SKYWORKS®

APPLICATION NOTE

Tolerance Analysis of Coaxial Inductors

Introduction

Voltage-Controlled Oscillator (VCO) designers often specify a coaxial inductor by designating a catalog resonator. The Skyworks coaxial resonator part numbering scheme includes the ceramic material designator, physical profile, and Self-Resonant Frequency (SRF).

The parts operate below the SRF to present an inductive reactance to the VCO active circuit. Whether analytically or empirically determined, specifying the SRF alone (specifically SRF tolerance) does not guarantee the same tolerance on the equivalent inductance (L_{EQ}) value. Unfortunately, there is no way short of a tolerance analysis that discloses the possible L_{EQ} variations.

Results are unique to the application, particularly the separation between the SRF and VCO frequency. Fortunately, the analysis is not difficult and can forewarn the designer of how much the part's nominal value of L_{EQ} can vary, unit-to-unit. An approximation to the L_{EQ} equivalent inductance can be modeled by a small lumped tab inductance (L_{TAB}) plus the contribution of the shorted ceramic transmission line.

$$L_{EQ} = L_{TAB} + \frac{60{,}000}{2\pi F_{VCO}\sqrt{\varepsilon_R}}\,\ell n\left(1.079\,\frac{W}{d}\right)\tan\frac{\pi F_{VCO}}{2F_{SRF}} \quad (1)$$

Where:

L_{EQ} = Total equivalent inductance of the coaxial inductor (nH).
L_{TAB} = Tab inductance (nH).
ℓn = Logarithm
F_{VCO} = VCO center frequency (MHz).
ε_R = Dielectric constant of the ceramic.
W = Coaxial line width (inches).
d = Coaxial line inner diameter (inches).
F_{SRF} = Coaxial line SRF (MHz).

The tangent function argument is evaluated in radians. For a given VCO center frequency, the components of L_{EQ} that are variables are the SRF, dimensions (W, d), and dielectric constant (ε_R). The SRF is usually specified with 1% or 0.5% accuracy.

The dielectric constants of the 8800 and 9000 material are given in Table 1. Values and tolerances for W, d, and the tab inductance are given in Table 2.

Due to the skin effect, the RF current flows in the metallization at the ceramic-metal interface. The W and d values here are ceramic dimensions, which differ from Skyworks catalog (metallized) values. A spreadsheet can be developed with the above formula as its core to test the contributions of the variables and cumulative variance in the L_{EQ}. As a rule, L_{EQ} varies least when the:

- SRF is as far as possible above the F_{VCO}, which is achieved by using a part with the lowest ε_R and the highest characteristic impedance (Z_O). Skyworks series SR8800LPQ (4 mm) resonators have $\varepsilon_R = 38.6$, and $Z_O = 14\ \Omega$.
- Part geometry is large enough where the effect of dimensional tolerances is minimized. This implies that the L_{EQ} varies most with very small (2 mm and 3 mm) resonators.

Table 1. Dielectric Constants (ε_R) of Coaxial Material

Material	ε_R
1000	10.5 ± 0.5
2000	20.6 ± 1.0
8800	39.0 ± 1.5
9000	90 ± 3

Table 2. Dimensions and Tab Inductance vs Profile

Profile	Width (W) (Inches)	Diameter (d) (Inches)	L_{TAB} (nH)
HP (12 mm)	0.476 ± 0.005	0.131 ± 0.004	1.8
EP (8 mm)	0.316 ± 0.005	0.101 ± 0.004	1.0
SP (6 mm)	0.237 ± 0.004	0.095 ± 0.004	1.0
LS (4 mm)	0.155 ± 0.004	0.062 ± 0.004	0.9
LP (4 mm)	0.155 ± 0.004	0.038 ± 0.003	1.0
MP (3 mm)	0.119 ± 0.004	0.032 ± 0.003	0.6
SM (2 mm)	0.080 ± 0.003	0.032 ± 0.003	0.6

To illustrate the analysis technique, suppose a VCO design with a center frequency of 915 MHz requires an equivalent inductance of 10.0 nH. Table 3 shows two coaxial resonators that satisfy this L_{EQ}, Skyworks parts SR9000SMQ0986BY (2 mm) and SR8800LPQ1098BY (4 mm).

