INDUCTOR DESIGN FOR THE Si41XX SYNTHESIZER FAMILY

1. Introduction

Silicon Laboratories' family of frequency synthesizers integrates VCOs, loop filters, reference and VCO dividers, and phase detectors in standard CMOS technology. Depending on the synthesizer being used, the frequency of operation may require an external inductance to establish the desired center frequency of operation. This may be implemented with either a printed circuit board (PCB) trace or a discrete "chip" inductor. This application note provides guidelines for designing these external inductors to ensure maximum manufacturing margin for frequency tuning.

2. Determining L_{EXT}

The center frequency for many of Silicon Laboratories' frequency synthesizers is established using an external inductor. The value for this inductor is determined by Equations 1 and 2:

$$f_{CEN} = \frac{1}{2\pi\sqrt{C_{NOM}(L_{PKG} + L_{EXT})}} \qquad \text{(Equation 1)}$$

from which

$$L_{EXT} = \frac{1}{(2\pi f_{CEN})^2 C_{NOM}} - L_{PKG} \qquad \text{(Equation 2)}$$

where f_{CEN} = desired center frequency of synthesizer
C_{NOM} = nominal tank capacitance from synthesizer data sheet
L_{PKG} = package inductance from synthesizer data sheet
L_{EXT} = external inductance required

3. Implementing L_{EXT}

Once the required value of external inductance is determined given the desired center frequency, a choice must be made regarding the implementation of the inductor. The two possible implementations are a discrete "chip" inductor or a printed circuit board trace.

3.1. Using a Discrete "Chip" Inductor

If the required value for L_{EXT} is greater than 3 nH, it is recommended that a discrete "chip" inductor be used. This inductor should be placed as close as possible to the device pins as shown in Figure 1.

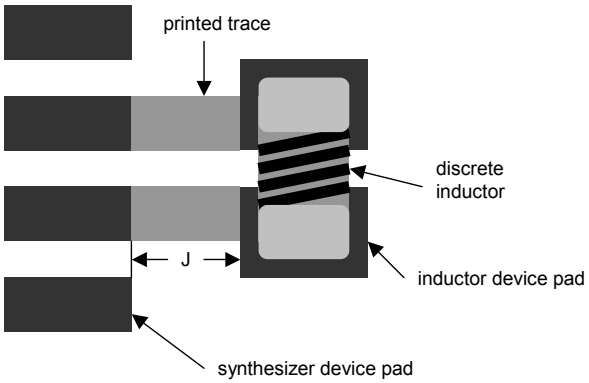

Figure 1. Placement of Discrete "Chip" Inductor

While close placement will minimize the inductance of the traces connecting the discrete inductor to the synthesizer, these traces, nonetheless, contribute to the total overall inductance.

The total external inductance includes contributions from both the discrete inductor and the connecting traces as indicated in Equation 3:

$$L_{EXT} = L_{NOM} + X(J + 0.3) \qquad \text{(Equation 3)}$$

where L_{EXT} = external inductance
L_{NOM} = nominal value of discrete "chip" inductor
X = constant of proportionality for MLP (X_{MLP}) or TSSOP (X_{TSSOP}) (nH/mm)
J = dimension shown in Figure 1 (mm)

Note that the term "J + 0.3" is the effective D dimension used in the next section. Also, the determination of X is described in the next section.

The discrete inductor should be selected such that the Q of the inductor is greater than 40, and the tolerance of the inductance is ±10% or better.

3.2. Using a Printed Trace Inductor

If the required value of L_{EXT} is less than 3 nH, it is recommended that a PCB trace be used as shown in Figure 2.

