AN1180: EFR32 Series 1 sub-GHz Discrete Matching Solutions

This application note describes the technical details of cost-effective, fully discrete sub-GHz single-band, novel wideband, dual-band and multi-band matching balun network designs for radios with high-Q differential TX and/or RX ports, applicable for and tested with EFR32 Series 1 family. Although the presented matching examples operate with the EFR32 wireless Gecko MCU chip family of Silicon Laboratories, the matching method is general and can be used for any other radio with high-Q TX and/or RX ports (e.g., additional example of multi-band RX matching balun solution is also shown for EZRadioPRO Si4x6x family in the appendix with the same matching topology but with different tuned component values). The design can be adopted to various operating frequency bands, power levels, and TX and/or RX impedances. Also, the technology of realization does not change the validity of the invention.

Patent applications in the name of Silicon Laboratories have been filed in regards to the solutions listed herein. This application note provides technical details of the following patent-pending matching solutions:

- Wideband match: US20190165754A1
- Dual-band match: US20190190149A1
- Multi-band match: US20190190482A1
- Dual-wideband match: US20200127605A1

The existing EFR32 sub-GHz, Si4x6x EZRadioPRO, Si4x5x, and Si401x EZRadio matches are single-band solutions, so separate designs are required for each UHF band.

However, worldwide IoT solutions are more cost effective if they are inherently able to operate in multiple frequency bands to reduce logistics and manufacturing cost.

Matching network design is a major challenge of designing wideband or multi-band modules. A multi-band matching network has multiple resonances with the proper impedance load. This paper introduces a novel 3-element resonator structure that behaves as a frequency-dependent inductance or capacitance, and thus can be the basic building blocks of multi-band circuits.

Additionally, this document provides matching solutions for single-band and wideband applications as well with utilizing discrete components only.

KEY POINTS

- Full discrete sub-GHz matching designs for EFR32 Series 1
- Technical details of wideband, dual- and multi-band matching balun network designs
- 3-element resonator structure - the basic building blocks of multi-band circuits
- Recommended component values and measured performance results provided for each solution

1. Introduction

The EFR32 Series 1 sub-GHz matching guide of AN923 describes the technical details of the matching network solution applied on the Silicon Labs' reference radio board designs, while this document focuses on other custom solutions where the matching network consists of pure discrete SMD components only, i.e. without an external ceramic balun. Moreover, unique matching network designs for operation in wide- or multiple frequency bands in the sub-GHz region are also presented. Due to the sub-GHz differential TX/RX ports of EFR32 Series 1, each matching network solution discussed in this application note does have a balun function as well.

1.1 Overview of the Presented Discrete Matching Options

Match Name	SMD BOM Count of Matching balun	Available in TX/RX Direct-Tie Topology	BW [MHz]	Phase Error [degree]	Performance Sacrifice [dB]	RF Bands to Cover
Single-band	4 for RX only 9 for TRX direct-tie	Yes	60	< 10	optimal	1 frequency band with relatively narrow BW, e.g. 426-434 MHz or 902-928 MHz
Wideband	7 for RX only 11 for TRX direct-tie	Yes	150	< 18	< 0.5	1 frequency band with large BW, e.g. 780-928 MHz
Dual-band	6 for RX 6 for TX	No, but applicable for both TX and RX	40 and 60	< 17	< 1	2 frequency bands with relatively narrow BWs, e.g. 426-434 and 868-928 MHz
Multi-band	5 for RX only	No, applicable for RX only	200 and 100	> 90	< 1…3	Multiple frequency bands, e.g. 315-434 and 868-928 MHz
Dual-wideband	9 for RX 10 for TX	No, but applicable for both TX and RX	200 and 150	< 25	< 1…2.5	2 frequency bands with large BWs, e.g. 310-510 and 780-928 MHz

The single-band match is basically the full discrete representation of the radio board matches documented in AN923. It has basically the same optimal RF performance as the ceramic balun matches shown in AN923 and is suitable for applications requiring operation in one frequency band without the need of large BW coverage. The wideband match is recommended for applications with large BW requirements around one frequency band. Both single- and wideband matches are available in TX/RX direct-tie matching configurations.

The dual-band match aims applications where two frequency bands falling relatively far from each other need to be covered by one match and BOM, but the BW requirements are relatively small in each band. The dual-wideband match can cover two far frequency bands with large bandwidths. Both dual-band and dual-wideband matches are available for TX and RX operation, but not in direct-tie topology.

The multiband match can cover multiple frequency bands, similarly as the dual-wideband match, but it has slightly bigger performance compromise compared to the optimum (due to the big phase error of balun function), but it is more BOM optimized.

2. Standard Single-Band 4-element Discrete Matching Balun Network Description

The standard 4-element matching balun networks are mainly utilized with the Si4x3x/Si4x6x RX path and Si401x TX single-band matches and more technical details on these networks can be found in AN427, AN643, and AN369 application notes. However, both TX and RX path matching circuits of the Wireless Gecko chip sets (i.e., EFR32 Series 1 families) can use this same matching approach with the 4-element discrete balun network. Also, this 4-element standard matching balun approach is the base or part of all the other presented full discrete matching network solutions in this document.

The figure below shows the standard 4-element matching balun network typically utilized for matching purposes of Silicon Labs radio chips with differential in- or outputs (example for RX path match). Low-Noise Amplifier Resistance (RLNA) and Low-Noise Amplifier Capacitance (CLNA) represent and model the Low-Noise Amplifier (LNA) circuitry and are on-chip. The network below does the impedance matching between PORT 1, typically 50 ohms, and RLNA, while CLNA is resonated out at the desired operating frequency. On the other hand, the differential-to-single-ended conversion is also ensured; i.e., there is a phase difference of 180° between the differential RX ports.

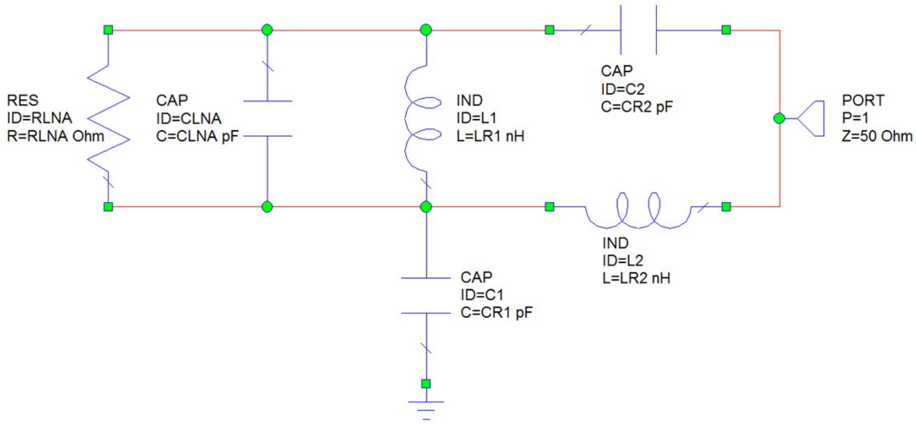

Figure 2.1. 4-Element Matching Balun

The following several figures are shown below to show the principle operation of the 4-element matching balun. The figure below shows the LR1 split into two parts where the component shown as LLNA is responsible to resonate the CLNA internal capacitance out at the operating frequency.

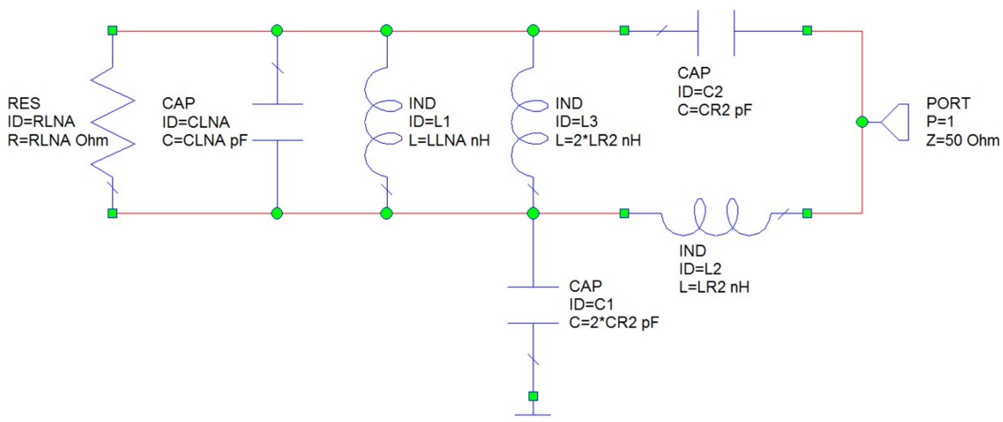

Figure 2.2. 4-Element Matching Balun, Exp. Part 1

The figure below shows the next step of balun representation, which introduces the virtual ground connection as well symmetrically to the differential ports. Note that the figure also explains the 2*LR2 and 2*CR2 component values shown in the figure above.

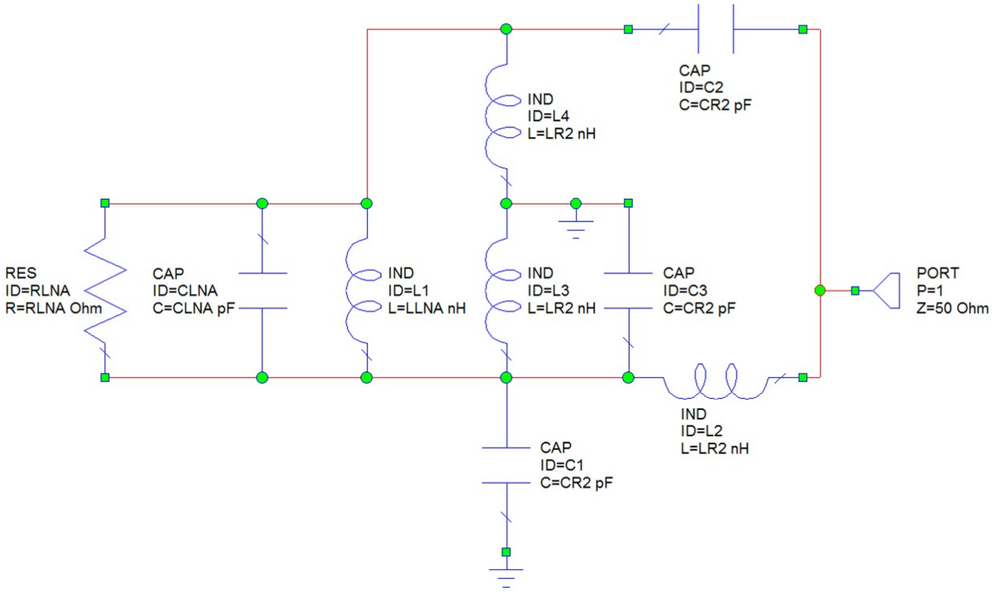

Figure 2.3. 4-Element Matching Balun, Exp. Part 2

The next figure shows the simplified balun representation when the following resonance conditions are met at the operating frequency: LLNA and CLNA, and LR2 and CR2 components have parallel resonance. This standard matching balun network shown in the figure below is widely being used in the market; thus, the impedance match between real parts of impedances with the proper opposite phase shift and balanced voltage gain between the differential ports (i.e., proper balun function).

