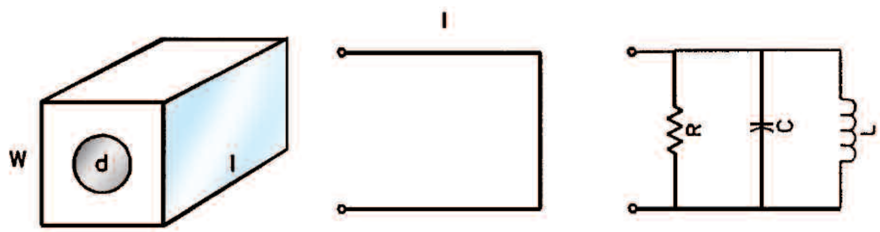
APPLICATION NOTE

No. 1008: Coaxial Resonators for VCO Applications*

Many engineers choose to design their own VCO circuits to reduce cost, size, and power consumption. Development of high 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 designer to Skyworks' coaxial resonator, outlines its use in a VCO, and details the method of selecting the correct part.

Coaxial Resonator & 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 SRF. When SRF is reached, the transmission line may be approximated by the following:[1,2]

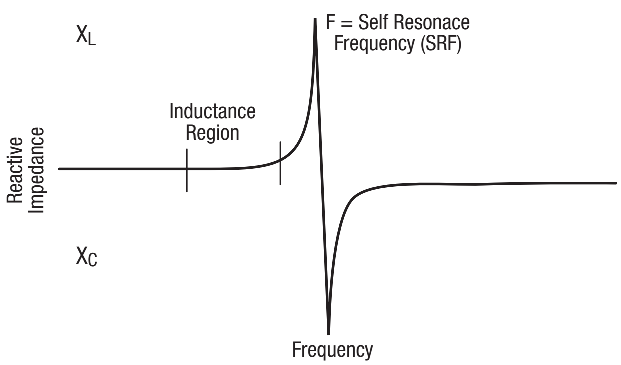


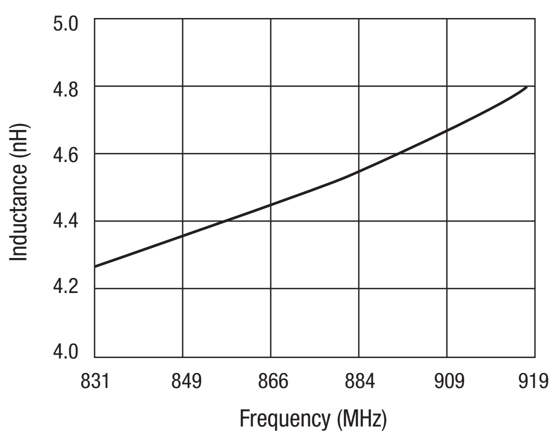
$$L = \frac{8 Z_o l \sqrt{\varepsilon_r}}{\pi^2 c} \qquad C = \frac{l \sqrt{\varepsilon_r}}{2 c Z_o} \qquad R = \frac{4 Z_o Q}{\pi} \qquad Z_o = \frac{60}{\sqrt{\varepsilon_r}} \ln\left(1.079 \frac{W}{d}\right)$$

*These products are produced by Trans-Tech (a wholly-owned subsidiary of Skyworks Solutions, Inc.)

Transmission Line as an Inductance

Below resonance, coaxial line elements simulate high Q, temperature-stable, compact inductors. More precisely, shorted coax lines will exhibit an inductive reactance when used below quarter-wave resonance, and will approximate the behavior of an ideal inductance or "coil" over a limited frequency range. As the operating frequency (f_0) approaches the self-resonant frequency (SRF) of the coax line element, the approximation will be less valid.





Typical Resonator Inductance

The formula below may be used to approximate the inductive reactance at the VCO operating frequency (f_0). The coaxial element's tab inductance will appear in series with the coax line's input impedance. An ideal, lossless transmission line is assumed to simplify the calculations. Minor corrections to part length may be evident from prototype circuit performance.