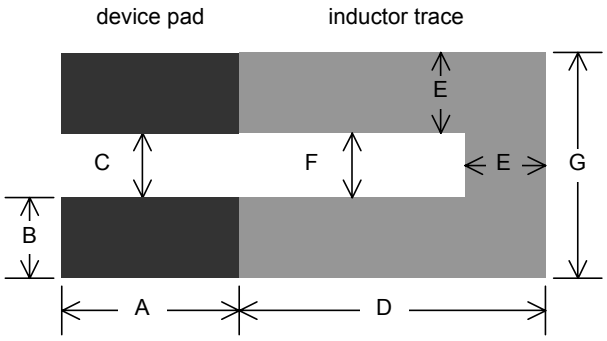

Figure 2. Printed Trace Inductor

Table 1 lists the dimensions to be used with a micro leadframe package (MLP), and Table 2 lists the dimensions to be used with a thin shrink small outline package (TSSOP).

Table 1. Dimensions to be used with MLP

Dimension	Value (mm)
A	0.80
B	0.30
C	0.20
D	(calculated)
E	0.30
F	0.20
G	0.80

Table 2. Dimensions to be used with TSSOP

Dimension	Value (mm)
A	1.50
B	0.30
C	0.35
D	(calculated)
E	0.30
F	0.35
G	0.95

The inductance of the shape shown in Figure 2 is directly proportional to the D dimension.

The constant of proportionality, X_{MLP} or X_{TSSOP}, is given by Equations 4 and 5 for an MLP and a TSSOP, respectively:

$$X_{MLP} = 0.620\left(1 - 0.823e^{\frac{-H}{130}}\right)\frac{nH}{mm} \quad \text{(Equation 4)}$$

$$X_{TSSOP} = 0.700\left(1 - 0.857e^{\frac{-H}{140}}\right)\frac{nH}{mm} \quad \text{(Equation 5)}$$

where X_{MLP} = constant of proportionality for MLP

X_{TSSOP}= constant of proportionality for TSSOP

H = thickness of dielectric between inductor trace and ground plane in µm

In each of these equations, H is the thickness of the dielectric between the “top” layer metal and the layer containing the ground plane measured in µm. Figure 3 illustrates the dimension H.

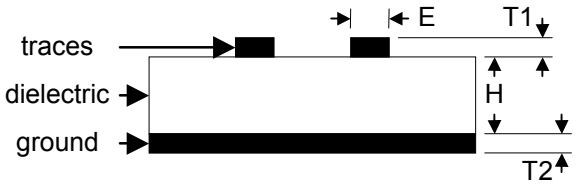

Figure 3. Side View of Printed Circuit Board

It is recommended that the H dimension be greater than 100 µm to reduce the sensitivity of the printed trace inductance to thickness variation in the PCB dielectric. To accomplish this, it may be necessary to remove copper from layer 2 and locate the ground plane on layer 3. In any case, H is the distance from the bottom of the inductor trace to the top of the ground plane. The thickness of the ground plane, T2, and the trace on layer 1, T1, do not have a material effect on the calculations and should be ignored.

Once the constant of proportionality (X) has been calculated using Equation 4 (MLP) or Equation 5 (TSSOP), it is necessary to calculate the length of the inductor trace. This is accomplished using Equation 6.

$$D = \frac{L_{EXT}}{X} \quad \text{(Equation 6)}$$

where D = trace length shown in Figure 2 in mm

L_{EXT} = calculated value of external inductance required

X = constant of proportionality for MLP (X_{MLP}) or TSSOP (X_{TSSOP})

With this calculation complete, the trace can be implemented as shown in Figure 2.

4. Checking the Value of L_{EXT}

Once the desired inductor has been implemented, and the PCB has been fabricated, the value of L_{EXT} should be verified. This can be done by following the steps listed below:

1. Measure the minimum operating frequency of the VCO in open-loop mode. This is accomplished by performing a sequence of register writes as described below.

   For the IF synthesizer:
   A. 0x000062 (hexadecimal)—power IF synthesizer and reference amplifier.
   B. 0x00024F—test register.
   C. 0x000F2D—test register.
   D. 0x010010—set the test bit in the main configuration register.
   E. 0x07FF1D—set the VCO to its minimum frequency.