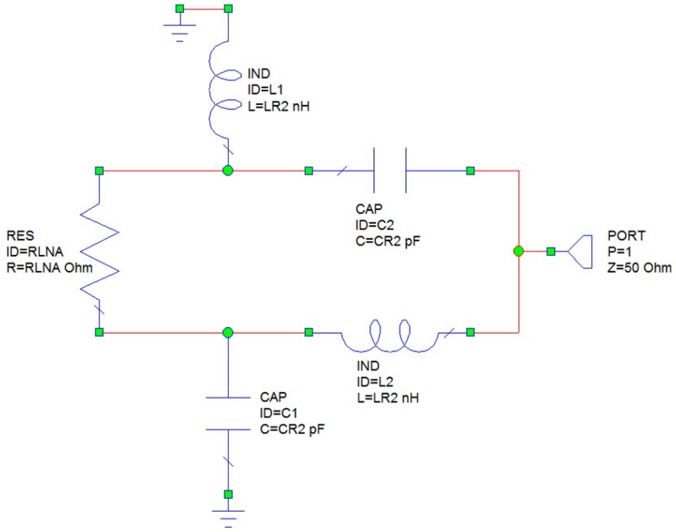

Figure 2.4. Standard Discrete Balun Widely Used in the Market

The following equations describe how to determine the required component values of the standard 4-element matching balun network shown in Figure 2.1 4-Element Matching Balun on page 3.

$$2\pi f \cdot LR2 = \frac{1}{2\pi f \cdot CR2} = \sqrt{RLNA \cdot 50R}$$

$$LLNA = \frac{1}{(2\pi f)^2 \cdot CLNA}$$

$$CR1 = 2 \cdot CR2$$

$$LR1 = \frac{2 \cdot LR2 \cdot LLNA}{2 \cdot LR2 + LLNA}$$

Table 2.1 Simulated Component Values of the Single-Band 4-Element Matching Balun Network Recommended for EFR32 RX Path Match on page 6 shows the simulated component values of the single-band 4-element matching balun network (Figure 2.1 4-Element Matching Balun on page 3) recommended for EFR32 RX path match. RLNA can be approximated as 600-700 ohms at the lower frequency bands, and 500-600 ohms at the higher frequency bands. This matches the possible highest voltage gain, i.e., possible highest impedance as mentioned in AN923. CLNA is approximately 1.1 pF. The schematic of the simulated structure shown above does not include some parasitic effects, like bonding wire inductance (which is about 1.5 - 2 nH), stray capacitance, and PCB and SMD component parasitics.

TX matching networks can utilize the same 4-element matching balun structure from Figure 2.1 4-Element Matching Balun on page 3 but with different component values, tuned to the optimum PA load impedance while resonating out the PA capacitance. So, instead of the RLNA // CLNA parallel equivalent circuit, in the TX networks the RPA // CPA is represented by the optimum PA load impedance and PA capacitance, respectively, and are considered on-chip. EFR32 Series 1 chips include a PA capacitance bank output tunable between about 2 and 7 pF, while the optimum PA load impedance is TX power and PA voltage dependent. More details on these can be found in AN923. The discrete matches presented in this document focus on the following two conditions: TX power of +20 dBm from 3.3 V main battery, or +13/14 dBm from the on-chip DCDC converter output, i.e. 1.8 V. The optimum PA load impedance in both of these cases is about 125 ohms, while the PA capacitance is set to its possible minimum (“sgpactune” to 0). Furthermore, TX networks can include an additional component, which can further improve the common-mode suppression and this component is a parallel capacitor mounted between the virtual ground of balun network (mid-point of parallel inductor between the RF ports) and GND. The capacitor value is tuned to enhance the 2nd harmonic suppression through the series LC notch filters from both TX ports to the GND. See figure below for reference matching network topology and Table 2.2 Simulated Component Values of the Single-Band 4-Element Matching Balun Network with Common-mode Suppressor Recommended for EFR32 TX Path Match on page 6 for simulated component values of the single-band 4-element matching balun network (with the so-called common-mode suppressor) recommended for EFR32 TX path match for +20 dBm at 3.3 V or +13/14 dBm at 1.8 V.

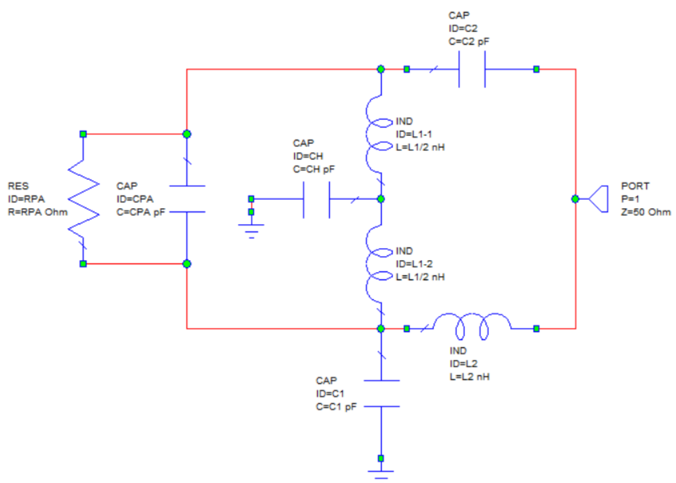

Figure 2.5. 4-Element Matching Balun with Common-mode Suppressor

Table 2.1. Simulated Component Values of the Single-Band 4-Element Matching Balun Network Recommended for EFR32 RX Path Match

Freq. Band	LR1	LR2	CR1	CR2
169 MHz	220 nH	175 nH	12 pF	5.1 pF
315 MHz	100 nH	82 nH	6.2 pF	2.7 pF
390 MHz	75 nH	68 nH	4.7 pF	2.2 pF
426 – 434 MHz	62 nH	62 nH	4.3 pF	2.2 pF
868 MHz	20 nH	27 nH	2.2 pF	1.2 pF
902 – 928 MHz	18 nH	24 nH	2.2 pF	1.1 pF

Table 2.2. Simulated Component Values of the Single-Band 4-Element Matching Balun Network with Common-mode Suppressor Recommended for EFR32 TX Path Match

Freq. Band	TXP	PAVDD	L1-1	L1-2	L2	C1	C2	CH
169 MHz	20 dBm	3.3 V	51 nH	51 nH	75 nH	24 pF	12 pF	4.3 pF
315 MHz	20 dBm	3.3 V	20 nH	20 nH	39 nH	18 pF	6.8 pF	3.2 pF
390 MHz	20 dBm	3.3 V	14 nH	14 nH	30 nH	15 pF	5.6 pF	3.0 pF
426 – 434 MHz	20 dBm	3.3 V	12 nH	12 nH	27 nH	10 pF	4.7 pF	2.5 pF
868 MHz	10 dBm	1.8 V	3.6 nH	3.6 nH	13 nH	5.6 pF	2.7 pF	2.2 pF
868 MHz	20 dBm	3.3 V	3.9 nH	3.9 nH	11 nH	5.6 pF	3.0 pF	2.1 pF
902 – 928 MHz	20 dBm	3.3 V	3.6 nH	3.6 nH	10 nH	5.1 pF	3.0 pF	2.0 pF
902 – 928 MHz	14 dBm	3.3 V	3.3 nH	3.3 nH	20 nH	3.9 pF	1.8 pF	2.2 pF
Note: TXP= 20 dBm at 3.3 V matches can be used and optimal for TXP= 13/14 dBm at 1.8 V as well.								

The L1 component in the standard 4-element matching balun structure needs to be divided into two equal parts to be able to insert into the CH common-mode suppressor capacitor in the virtual ground in differential mode, which is tuned to the 2nd harmonic to enhance the harmonic suppression at that harmonic frequency. In order to keep the symmetry, which is important to have the proper balun function of circuitry, L1-1 should be kept equal with L1-2 in as shown in the figure and table above. If the common-mode suppressor capacitor, CH, is not used then the first parallel component between the differential ports should only be one inductor with a value of L1= ‘L1-1’ + ’L1-2’.

3. Discrete Single-Band Matching Network

Silicon Labs provides discrete matching network designs for single-band applications based on the standard single-band 4-element discrete matching balun designs. The matching network utilizes SMD components only and is tuned for one frequency band with relatively narrow bandwidth, i.e. there are separated recommended BOM, component values, for each major ISM frequency bands, e.g., 434, 490, 868 or 915 MHz.

3.1 Direct-Tie Schematic and Recommended Component Values

This matching solution discussed in this section is basically the full discrete representation of the official radio board matches with the external ceramic balun publicly available also in AN923. The TX part of the matching network utilizes the standard 4-element matching balun approach with the so-called common-mode suppressor, as discussed in the previous chapter, while the RX path has a 3-element differential-to-differential match, similarly to the official radio board matches and as documented in AN923, connected to the differential ports of the TX matching balun network without the need of external RF switch (i.e. in direct-tie topology).

The single-ended 50-ohm antenna port (via a 50-to-50 ohms LPF) is transformed to the differential optimum PA load impedance (typically, 125 ohms) by the 4-element matching balun (with the common-mode suppressor), while the 3-element differential-to-differential RX match further converts this PA load impedance up to around 500 ohms (or slightly higher) for maximizing the voltage gain for the LNA inputs in receiver mode.

