω	9.5 Ω	6.3 Ω	0.6 nH

Table 2. Wavelength (λ_G) in Dielectric

Material	ε_R	Wavelength Formula for λ_G (Inches)
1000	10.5 ± 0.5	$3642/f_0$
2000	20.6 ± 1.0	$2601/f_0$
8800	39.0 ± 1.5	$1890/f_0$
9000	90.0 ± 3.0	$1244/f_0$

Typical Performance Characteristics

The SRF must lie within the recommended frequency range for a coaxial resonator of the same profile and material. This manufacturing restriction places constraints upon the range of inductance reactance that can be achieved using this technique, although arbitrarily high reactance values can be achieved close to the SRF. The designer should carefully analyze the circuit response when f_O is near the SRF. The SRF may be calculated from previously-determined values as follows:

$$\mathrm{SRF} = \frac{\lambda_G f_O}{4} \bullet \frac{1}{\ell}\ \mathrm{MHz}$$

The center conductor tab presents a small additional series inductance that may be included in the total preferred inductive reactance. The tab inductance has been measured with the values given in Table 1.

Design Example 1

Use a shorted coaxial line element to give an inductive reactance of 25 Ω at 900 MHz. The smallest height is required. The SM profile is chosen with 8800 material ($\varepsilon_R = 39$). The 0.6 nH tab inductance contributes 3.4 Ω, and is subtracted from the 25 Ω to give 21.6 Ω. From Table 2, the wavelength in the dielectric at 900 MHz is as follows:

$$\lambda_G = 1890 / 900 = 2.1 \text{ inches}$$

With $Z_O = 9.2\ \Omega$ from Table 1:

$$\ell = \left(\frac{2.111}{2\pi}\right) \tan^{-1} \frac{21.6}{9.5} = 0.392 \text{ inches}$$

As well as:

$$\mathrm{SRF} = \frac{(2.1)\,(900)}{(4)\,(0.392)} = 1205 \text{ MHz}$$

The coaxial line in the above equations is 0.392 / 2.111 = 0.186 λ_G long. This part can be ordered from Skyworks using part number SR8800SMQ1210BY. This part would be manufactured and tested for self-resonance at 1210 MHz.

Design Example 2

Use a shorted coaxial line element to give an inductive reactance equivalent to that of an ideal 4.0 nH coil at 800 MHz. Low loss is required, but the part must be less than 0.250 inches high. Choose an SP profile (0.237 inches high) in 8800 material ($\varepsilon_R = 38.6$). The 1.0 nH tab inductance is subtracted from the preferred inductance, allowing 4.0 – 1.0 = 3.0 nH equivalent inductance from the coaxial line. An inductive reactance of 2π (800 x 106) (3.0 x 10 – 9) = 15.1 Ω is required. Figure 5 shows the wavelength in the dielectric at 800 MHz from Table 2.

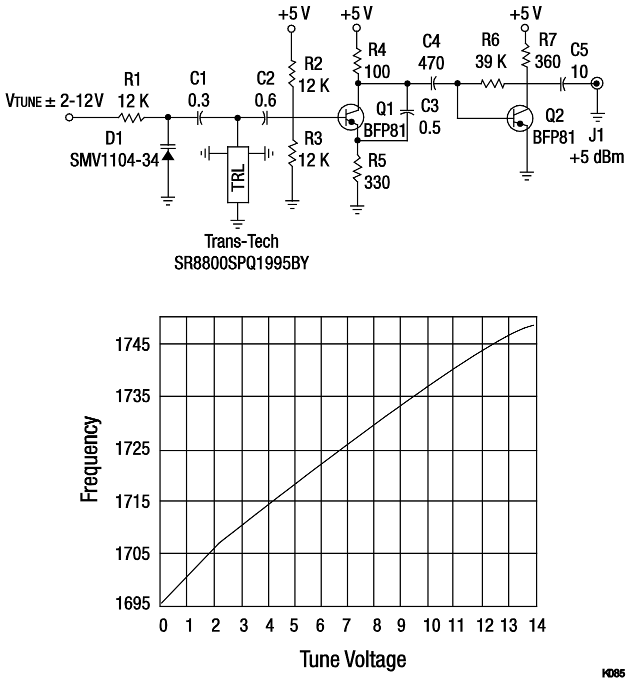

Figure 5. Wavelength in the Dielectric at 800 MHz

With $Z_O = 9.4\ \Omega$ from Table 1:

$$i = \frac{2.375}{2\pi} \tan^{-1}\left(\frac{15.1}{9.4}\right) = 0.383 \text{ inches}$$

$$Q = 240\sqrt{800}\ \frac{\mathrm{LN}\left(\frac{0.236}{0.097}\right)}{\left(\frac{1}{0.236}\right)+\left(\frac{1}{0.097}\right)} = 415$$

$$\mathrm{SRF} = \frac{(2.375)\,(800)}{(4)\,(0.383)} = 1239 \text{ MHz}$$

The coaxial line is 0.383 / 2.375 = 0.161 λ_G long. This part could be ordered from Skyworks using part number SR8800SPQ1239BY. This part would be manufactured and tested for self-resonance at 1239 MHz.

References

[1] H. Riblet: *An Accurate Approximation of the Impedance of a Circular Concentric with an External Square Tube* (IEEE Transactions *Microwave Theory and Techniques*, volume MTT-31, pages 841-844, October 1983).

[2] Theodore Moreno: *Microwave Transmission Design Data* (1948; Norwood, Artech House, 1989, page 40).

[3] W. Johnson: *Transmission Lines and Networks* (McGraw-Hill, 1950).

[4] Used by permission of Les Reading, Scientific Research Labs, Santa Maria, CA.

[5] Brendan Kelly: *1.8 GHz Direct Frequency VCO with CAD Assessment* (RF Design, page 29, February 1993).

[6] Randall Rhea: *Oscillator Design & Computer Simulation* (1990; Englewood Cliffs: Prentice Hall).

Additional Reading

- Ulrich Rohde: *Oscillator Design for Lowest Phase Noise* (Microwave Engineering Europe, page 31, May 1994).
- Ulrich Rohde and C.R. Chang: *The Accurate Simulation of Oscillator and PLL Phase Noise in RF Sources* (Proceedings of the Second Annual Wireless Symposium, Santa Clara, CA, February 15–18, 1994).

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