   For the RF1 synthesizer:
   A. 0x000052 (hexadecimal)—power RF synthesizer and reference amplifier.
   B. 0x010003—dummy write to select RF1 synthesizer.
   C. 0x00024F—test register.
   D. 0x000F2D—test register.
   E. 0x010010—set the test bit in the main configuration register.
   F. 0x07FF0D—set the VCO to its minimum frequency.

   For the RF2 synthesizer:
   A. 0x000052 (hexadecimal)—power IF synthesizer and reference amplifier.
   B. 0x010004—dummy write to select RF2 synthesizer.
   C. 0x00024F—test register.
   D. 0x000F2D—test register.
   E. 0x010010—set the test bit in the main configuration register.
   F. 0x07FF0D—set the VCO to its minimum frequency.

   After programming the VCO to its minimum open-loop frequency, measure the value of f_{MIN}. Note that this sequence of register writes leaves the device in a test mode. All the registers described in the data sheet should be re-written with normal values for proper closed-loop operation.

2. Measure the maximum operating frequency of the VCO in open-loop mode. This is accomplished by performing a sequence of register writes as described below.

   For the IF synthesizer:
   A. 0x000062 (hexadecimal)—power IF synthesizer and reference amplifier.
   B. 0x00024F—test register.
   C. 0x000F2D—test register.
   D. 0x010010—set the test bit in the main configuration register.
   E. 0x00001D—set the VCO to its maximum frequency.

   For the RF1 synthesizer:
   A. 0x000052 (hexadecimal)—power RF synthesizer and reference amplifier.
   B. 0x010003—dummy write to select RF1 synthesizer.
   C. 0x00024F—test register.
   D. 0x000F2D—test register.
   E. 0x010010—set the test bit in the main configuration register.
   F. 0x00000D—set the VCO to its maximum frequency.

   For the RF2 synthesizer:
   A. 0x000052 (hexadecimal)—power IF synthesizer and reference amplifier.
   B. 0x010004—dummy write to select RF2 synthesizer.
   C. 0x00024F—test register.
   D. 0x000F2D—test register.
   E. 0x010010—set the test bit in the main configuration register.
   F. 0x00000D—set the VCO to its maximum frequency.

   After programming the VCO to its maximum open-loop frequency, measure the value of f_{MAX}. Note that this sequence of register writes leaves the device in a test mode. All the registers described in the data sheet should be re-written with normal values for proper closed-loop operation.

3. Calculate the measured center frequency for the synthesizer using Equation 7.

$$f_{MEAS} = \frac{f_{MIN} + f_{MAX}}{2} \quad \text{(Equation 7)}$$

where f_{MEAS} = measured center frequency

f_{MIN} = measure minimum frequency of operation
f_{MAX} = measured maximum frequency of operation

4. Calculate the measured external inductance, L_{MEAS}, using Equation 8.

$$L_{MEAS} = \frac{1}{(2\pi f_{MEAS})^2 C_{NOM}} - L_{PKG} \quad \text{(Equation 8)}$$

where L_{MEAS} = measured external conductance
f_{MEAS} = measured center frequency
C_{NOM} = nominal tank capacitance from synthesizer data sheet
L_{PKG} = package inductance from synthesizer data sheet

5. Refining the Implementation of L_{ext}

If the measured center frequency (f_{MEAS}) is more than 2% away from the desired center frequency (f_{CEN}), it is suggested that the external inductor be adjusted to provide maximum manufacturing margin.