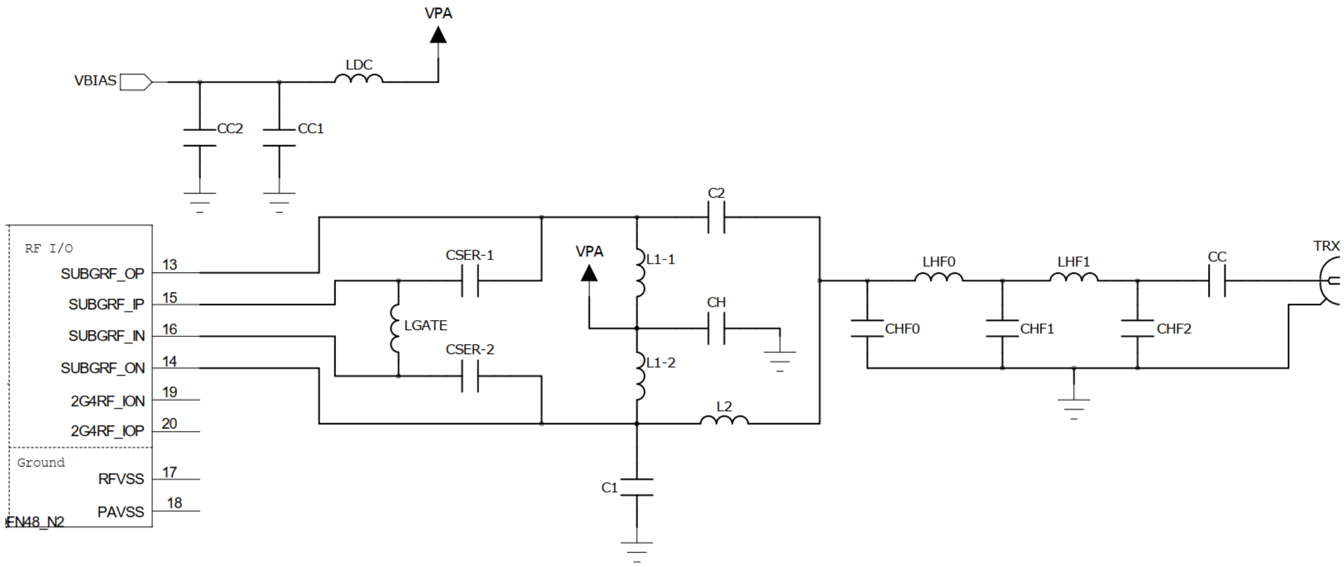

Figure 3.1. Discrete Single-Band Direct-Tie Matching Network

Table 3.1. Recommended Tuned Component Values

Direct-tie TX/RX matching balun										
Freq. Band	CSER-1	CSER-2	LGATE	L1-1	L1-2	CH	C1	C2	L2	LDC	CC
434 MHz	1.8 pF	1.8 pF	75 nH	12 nH	12 nH	2.5 pF	7.5 pF	4.7 pF	27 nH	330 nH	270 pF
490 MHz	1.7 pF	1.7 pF	62 nH	12 nH	12 nH	2.0 pF	10 pF	5.6 pF	18 nH	330 nH	270 pF
610 MHz	1.6 pF	1.6 pF	39 nH	6.2 nH	6.2 nH	3.0 pF	7.0 pF	3.6 pF	15 nH	270 nH	270 pF
868 MHz	1.5 pF	1.5 pF	20 nH	3.6 nH	3.6 nH	2.2 pF	5.6 pF	3.6 pF	9.1 nH	180 nH	270 pF
915 MHz	1.4 pF	1.4 pF	18 nH	3.3 nH	3.3 nH	2.0 pF	5.1 pF	3.0 pF	6.8 nH	180 nH	270 pF
868/915 MHz	1.4 pF	1.4 pF	18 nH	3.6 nH	3.6 nH	2.0 pF	5.1 pF	3.0 pF	6.8 nH	180 nH	270 pF
Low-pass filter											
Freq. Band	Order	CHF0	LHF0	CHF1	LHF1	CHF2	CC				
434 MHz	N = 5	6.2 pF	24 nH	10 pF	24 nH	5.6 pF	120 pF				
490 MHz	N = 5	6.2 pF	22 nH	10 pF	22 nH	6.2 pF	120 pF				
610 MHz	N = 5	4.3 pF	15 nH	7.5 pF	15 nH	4.3 pF	270 pF				
868 MHz	N = 5	3.0 pF	11 nH	5.6 pF	11 nH	3.0 pF	33 pF				
915 MHz	N = 5	3.3 pF	10 nH	5.6 pF	10 nH	3.3 pF	33 pF				
868/915 MHz	N = 5	3.3 pF	10 nH	5.6 pF	10 nH	3.3 pF	33 pF				

Note:

1. Matching component values are optimized for both TXP=20 dBm at 3.3 V and TXP=14 dBm at 1.8 V (DCDC).
2. Inductors from Murata LQP03HQ or LQW15C series, capacitors from Murata GRM0335C series.

3.2 Measured Performance Data of Direct-Tie Single-Band and Discrete Match

Table 3.2. Measured Performance Data at 3.3 V for 20 dBm

Freq. Band	PAVDD	LPF	Sensitivity	TXP	H2	H3	H4	TX Current	RX Current
434 MHz	3.3 V	N=5	-106.8 dBm	20.2 dBm	-36.7 dBm	-50.8 dBm	-52.8 dBm	95.6 mA	10.5 mA
490 MHz			-106.9 dBm	19.9 dBm	-39.0 dBm	-50.3 dBm	-48.2 dBm	97.8 mA	10.8 mA
610 MHz			-106.3 dBm	19.8 dBm	-36.2 dBm	-52.3 dBm	-47.4 dBm	95.6 mA	10.8 mA
868 MHz			-109.4 dBm	19.7 dBm	-36.7 dBm	-42.0 dBm	-68.0 dBm	86.7 mA	10.6 mA
915 MHz			-105.5 dBm	20.0 dBm	-37.6 dBm	-44.7 dBm	-65.0 dBm	92.2 mA	10.7 mA
868 MHz[1]			-108.6 dBm	19.7 dBm	-36.5 dBm	-40.4 dBm	-63.8 dBm	87.8 mA	10.6 mA
915 MHz[1]			-105.3 dBm	20.0 dBm	-36.0 dBm	-50.8 dBm	-63.8 dBm	93.2 mA	10.7 mA

Note:

1. 868/915 MHz single-BOM solution measured at 868 and 915 MHz frequencies.
2. RX sensitivity test conditions at 434, 490, 610, and 915 MHz: 2-GFSK, 100 kbps data rate, 50 kHz deviation, BER<0.1%.
3. RX sensitivity test conditions at 868 MHz: 2-GFSK, 38.4kbps data rate, 20 kHz deviation, BER<0.1%.

Table 3.3. Measured Performance Data at 1.8 V for Lower Power Levels

Freq. Band	PAVDD	Rail TXP	Sensitivity	TXP	H2	H3	H4	TX current	RX current
434 MHz	1.8 V	125	-106.8 dBm	14.0 dBm	-56.0 dBm	-65.4 dBm	-58.7 dBm	36.5 mA	11.0 mA
610 MHz		157	-106.3 dBm	14.4 dBm	-66.0 dBm	-60.5 dBm	-54.8 dBm	37.1 mA	11.0 mA
868 MHz		155	-109.4 dBm	14.6 dBm	-44.9 dBm	-49.9 dBm	-70.6 dBm	38.0 mA	10.7 mA
915 MHz		135	-105.5 dBm	14.2 dBm	-45.9 dBm	-52.4 dBm	-67.3 dBm	38.1 mA	10.8 mA
434 MHz		100	-106.8 dBm	10.4 dBm	-51.0 dBm	-68.8 dBm	-61.2 dBm	21.5 mA	11.0 mA
490 MHz		100	-106.9 dBm	10.3 dBm	-53.8 dBm	-60.8 dBm	-62.0 dBm	27.8 mA	11.0 mA

Note:

1. RX sensitivity test conditions at 434, 490, 610, and 915 MHz: 2-GFSK, 100 kbps data rate, 50kHz deviation, BER<0.1%.
2. RX sensitivity test conditions at 868 MHz: 2-GFSK, 38.4kbps data rate, 20 kHz deviation, BER<0.1%.

3.3 Considerations of Split Matching Configuration

In RX mode operation the entire circuit schematic can be considered as part of the impedance matching, while in TX mode due the on-chip LNA switches, which ground the RX pins together and to the GND, the effective TX matching circuit is the schematic as being shown in Figure 3.1 Discrete Single-Band Direct-Tie Matching Network on page 7 but excluding LGATE, CSER-1 and CSER-2. However, an extra but small amount of capacitive load appears on the TX match parallel with the differential TX ports, which value is CSER-1 X CSER-2. However, the TX match has enough wide bandwidth to resist against this extra load capacitance without the need of required component value changes, while it can also be compensated out by tuning the internal PA capacitance bank, “sgpactune” register.

So, for TX-only applications the matching network is recommended as shown in Figure 3.1 Discrete Single-Band Direct-Tie Matching Network on page 7 but without LGATE, CSER-1 and CSER-2.

For RX-only application, Silicon Labs recommends utilizing the standard 4-element discrete matching balun network as shown in Figure 2.1 4-Element Matching Balun on page 3 with simulated component values in Table 2.1 Simulated Component Values of the Single-Band 4-Element Matching Balun Network Recommended for EFR32 RX Path Match on page 6.

4. Discrete Wideband Matching Network

Silicon Labs provides discrete matching network designs for wideband applications based on the standard single-band 4-element discrete matching balun designs and wideband matching techniques (e.g., Youla matching approach). The matching network utilizes SMD components only and is tuned for one frequency band with large bandwidth (i.e., tuned for multiple frequency bands that are relatively falling close to each other). There are two single-BOM matching networks recommended and presented in this application note that can cover the following ISM frequency bands (e.g., from 315 MHz up to 510 MHz, from 780 MHz up to 928 MHz).

The wideband matching network is based on the discrete single-band matching design but with a modified RX path match. The high-Q RX path match utilizes the Youla wideband matching technique.

4.1 Design Details of Discrete Wideband Matching Network

4.1.1 Principle of Operation

General block diagram of the recommended wideband matching network is shown in Figure 4.1 below. This matching architecture is similar to the single-band matching network but designed for wideband operation.

In RX mode the single-ended signal from the 50 ohms antenna is filtered and led to the so-called “TX Balun & match” block. This block transforms the 50 ohms single-ended impedance to 125 ohms differential and connected to the differential TXP and TXN outputs of the on-chip PA. Here, the match should be resonating with the IC’s internal parasitics, i.e. with the series parasitic inductances and with the internal tunable PA capacitance. The default value of this PA internal cap is ~2.5 pF and it can be tuned up to ~7 pF, if required, but the proposed wideband match does not require any tuning, it covers the targeted wideband operation with the default ~2.5 pF of PA capacitance value.

The “RX match” block is also connected to the 125 ohms differential side of the TX balun (i.e., to the TXN and TXP TX pins in a so-called direct-tie connection) and converts up the impedance to ~500 ohms at the RXP and RXN RX pins. Here, it is also resonating with the series parasitic inductances (bonding wires) and with the LNA internal parasitic capacitance which is ~1.1 pF.

In the match the TX and RX path are tied directly together without the usage of any TX/RX RF switch to save BOM cost.