Let the desired inductive reactance at the design frequency f_0 be approximated by:[3]

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

where:

Z_{INPUT} = impedance at the coax line terminals (Ω)

Z_0 = coax line characteristic impedance (Ω)

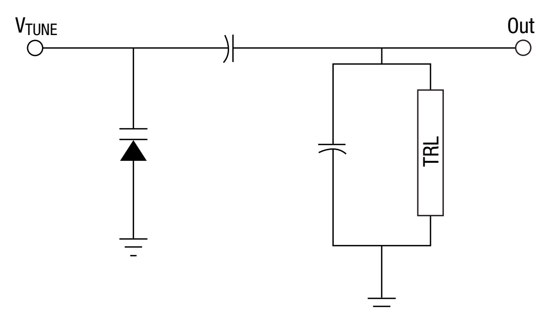
$\Theta = \frac{2\pi\iota}{\lambda_G}$ coax electrical length (radians)

ℓ = coax line physical length (inches)

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

VCO Basics

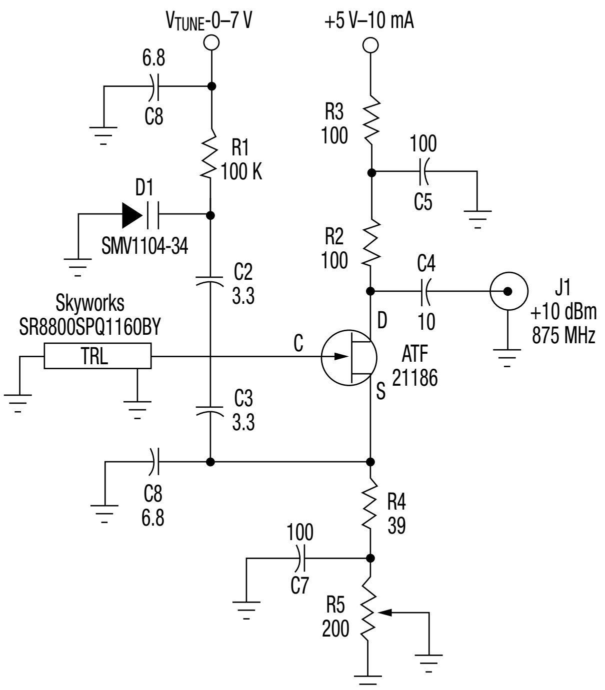
A varactor diode is the most widely used method to vary the operating frequency of an oscillator. Because a shorted transmission line will look inductive when operated below the Self Resonant Frequency (SRF) of the line, a varactor can tune the following circuit.

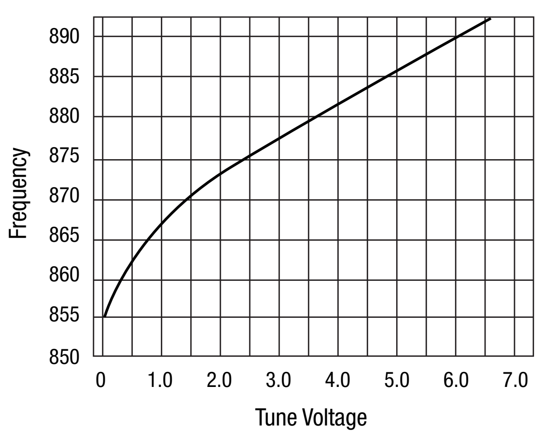


Transmission Line in Varactor Tuned Resonant Circuit

Typical VCO Circuit Using a Skyworks Resonator

The circuit below 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 varactor coupling capacitor, C2.
As the value of C2 is increased, the tuning range will increase at the expense of circuit Q[5]. It is important to note that component parasitics are significant at these operating frequencies, and should be estimated and included if computer modeling is used[6].





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' "Coaxial Resonator Design Program for Windows™" for frequency, material, and size guidelines. The following pages also provide a step-by-step process to specify the proper Skyworks part.

1. Determine a desired inductance or circuit impedance (Z_{INPUT}).
2. Choose an operating frequency.
3. Select an initial profile and material from Table 2 below.
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 below.