If the inductor is implemented with a discrete chip inductor, change the nominal value of this inductor using Equation 9.

$$L_{NEW} = 2L_{OLD} - L_{MEAS} \quad \text{(Equation 9)}$$

where L_{NEW} = nominal external inductance for next implementation
L_{OLD} = nominal external inductance from current implementation
L_{MEAS} = measured external inductance from current implementation

If the inductor is implemented with a printed trace, change the D dimension of the trace using Equation 10.

$$D_{NEW} = D_{OLD} + \frac{L_{CALC} - L_{MEAS}}{X} \quad \text{(Equation 10)}$$

where D_{NEW} = dimension shown in Figure 2 for next implementation in mm
D_{OLD} = dimension shown in Figure 2 from current implementation in mm
L_{CALC} = calculated value of external inductance from current implementation in nH
L_{MEAS} = measured external inductance from current implementation in nH
X = constant of proportionality for MLP (X_{MLP}) or TSSOP (X_{TSSOP}) in nH/mm

After the inductor has been adjusted, check the new value of L_{EXT} as described in the previous section.

6. Example 1

Assume that the application requires the center frequency of the RF1 synthesizer on the Si4133-BM to be 1.6 GHz. The thickness of the dielectric is 210 μm. The first step is to calculate the required external inductance value, L_{EXT}, from Equation 2:

$$L_{EXT} = \frac{1}{(2\pi 1.6 \cdot 10^9)^2 (4.3 \cdot 10^{-12})} - (1.5 \cdot 10^{-9}) = 0.80 \text{ nH}$$

Since the value is less than 3 nH, a printed trace implementation will be used. The constant of proportionality is calculated from Equation 4:

$$X_{MLP} = 0.620\left(1 - 0.823e^{\frac{-210}{130}}\right) = 0.519 \text{ nH/mm}$$

Finally, from Equation 6:

$$D = \frac{0.80}{0.519} = 1.54 \text{ mm}$$

This is the calculated value in Table 1 for Figure 2, showing the appropriate printed trace inductor for this application.

7. Example 2

Assume that the application requires the center frequency of the IF synthesizer on the Si4133-BM to be 550 MHz. The thickness of the dielectric is 210 μm. The first step is to calculate the required external inductance value, L_{EXT}, from Equation 2:

$$L_{EXT} = \frac{1}{(2\pi 550 \cdot 10^6)^2 (6.5 \cdot 10^{-12})} - (1.6 \cdot 10^{-9}) = 11.28 \text{ nH}$$

Since the value is greater than 3 nH, a discrete "chip" inductor is recommended for the implementation. An inductor with a nominal value of 10.0 nH must be placed according to Figure 1 with the J dimension calculated by rearranging terms in Equation 3:

$$J = \frac{L_{EXT}(nH) - L_{NOM}(nH)}{X_{MLP}(nH/mm)} - 0.3 \text{ mm}$$

$$= \frac{11.28 - 10.0}{0.519} \text{ mm} - 0.3 \text{ mm} = 2.17 \text{ mm}$$

Note that the inductor must have a Q greater than 40 at 550 MHz, and the tolerance must be ±10% or better.

8. Verifying Margin in Design

Important: Please note that this procedure is only intended for initial verification of the design of the board and external VCO tuning inductor.

It is possible to determine the frequency tuning margin on a design implementation. This is accomplished by reading back from the synthesizer register values which indicate the tuning range of the VCOs using the following procedure:

IF synthesizer:

1. Program the IF synthesizer to its highest frequency in the application.
2. Write 0x0001DE (hexadecimal) to enable a read of the IF tuning code.
3. Read 18 bits from the serial interface. (See “Serial Read Timing.")
4. The 18-bit value read from the interface is the tuning code. This value should be greater than 0x40 (hexadecimal) if the unit has adequate tuning margin.
5. Program the IF synthesizer to its lowest frequency in the application.
6. Write 0x0001DE (hexadecimal) to enable a read of the IF tuning code.
7. Read 18 bits from the serial interface. (See “Serial Read Timing.")
8. The 18-bit value read from the interface is the tuning code. This value should be less than 0x780 (hexadecimal) if the unit has adequate tuning margin.