The wideband solution realizes the 500 ohms RX impedance in a wider band to cover as much bandwidth as possible with a single-BOM solution, minimizing the tuning and spreading sensitivity of the original matching concept of AN923 matches, while still providing the required impedance transformation and thus RX and TX performances.

The “TX Balun & match” block is also realized by using discrete SMD elements only (i.e., with the so-called 4-element discrete matching balun with the common-mode suppressor) similarly as applied in the single-band discrete designs and discussed in the previous section of this document.

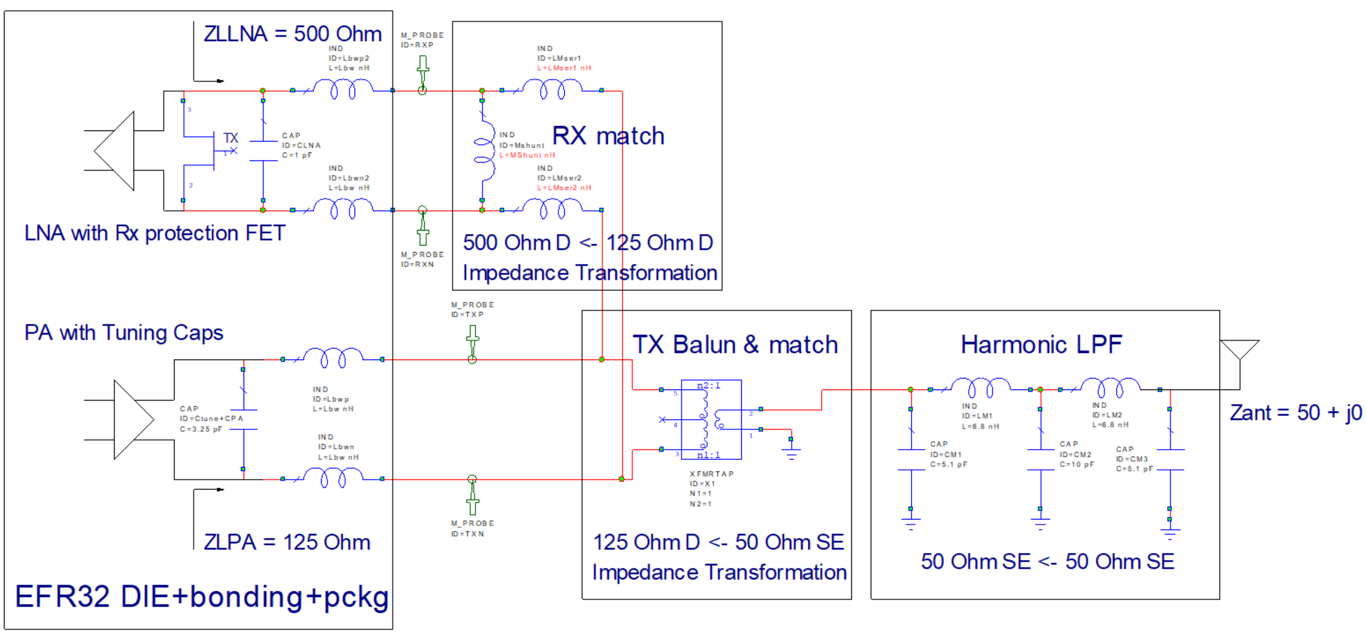

Figure 4.1. Discrete Wideband Direct-Tie Matching Approach

4.1.2 Wideband Matching Design

The main challenge in the RX path is to replace the high voltage gain and high-Q response of the narrowband solution by a wideband match which achieves similar voltage gain and impedance transformation but in a much bigger frequency bandwidth. As mentioned above, the target here is to match a 125 ohms differential impedance to 500 ohms differential with ~1-1.1 pF parallel LNA capacitance in a wide bandwidth. As a starting point, it is advantageous to simplify the problem by designing only the half of the differential RX match between a single-ended 62.5 ohms generator and single-ended 250 ohms load with ~2 pF parallel capacitance. Finally, the differential match can easily be created by unifying the two single-ended halved circuits.

The starting point of the match design is based on the Youla's direct wideband matching network synthesis theory.

The background mathematics of the method is extremely difficult, but in some publications [1] ready solutions are derived for some simple terminations (e.g., for parallel RC loads) which is exactly our interest here. The Figure below shows the 2nd-order single-ended Youla matching circuit, if the generator and termination impedances have the same real part. These solutions give maximal flat low-pass S11 responses up to the -3 dB cut-off frequency.

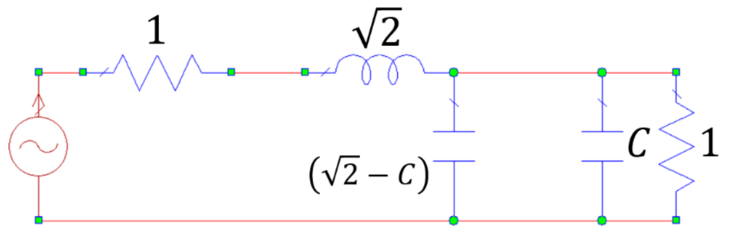

Figure 4.2. 2nd-Order Single-Ended Youla Wideband Match Prototype

The following equations help determine the component values [1]:

$$R = R_e;\ \omega_h = \omega_e;\ L_e = \frac{R_e}{\omega_e};\ C_e = \frac{1}{R_e \cdot \omega_e}$$

The first step of the Youla network synthesis is to determine the relative frequency (ωe) unit, which is equal to the targeted cut-off frequency and to determine the relative resistance (Re) unit as shown in the equations above. The relative capacitance and inductance units (denoted by Ce and Le) are derived from these. All element values in the figure above are calculated in these relative units.

If the load capacitance (C) value (again in Ce relative units) exceeds $\sqrt{2}$, then the parallel capacitance of the match (the one with the value of $\sqrt{2} - C$) is negative. In this case the parallel capacitance needs to be replaced by a parallel inductance. This is a bandwidth restricting step as the inductor frequency characteristic is different from a capacitor, but as shown later, it is a good compromise, which makes the concept realizable with low cost (and still in relatively wide bandwidth).

A design example with calculations of a 2nd-order Youla match of a differential RX match working between differential 125 ohms load and 500 ohms termination with 1 pF capacitance for 899 MHz -3 dB cut-off frequency is presented in this section below.

Example calculations for Z_T=R_{LNA}=500 ohms // C_{LNA}=1 pF → Z_L=125 ohms differential:

1. Half of the differential match is calculated first between equal Real(Z_T)/2= 250 ohms single-ended terminations and with 2*C_{LNA}= 2 pF capacitance at the termination side. The L-C match appears to be 62.6 nH inductor in series and -1.0 pF capacitor in parallel which will be a parallel inductor in hardware realization.

$$L_e = \frac{R_e}{\omega_e} = \frac{250}{2 \cdot \pi \cdot 899MHz} = 44.3nH$$

$$L_{serSE} = L_e \cdot \sqrt{2} = 62.6nH$$

$$C_e = \frac{1}{R_e \cdot \omega_e} = \frac{1}{250 \cdot 2 \cdot \pi \cdot 899MHz} = 0.71pF$$

$$C_{parSE} = \left(\sqrt{2} - \frac{2pF}{C_e}\right) \cdot C_e = -1.0pF$$

2. As a next step the matching circuit can be tuned to work between non-equal (still single-ended) termination impedances, i.e. between $Z_L/2$= 62.5 ohms and $Z_T/2$= 250 ohms. The below calculations show an estimation on the component values, which can further be optimized by circuit simulators. As a first step, an additional inductor L_x is introduced which can be added to the prototype circuit in parallel with the series inductor of L_{serSE}. The calculations provide a good approximation (in the given range of Q of matching network) on the component values in the matching network if the termination and load impedances are not equal.

$$L_x = \frac{\sqrt{\frac{Z_T}{2} \cdot \frac{Z_L}{2}}}{2 \cdot \pi \cdot 899MHz} = 22.1nH$$

$$L_{ser} = \frac{L_{serSE} \cdot L_x}{L_{serSE} + L_x} = 16.3nH$$

3. Creating the differential match from the single-ended one is the next step. The series inductor value in the differential match will be the same (L_{ser}) but placed on both differential termination ports, while the parallel capacitance needs to be halved and will be placed between the differential ports of the load. Due to the negative value of C_{par}, it needs to be replaced by an inductor for realization which value can be calculated by the Thompson formula.

$$C_{par} = \frac{C_{parSE}}{2} = -0.5pF$$

$$L_{par} = \frac{-1}{(2 \cdot \pi \cdot 899MHz)^2 \cdot C_{par}} = 62.8nH$$

The component values calculated above can further be tuned and optimized by an optimization task of a circuit simulator. The optimum values for the sub-GHz high-band region ended up being L_{ser}=19.6 nH and C_{par}=-0.38 pF, L_{par}=87 nH.

The S11 characteristics are shown in the figure below. As the matching responses are working between different generator and load impedances the characteristics are no longer low-pass, they have pass-band characteristics. In the figure, the red curve shows the result of the match with the estimated component values, while the blue curve is with the optimized matching circuit with negative parallel capacitance (C_{par}). It gives a -10 dB S11 bandwidth of ~400 MHz. The brown curve shows the characteristic of the matching if a parallel inductor replaces the negative parallel capacitance for realization. As one can see the -10 dB S11 bandwidth is narrower, but still has ~240 MHz bandwidth, which is still enough for our wideband matching purposes.

It can also be confirmed that the S11 curve is not changed significantly if the ideal loss free lumped elements are replaced by a real 0201-sized SMD elements.

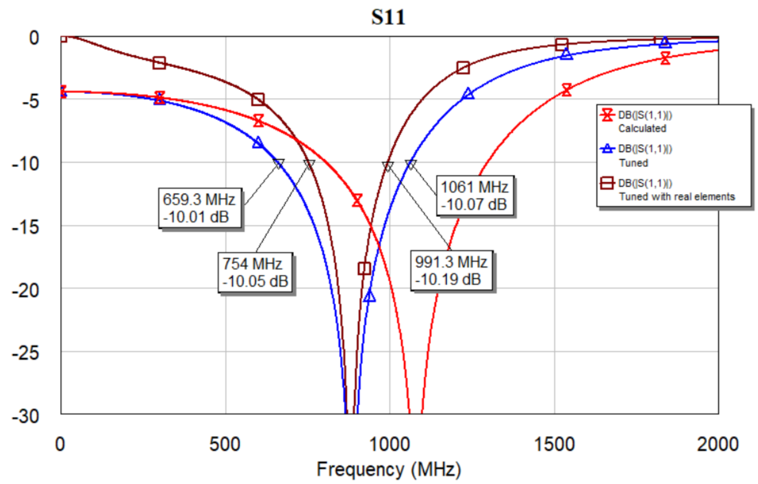

Figure 4.3. Wideband Discrete RX Match Simulated S11 Curves

The differential RX match between a differential 125 ohms generator and a parallel RC (500 ohms // 1 pF) termination is created from two single-ended circuits. The figure below shows the final RX match schematic bench-tuned on PCB, where the component values further deviate from the calculated, simulated component values a bit due to the PCB parasitics and discrete steps in the typical component values. C10 and C11 capacitors are dc-bypass capacitors, which are required in the EFR32 Series 1 RX paths, since the TX path will directly be connected to the RX path where the dc biasing is required for the PA.