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Table 3. Resonator Comparisons for L_{EQ} = 10 nH @ 915 MHz

Parameter	Symbol	Resonators	
		SR9000SMQ0986BY (2 mm)	SR8800LPQ1098BY (4 mm)
Tab inductance (nH)	L_{TAB}	0.6	1.0
Dielectric constant	ε_R	90.0 ± 3.0	39.0 ± 1.5
Width (inches)	W	0.080 ± 0.003	0.155 + 0.004
Diameter (inches)	d	0.032 ± 0.003	0.038 ± 0.003
Resonant frequency (MHz)	F_{SRF}	986	1098
Sensitivity to ε_R	$\Delta L_{EQ}\Delta\varepsilon_R$	±1.6%	±1.8%
Sensitivity to W	$\Delta L_{EQ}\Delta W$	±3.4%	±1.6%
Sensitivity to d	$\Delta L_{EQ}\Delta d$	±8.4%	±4.6%
Sensitivity to F_{SRF}	$\Delta L_{EQ}\Delta F_{SRF}$	±14.4%	±5.1%

The results in Table 3 demonstrate the importance of the separation between the F_{VCO} and F_{SRF}. The components of sensitivity may be statistically manipulated with a Monte-Carlo process or other analysis method. If the tolerance on the F_{SRF} was reduced from 1% to 0.5%, the $\Delta L_{EQ}/\Delta F_{SRF}$ component reduces from the above figures to ±6.65% and ±3.88% for the 2 mm and 4 mm parts, respectively.

An alternative solution can be to shunt-load the resonator with a small capacitor, making the required equivalent inductance smaller and raising the F_{SRF}. The effect of the additional capacitance on the MHz/V sensitivity of the VCO should then be circuit-analyzed, because that performance is also influenced by the placement of the F_{SRF}.

Ceramic Filters—A Bandpass Filter using Coaxial Resonators

Coaxial resonators can be used as high-Q circuit elements in the design of filters. This Application Note demonstrates the Touchstone simulation of a three-pole filter using quarter-wave resonators.

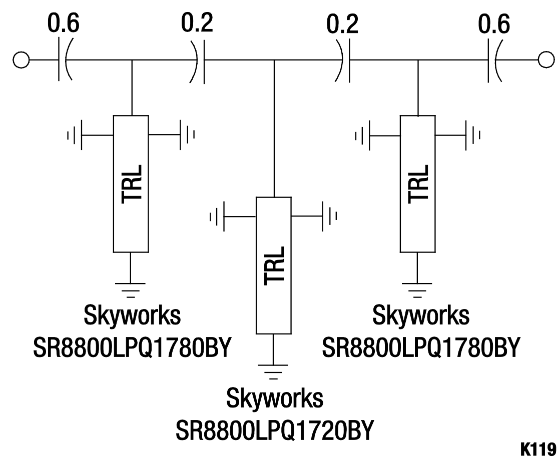

Figure 1. Coaxial Resonators used as High-Q Circuit Elements

Because the center shunt resonator is loaded less than the input and output shunt resonators, it has a lower SRF.

The TouchTone circuit file is shown in Figure 2, and the output plot is shown in Figure 3.

```
DIM
        FREQ     MHz
        CAP      PF
        LNG      IN
VAR
        C1 = 0.6    !     series cap input and output
        C2 = 0.2    !     series coupling caps
        L1 = 0.267  !     length of input and output resonator
        L2 = 0.276  !     length of center resonator
CKT
        CAP      1     2     C^C1                                          !     INPUT CAP
        TLPSC    2     0     Z = 14    L^L1 K = 38.6 A = 0.05   F = 1781   !     INPUT SHUNT LINE
        CAP      2     4     C^C2                                          !     COUPLING CAP
        TLPSC    4     0     Z = 14    L^L2 K = 38.6 A = 0.05   F = 1717   !     CENTER SHUNT LINE
        CAP      4     6     C^C2                                          !     COUPLING CAP
        TLINP    6     0     Z = 14    L^L1 K = 38.6 A = 0.05   F = 1781   !     OUTPUT SHUNT LINE
        CAP      6     8     C^C1                                          !     OUTPUT CAP
        DEF2P    1     8     RESP
FREQ
        SWEEP    1420  1920   1
OUT
        RESP     DB    [S11]  GR1
        RESP     DB    [S21]  GR1
GRID
        RANGE    1420  1920   50
        GR1      0     60     10
```

Figure 2. Touchstone Circuit File

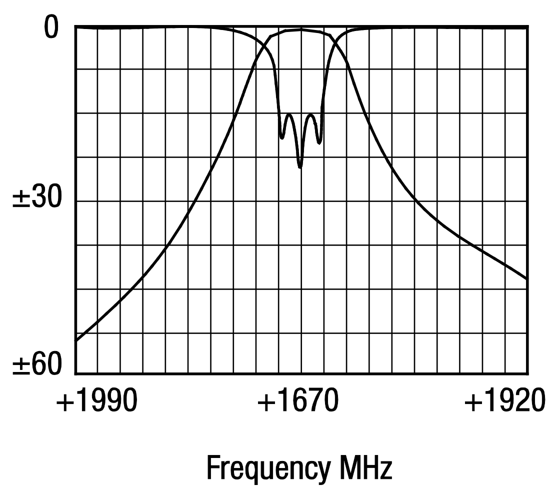

Figure 3. Output Plot