5. Choose the final profile.

Table 1. 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	$1244/f_0$

Table 2. Coax Line Properties vs. Profile and Material

Profile	1000	2000	8800	9000	Tab Inductors
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

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 which can be realized by this technique, although arbitrarily high reactance values can be achieved close to SRF. The designer should prudently analyze the circuit response when f_0 is near SRF.

SRF may be calculated from previously determined values:

$$SRF = \frac{\lambda_G f_0}{4} \bullet \frac{1}{\ell} \text{ MHz}$$

The center conductor tab will present a small additional series inductance which may be included in the total desired inductive reactance. The tab inductance has been measured with values given in Table 2.

Design Example 1

Use a shorted coax line element to give an inductive reactance of 25 Ω at 900 MHz. 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 1, the wavelength in the dielectric at 900 MHz is:

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

With $Z_0 = 9.2\ \Omega$ from Table 2, we have

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

also,

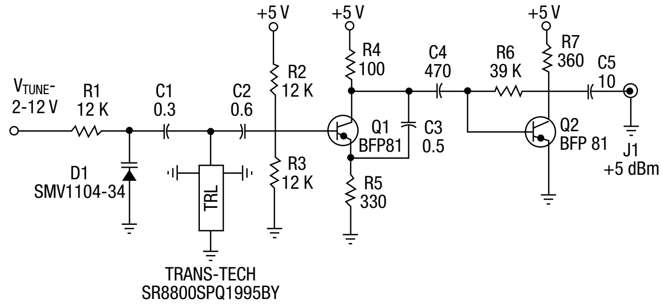
$$SRF = \frac{(2.1)(900)}{(4)(0.392)} = 1205 \text{ MHz}$$

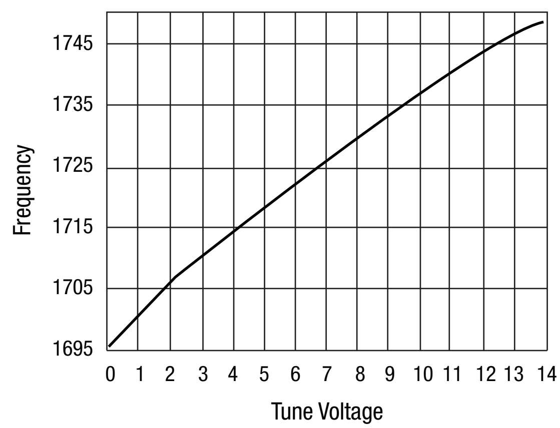
Notice that the coax line is 0.392/2.111 = 0.186 λ_G long. This part could be ordered from Skyworks as part number SR8800SMQ1210BY. It would be manufactured and tested for self-resonance at 1210 MHz.

Design Example 2

Use a shorted coax 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 part must be less than 0.250" high.

Choose an SP profile (0.237" high) in 8800 material, $\varepsilon_R = 38.6$. The 1.0 nH tab inductance is subtracted from the desired inductance, allowing 4.0 - 1.0 = 3.0 nH equivalent inductance from the coax line. An inductive reactance of $2\pi\,(800 \times 10^6)\,(3.0 \times 10^{-9}) = 15.1\ \Omega$ is required. From Table 1, the wavelength in the dielectric at 800 MHz is:





With $Z_0 = 9.4\ \Omega$ from Table 2, we have:

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

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

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

The coax line is 0.383/2.375 = 0.161 λ_G long. This part could be ordered from Skyworks as part number SR8800SPQ1239BY. It 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 Trans. Microwave Theory Tech.*, vol. MTT-31, pp. 841-844, Oct. 1983.
2. Theodore Moreno, *Microwave Transmission Design Data* (1948; Norwood: Artech House, 1989) p. 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*, p. 29, Feb. 1993.
6. Randdell Rhea, *Oscillator Design & Computer Simulation* (1990; Englewood Cliffs: Prentice Hall).

Additional Reading

Ulrich Rohde, "Oscillator Design for Lowest Phase Noise," *Microwave Engineering Europe*, p. 31, May 1994.

Ulrich Rohde, 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.