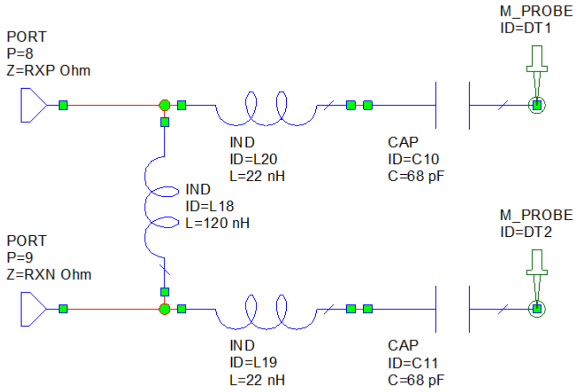

Figure 4.4. Wideband Discrete RX Match for sub-GHz High-Band Frequencies

The same procedure can be applied to create the matching circuit for other frequencies, that is to the lower UHF bands (e.g., to cover 315-510 MHz range). At lower frequencies the capacitance unit (C_e) is higher and thus, the parallel capacitance next to the parallel RC load can be even positive. The figure below shows the differential wideband RX match between the same terminations for 315-510 MHz frequency band. C10 and C11 capacitors are dc-bypass capacitors.

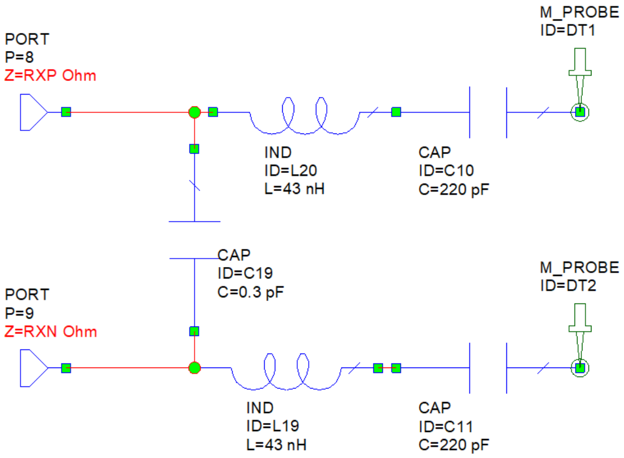

Figure 4.5. Wideband Discrete RX Match for sub-GHz Low-Band Frequencies

4.1.3 Connecting the Wideband RX Match to the TX Match

The TX path is the “TX balun & match” block and the LPF in Figure 4.1. The low-pass filter design is well known from the other literatures and thus it is not detailed here. The required number of filter sections depends on the harmonic emission of the applied radio IC and on the emission standard limits in the bands. For the EFR32 Series 1 radio chip family matches, 5^{th}-order Chebyshev filters are used.

The “TX balun & match” block matches the 50 ohms single-ended antenna port to the differential 125 ohms required by the TX outputs and by the RX match. As the impedance levels are lower, conventional balun design methods give the required ~200 MHz bandwidth. It can be either a full discrete solution or may comprise a coil/film type balun as well. In the figure below, a full discrete direct-tie matching circuit is shown optimized for 780 MHz…950 MHz operation. This match also utilizes the previously designed RX match (given in Figure 4.4 Wideband Discrete RX Match for sub-GHz High-Band Frequencies on page 13), while the discrete TX balun uses an additional 2^{nd} harmonic trap formed by the L15 and L16 inductors and by the C7 capacitor. Also, one can see the C10 and C11 RX bypass capacitors and the L26 DC choke inductor close to the TX, requirements of this particular radio IC. These elements can be omitted if the RX is DC-blocked and the PA is DC-fed internally. In TX mode, the RX protection FET switches on and shorts the RX match parallel inductor (L18). As shown in the second figure below, in this case the series L19 and L20 RX inductors are connected in parallel with the L15 and L16 TX balun inductors.

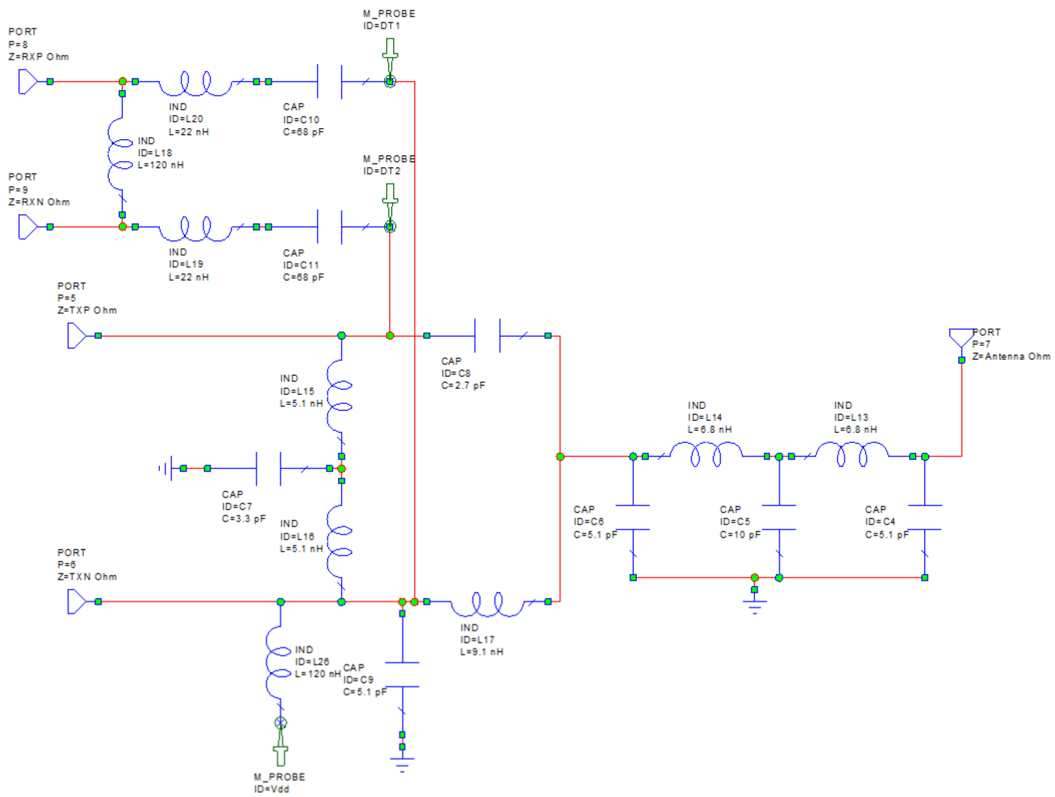

Figure 4.6. Wideband Discrete TX-RX Direct-Tie Match for sub-GHz High-Band Frequencies

For the simplicity in the figure below, the on state resistance of the RX protection FET is neglected and also the RX dc blocking capacitors are eliminated. As the RX inductors have much higher values than the TX balun inductors their effect is very small to the TX operation and can be eliminated easily with slight tuning of the TX inductors.

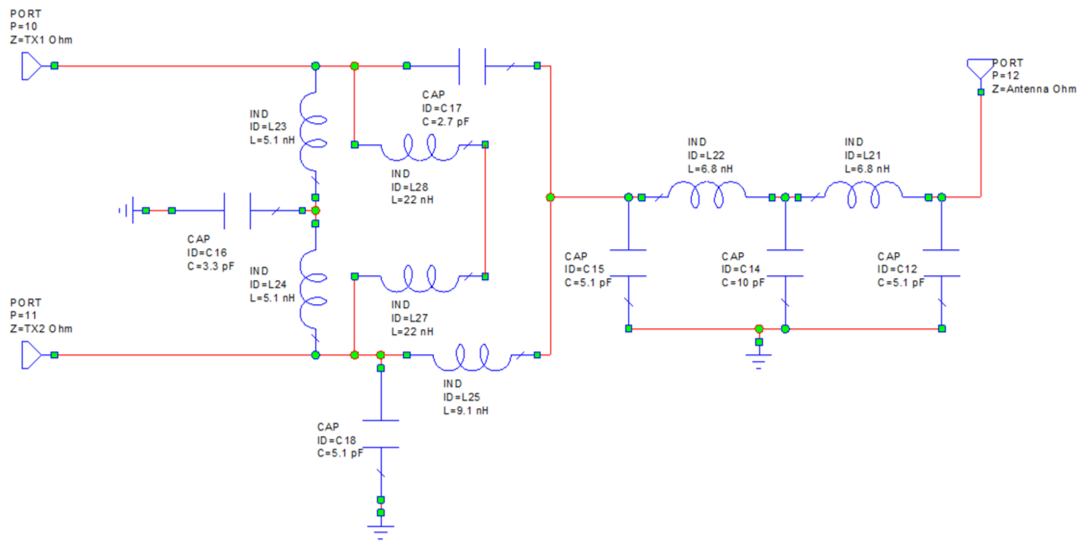

Figure 4.7. Wideband Discrete TX-RX Direct-Tie Match for sub-GHz High-Band Frequencies in TX Mode

Simulation results of the discrete wideband matching network in the so-called direct-tie TX-RX connection, including SMD and PCB parasitics, is shown in the figure below.