RF1 synthesizer:

1. Program the RF1 synthesizer to be active and at its highest frequency in the application.
2. Write 0x0000DE (hexadecimal) to enable a read of the RF tuning code.
3. Read 18 bits from the serial interface. (See “Serial Read Timing.")
4. The 18-bit value read from the interface is the tuning code. This value should be greater than 0x40 (hexadecimal) if the unit has adequate tuning margin.
5. Program the RF1 synthesizer to be active and at its lowest frequency in the application.
6. Write 0x0000DE (hexadecimal) to enable a read of the RF tuning code.
7. Read 18 bits from the serial interface. (See “Serial Read Timing.")
8. The 18-bit value read from the interface is the tuning code. This value should be less than 0x780 (hexadecimal) if the unit has adequate tuning margin.

RF2 synthesizer:

1. Program the RF2 synthesizer to be active and at its highest frequency in the application.
2. Write 0x0000DE (hexadecimal) to enable a read of the RF tuning code.
3. Read 18 bits from the serial interface. (See “Serial Read Timing.")
4. The 18-bit value read from the interface is the tuning code. This value should be greater than 0x40 (hexadecimal) if the unit has adequate tuning margin.
5. Program the RF2 synthesizer to be active and at its lowest frequency in the application.
6. Write 0x0000DE (hexadecimal) to enable a read of the RF tuning code.
7. Read 18 bits from the serial interface. (See “Serial Read Timing.")
8. The 18-bit value read from the interface is the tuning code. This value should be less than 0x780 (hexadecimal) if the unit has adequate tuning margin.

8.1. Serial Read Timing

In addition to the functions described in the data sheet, the AUXOUT pin can be used to read the contents of some synthesizer registers. By writing the values of 0x0001DE and 0x0000DE as described above, the serial interface is configured to read the tuning codes. During the readback, the function of the AUXOUT pin is to provide the serial data output from the device. Writing to any of the registers described in the data sheet will cause the function of AUXOUT to revert to its previously programmed function. This is illustrated in Figure 4 below. Refer to Table 3 for timing values.

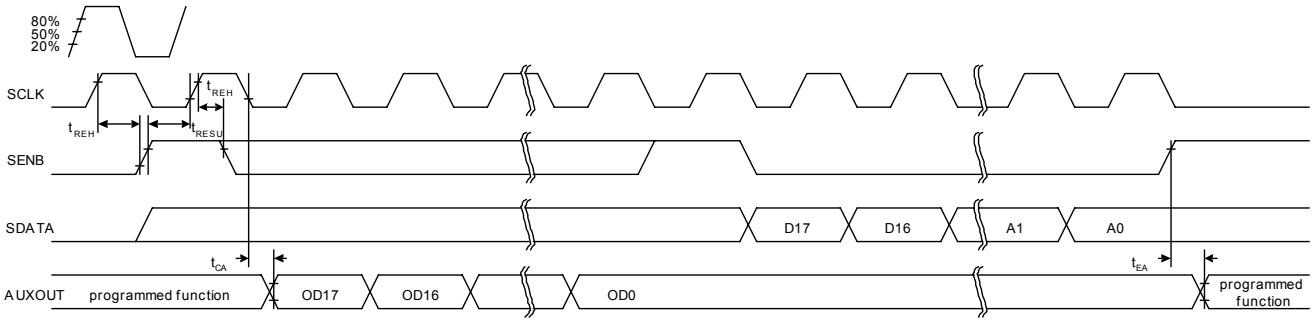

Figure 4. Read Timing Diagram

Table 3. Serial Read Timing Values

Parameter	Symbol	Minimum	Maximum	Units
Read Operation SCLK to $\overline{SEN}$ Hold Time	t_{REH}	16	—	ns
Read Operation $\overline{SEN}$ to SCLK Setup Time	t_{RESU}	16	—	ns
SCLK to AUXOUT	t_{CA}	—	16	ns
$\overline{SEN}$ to AUXOUT	t_{EA}	—	16	ns

9. Summary

Silicon Laboratories' frequency synthesizers have been designed to provide robust operation over extreme conditions. This application note provides the designer with information to maximize the operating margins of both the synthesizer and the system in which it is to be used.

NOTES:

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