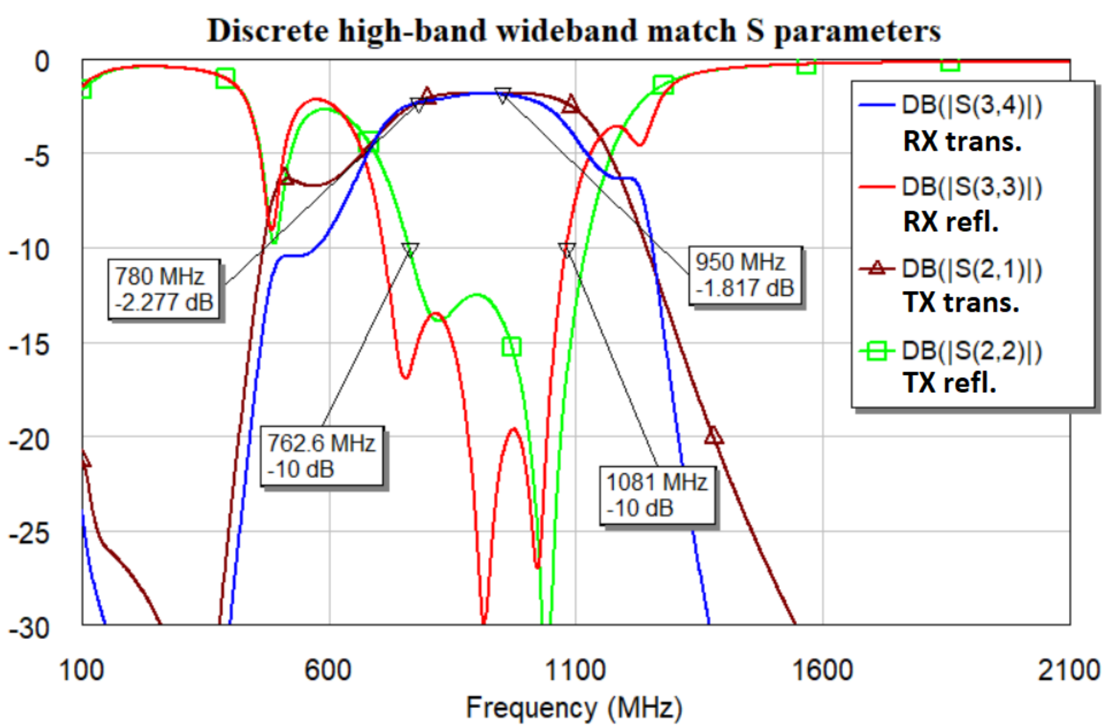

Figure 4.8. Simulated S Parameters of Wideband Discrete TX-RX Direct-Tie Match for sub-GHz High-Band Frequencies

4.2 Direct-Tie Schematic and Recommended Component Values

4.2.1 Discrete High-Band Wideband Matching Network

This section provides recommended schematics and measured results for the discrete wideband matching network applicable for frequencies from 780 MHz up to 930 MHz. The tuned component values use SMD 0201 size. Also, depending on the SMD inductor type there are slightly different component values recommended as shown in the following figures. The SMD capacitors are used from the GRM0335 series, but the exact part number and product series are not that crucial for capacitors, since their Q is much higher than the inductors, which will determine the overall loss of the matching network.

The recommended schematic is shown in Figure 4.9 below when SMD inductors are being utilized from the LQP03TN series.

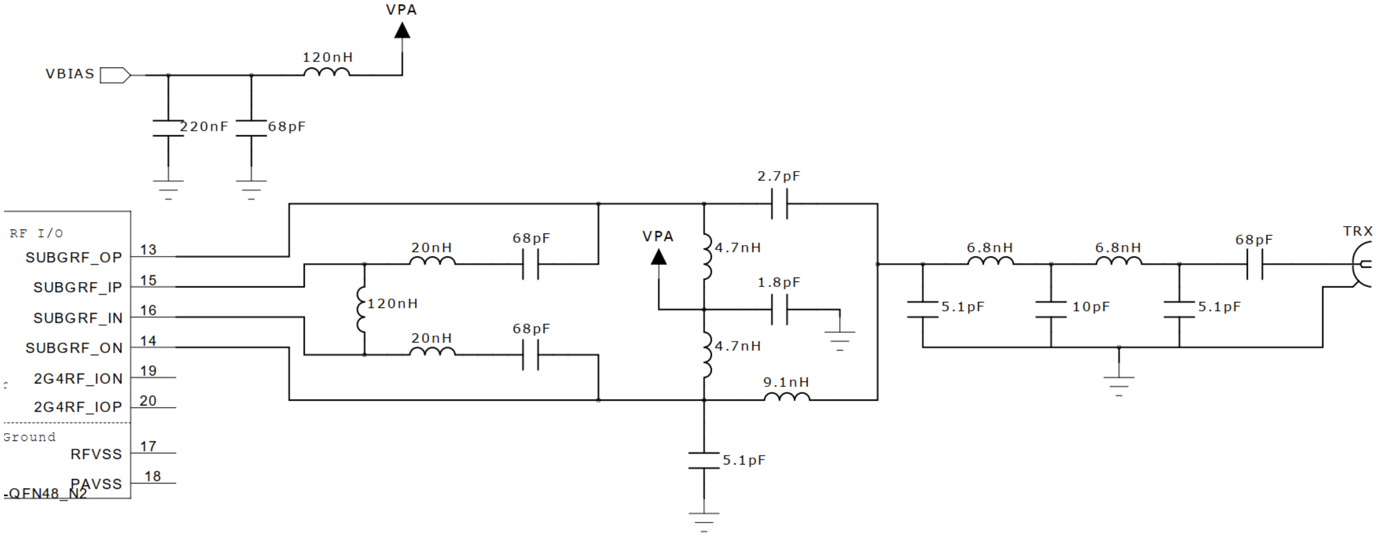

Figure 4.9. Discrete Wideband Direct-tie Matching Network for 780-930 MHz frequencies, LQP03TN inductors

The recommended schematic is shown in Figure 4.10 below when SMD inductors are being utilized from the LQP03HQ series.

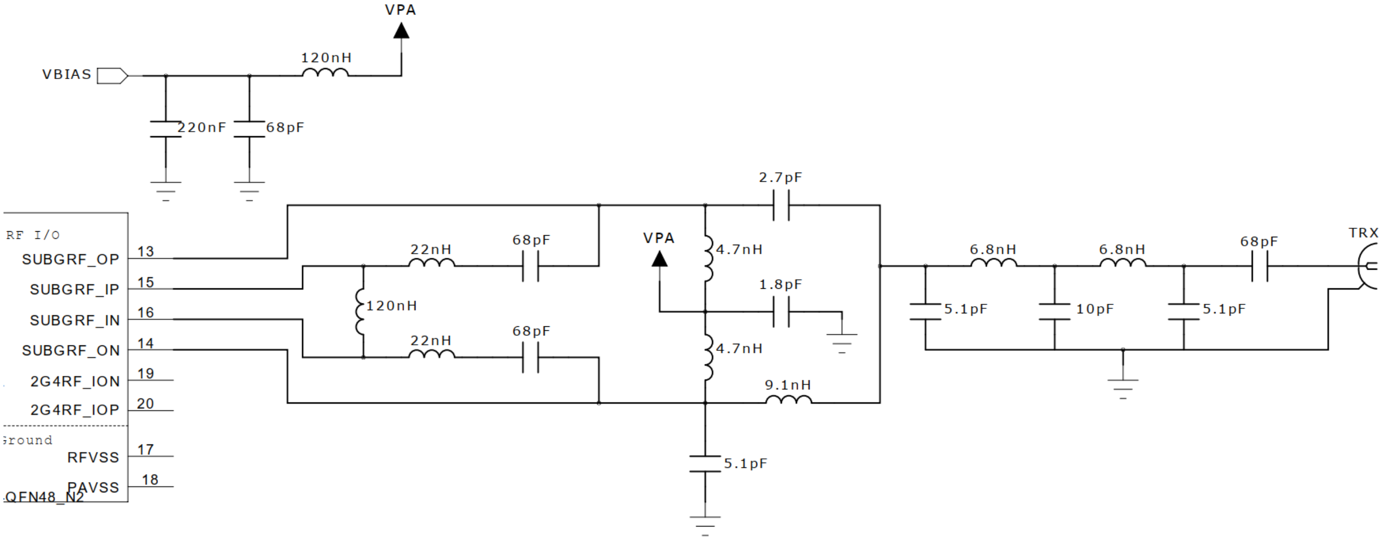

Figure 4.10. Discrete Wideband Direct-tie Matching Network for 780-930 MHz frequencies, LQP03HQ inductors

4.2.2 Discrete Low-Band Wideband Matching Network

This section provides recommended schematics and measured results for the discrete wideband matching network applicable for frequencies from 310 MHz up to 510 MHz. The tuned component values use SMD 0201 size.

The recommended schematic is shown in the figure below and the component values are tuned with both LQP03TN and LQP03HQ series.

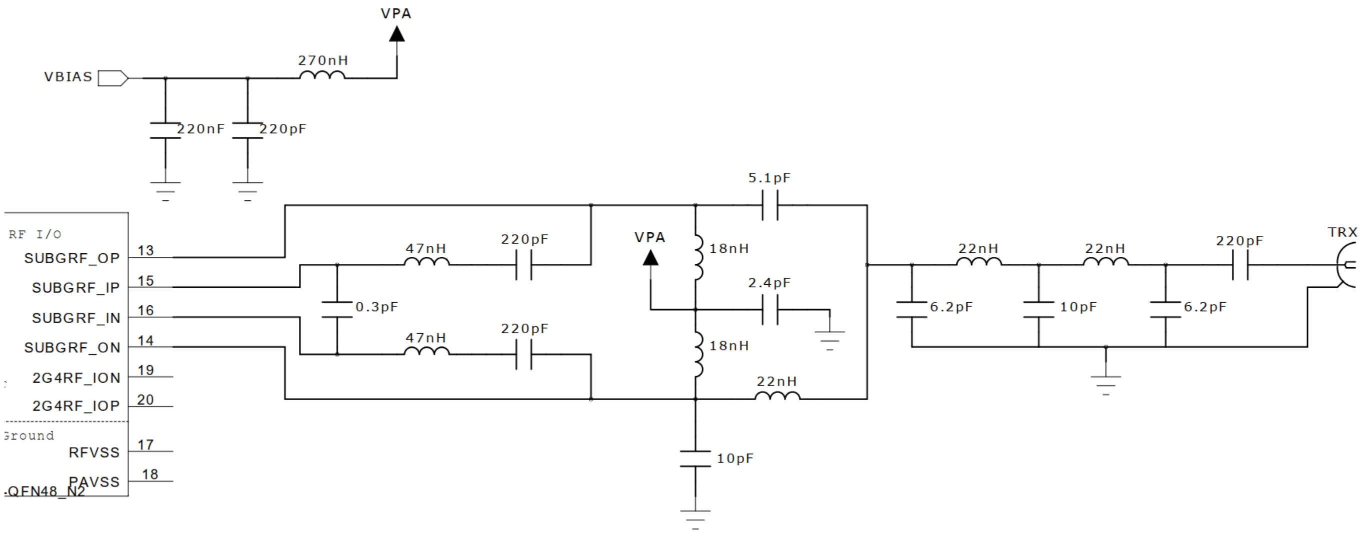

Figure 4.11. Discrete Wideband Direct-tie Matching Network for 310-510 MHz frequencies, LQP03TN or LQP03HQ Inductors

4.3 Measured Performance Data of Direct-Tie Wideband Discrete Match

Table 4.1. Measured Performance Data at 3.3 V for 20 dBm

Freq. Band	Match	Sensitivity	TXP	H2	H3	TX current
315 MHz	low-band wide-band with LQP03TN inductors	-104.0 dBm	18.3 dBm	-6.8 dBm	-30.1 dBm	94.2 mA
390 MHz		-106.3 dBm	18.2 dBm	-30.2 dBm	-41.0 dBm	93.5 mA
434 MHz		-107.0 dBm	18.2 dBm	-40.8 dBm	-41.3 dBm	101 mA
490 MHz		-106.8 dBm	18.7 dBm	-46.3 dBm	-45.5 dBm	95.5 mA
510 MHz		-106.3 dBm	18.4 dBm	-43.2 dBm	-45.8 dBm	94.6 mA
315 MHz	low-band wide-band with LQP03HQ inductors	-104.5 dBm	19.2 dBm	-2.3 dBm	-29.4 dBm	95.6 mA
390 MHz		-106.5 dBm	19.1 dBm	-33.0 dBm	-39.8 dBm	95.1 mA
434 MHz		-107.5 dBm	19.0 dBm	-40.6 dBm	-44.2 dBm	104 mA
490 MHz		-107.8 dBm	19.8 dBm	-41.2 dBm	-43.5 dBm	98.1 mA
510 MHz		-107.5 dBm	19.4 dBm	-45.5 dBm	-44.1 dBm	97.2 mA
780 MHz	high-band wide-band with LQP03TN inductors	-105.5 dBm	18.0 dBm	-31.4 dBm	-38.9 dBm	94.5 mA
830 MHz		-105.5 dBm	18.4 dBm	-36.8 dBm	-38.8 dBm	89.3 mA
850 MHz		-105.5 dBm	18.7 dBm	-42.0 dBm	-42.5 dBm	87.8 mA
868 MHz		-106.0 dBm	18.9 dBm	-46.1 dBm	-46.6 dBm	86.8 mA
915 MHz		-105.5 dBm	18.9 dBm	-51.6 dBm	-52.6 dBm	91.8 mA
928 MHz		-105.3 dBm	18.7 dBm	-50.3 dBm	-53.6 dBm	94.8 mA
950 MHz		-104.3 dBm	18.6 dBm	-46.1 dBm	-54.3 dBm	98.2 mA

Freq. Band	Match	Sensitivity	TXP	H2	H3	TX current
780 MHz	high-band wide-band with LQP03HQ induc-tors	-106.8 dBm	18.7 dBm	-32.6 dBm	-39.7 dBm	95.4 mA
830 MHz		-106.8 dBm	19.2 dBm	-41.8 dBm	-38.8 dBm	91.6 mA
850 MHz		-106.8 dBm	19.5 dBm	-45.1 dBm	-43.3 dBm	90.2 mA
868 MHz		-107.3 dBm	19.6 dBm	-49.6 dBm	-47.1 dBm	89.2 mA
915 MHz		-107.3 dBm	19.4 dBm	-46.7 dBm	-51.2 dBm	95.2 mA
928 MHz		-107.0 dBm	19.3 dBm	-43.3 dBm	-51.2 dBm	98.0 mA
950 MHz		-106.3 dBm	19.0 dBm	-40.1 dBm	-52.3 dBm	99.7 mA

Note: RX sensitivity test conditions: 2-GFSK, 100kbps data rate, 50kHz deviation, BER<1%.

5. The 3-Element Resonators

The 3-element resonators have frequency-dependent inductance or capacitance characteristics. These resonators also have a series and parallel resonance, as it is already applied in several prior art of inventions. However, for multi-band circuit design implementations, the focus is on the frequency-dependent inductance/capacitance behavior and value presented by these 3-element resonators at the lower and higher frequencies from these resonances. There are 2-2 network variants of 3-element resonators existing for both frequency-dependent inductors and capacitors as shown in the figures below.

Since these resonators have frequency-dependent parameters they can be the basic building blocks of dual- or multi-band circuits.

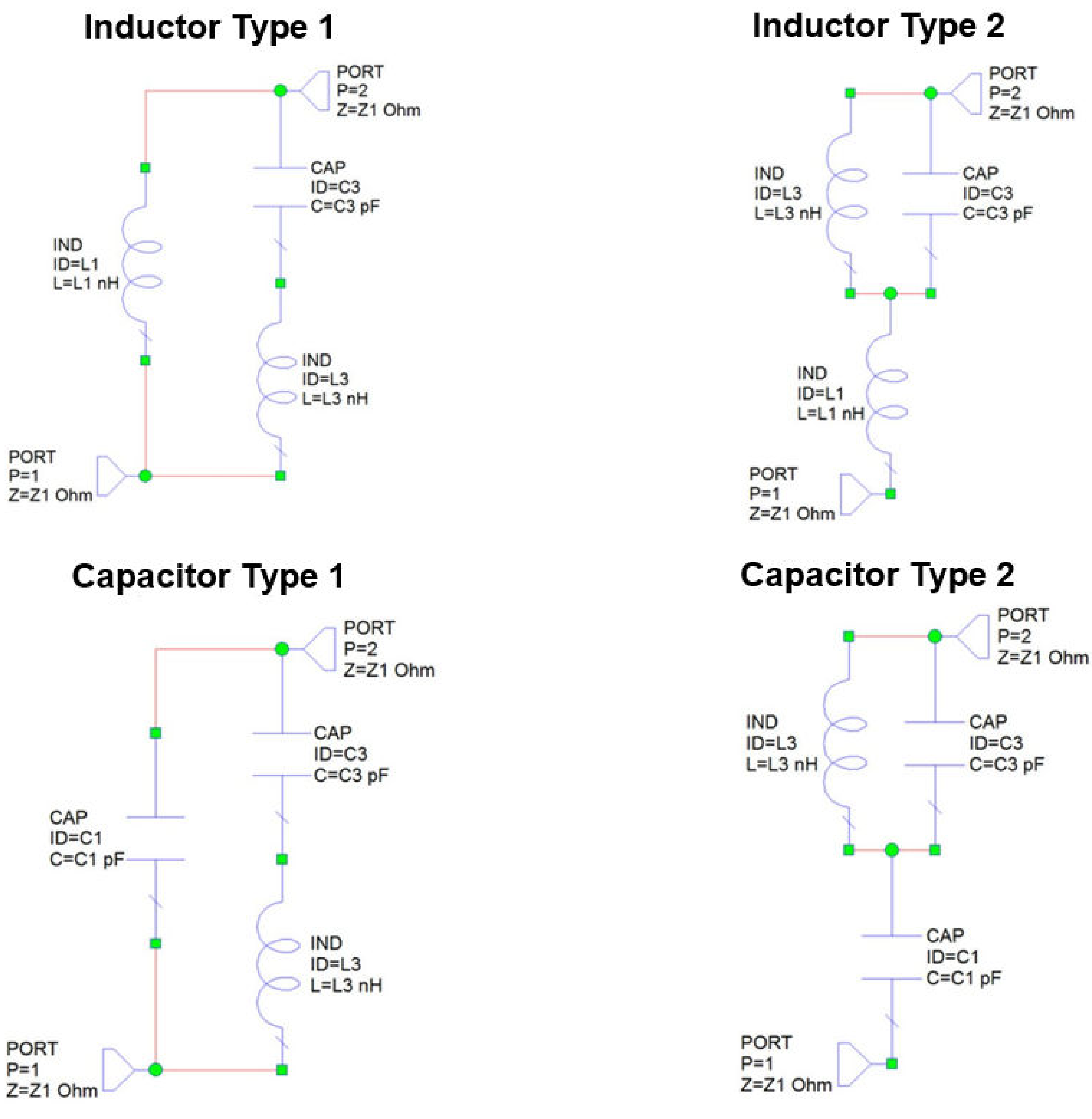

Figure 5.1. Frequency-Dependent 3-Element Resonators

The next figures show the frequency-dependent behavior of the 3-element resonators. As mentioned above, the resonators have a series and parallel resonance as well, but the focus is the lower and upper frequency ranges where the total shown inductance/capacitance is different (i.e., frequency-dependent). On the other hand, these frequency-dependent total shown inductance or capacitance values are quite stable in frequency. Both types of inductors and capacitors have similar characteristics.

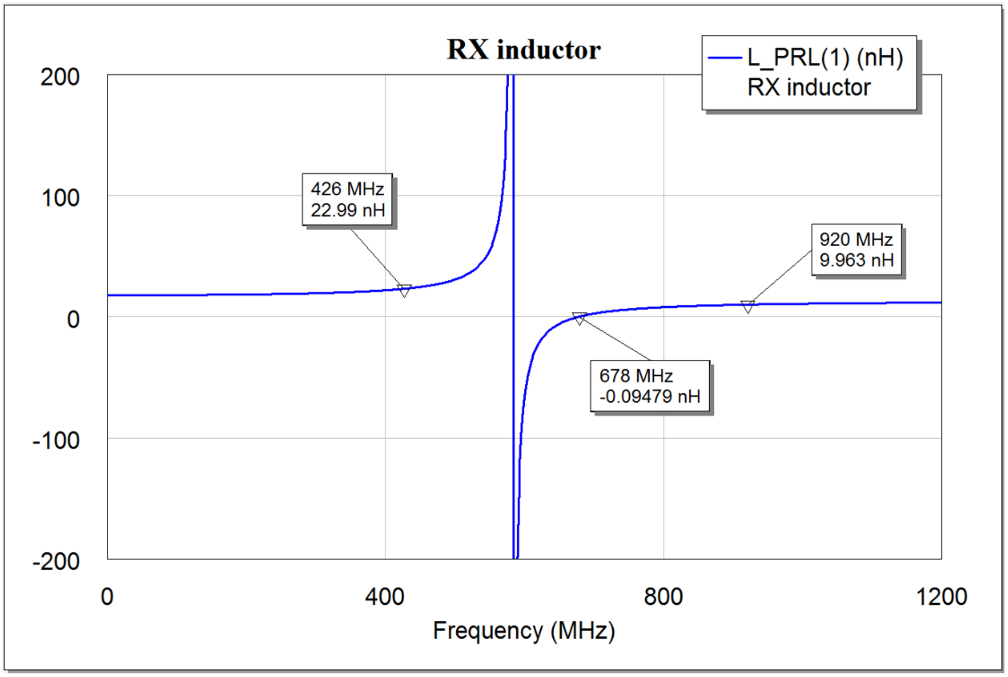

Figure 5.2. Inductance of 3-Element Resonator, Inductor Type 1

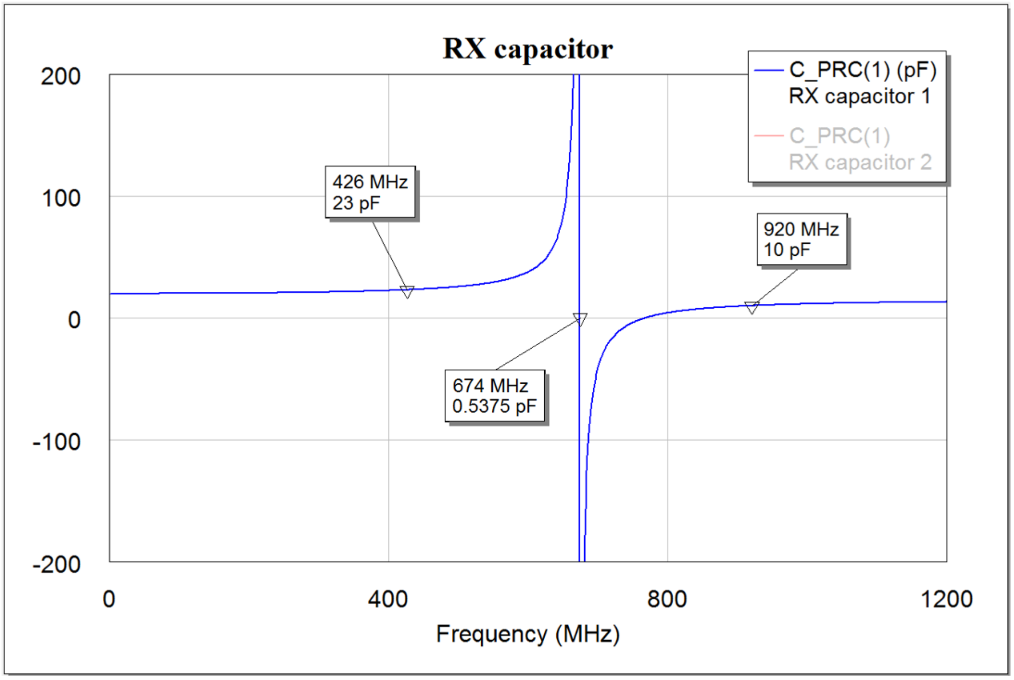

Figure 5.3. Capacitance of 3-Element Resonator, Capacitor Type 1

The formulas and equations shown below help to determine the component values of the 3-element resonators under the desired conditions (e.g., required total shown inductance and capacitance at the desired frequencies).

Table 5.1. Inductor Type 1

$Z = j \cdot 2\pi f \cdot L1 \cdot \dfrac{1-(2\pi f)^2 \cdot L3 \cdot C3}{1-(2\pi f)^2 \cdot C3 \cdot (L1+L3)}$	Z: impedance j: imaginary unit f: frequency L1: inductance of L1 component L3: inductance of L3 component C3: capacitance of C3 component ω: angular frequency X1: desired inductance at f_1 X2: desired inductance at f_2 $f_1 < f_2$ X1 > X2 $Z = j\omega X$ $\omega_1 < \omega_0 < \omega_2$ f_0: series resonant point, recommended to be equal with $(f_1 + f_2)/2$
$\omega_x = 2\pi f_x$	
$L3 = \dfrac{X1 \cdot X2}{X1 - X2} \cdot \dfrac{\omega_1^2 - \omega_2^2}{\omega_0^2 - \omega_1^2 - \omega_2^2 + \dfrac{\omega_1^2 \cdot \omega_2^2}{\omega_0^2}}$	
$L1 = X1 \cdot \dfrac{\omega_0^2 - \omega_1^2}{\omega_0^2 - \omega_1^2 + \dfrac{\omega_1^2 \cdot X1}{L3}}$	
$C3 = \dfrac{1}{\omega_0^2 \cdot L3}$	

Table 5.2. Inductor Type 2

$Z = j \cdot 2\pi f \cdot \left(L1 + \dfrac{L3}{1-(2\pi f)^2 \cdot L3 \cdot C3}\right)$	Z: impedance j: imaginary unit f: frequency L1: inductance of L1 component L3: inductance of L3 component C3: capacitance of C3 component ω: angular frequency X1: desired inductance at f_1 X2: desired inductance at f_2 $f_1 < f_2$ X1 > X2 $Z = j\omega X$ $\omega_1 < \omega_0 < \omega_2$ f_0: parallel resonant point, recommended to be equal with $(f_1 + f_2)/2$
$\omega_x = 2\pi f_x$	
$L3 = \dfrac{X1 - X2}{\dfrac{\omega_0^2}{\omega_0^2 - \omega_1^2} - \dfrac{\omega_0^2}{\omega_0^2 - \omega_2^2}}$	
$L1 = X2 - L3 \cdot \dfrac{\omega_0^2}{\omega_0^2 - \omega_2^2}$	
$C3 = \dfrac{1}{\omega_0^2 \cdot L3}$	

Table 5.3. Capacitor Type 1

$$\mathrm{Y} = \mathrm{j} \cdot 2\pi f \cdot \left(C1 + \frac{C3}{1 - (2\pi f)^2 \cdot L3 \cdot C3} \right)$$

$$\omega_x = 2\pi f_x$$

$$\mathrm{C3} = \frac{B1 - B2}{\frac{\omega_0^2}{\omega_0^2 - \omega_1^2} - \frac{\omega_0^2}{\omega_0^2 - \omega_2^2}}$$

$$\mathrm{C1} = B2 - C3 \cdot \frac{\omega_0^2}{\omega_0^2 - \omega_2^2}$$

$$\mathrm{L3} = \frac{1}{\omega_0^2 \cdot C3}$$

Y: admittance

j: imaginary unit

f: frequency

C1: capacitance of C1 component

L3: inductance of L3 component

C3: capacitance of C3 component

ω: angular frequency

B1: desired capacitance at f_1

B2: desired capacitance at f_2

$f_1 < f_2$

B1 > B2

$Y = j\omega B$

$\omega_1 < \omega_0 < \omega_2$

f_0: series resonant point, recommended to be equal with $(f_1 + f_2)/2$

Table 5.4. Capacitor Type 2

$$\mathrm{Y} = \mathrm{j} \cdot 2\pi f \cdot \mathrm{C1} \cdot \frac{1 - (2\pi f)^2 \cdot L3 \cdot C3}{1 - (2\pi f)^2 \cdot L3 \cdot (C1 + C3)}$$

$$\omega_x = 2\pi f_x$$

$$\mathrm{C3} = \frac{B1 \cdot B2}{B1 - B2} \cdot \frac{\omega_1^2 - \omega_2^2}{\omega_0^2 - \omega_1^2 - \omega_2^2 + \frac{\omega_1^2 \cdot \omega_2^2}{\omega_0^2}}$$

$$\mathrm{C1} = \mathrm{B1} \cdot \frac{\omega_0^2 - \omega_1^2}{\omega_0^2 - \omega_1^2 + \frac{\omega_1^2 \cdot B1}{C3}}$$

$$\mathrm{L3} = \frac{1}{\omega_0^2 \cdot C3}$$

Y: admittance

j: imaginary unit

f: frequency

C1: capacitance of C1 component

L3: inductance of L3 component

C3: capacitance of C3 component

ω: angular frequency

B1: desired capacitance at f_1

B2: desired capacitance at f_2

$f_1 < f_2$

B1 > B2

$Y = j\omega B$

$\omega_1 < \omega_0 < \omega_2$

f_0: parallel resonant point, recommended to be equal with $(f_1 + f_2)/2$

The quantity f_0 is set to be at one of the resonance points between f_1 and f_2. It is recommended to have it at $(f_1 + f_1)/2$, but other values (between f_1 and f_2) may be used, as desired.

6. Dual-Band Matching Balun Network

Silicon Labs provides discrete matching network designs for dual-band applications based on the standard single-band 4-element discrete matching balun designs and 3-element resonators. The matching network utilizes SMD components only and is tuned for two frequency bands with relatively small bandwidths, i.e. tuned for two frequency bands that are relatively falling far from each other. There is a single-BOM, dual-band matching network presented and measured in this application note that can cover the following ISM frequency bands (e.g., 434 and 868 MHz with relatively small bandwidths). The recommended dual-band matching balun structure can be tuned for other frequencies as well, if desired.

Introducing 3-element resonators in the single-band 4-element discrete matching balun makes the network dual-band or multi-band. The figure below shows the dual-band variant of matching balun with Lumped Reactive Elements (LRE) as the representations of the 3-element resonators.

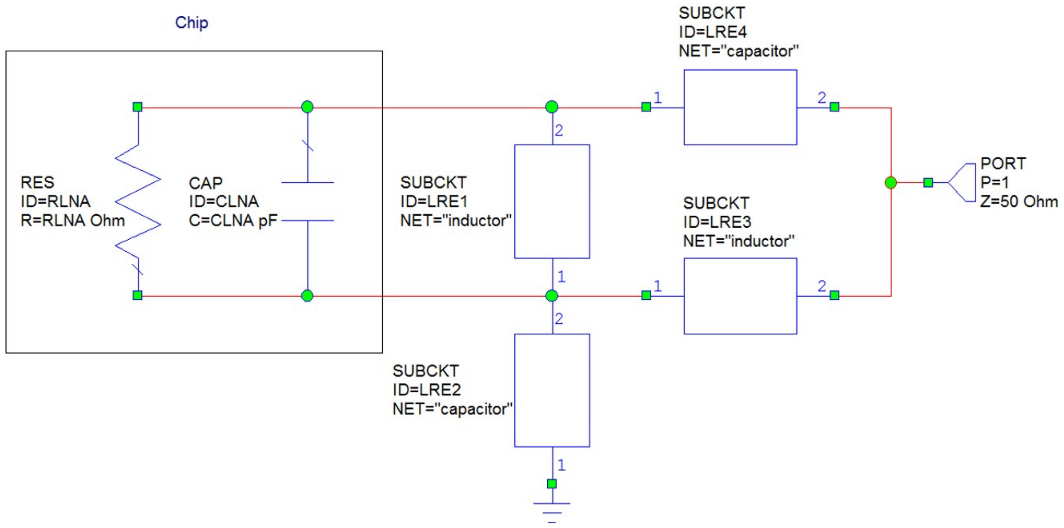

Figure 6.1. Dual-Band Matching Balun Network

Below is a list of possible dual-band matching balun options:

1. 12-element balun
   - Each component is replaced with a 3-element resonator
2. 10-element balun
   - L1 is kept as single component and C1, L2, and C2 are replaced with a 3-element resonator
   - L2 is kept as single component and C1, L1, and C2 are replaced with a 3-element resonator
   - C1 is kept as single component and L1, L2, and C2 are replaced with a 3-element resonator
   - C2 is kept as single component and C1, L2, and L1 are replaced with a 3-element resonator
3. 8-element balun
   - L1 and C1 are kept as single components, L2 and C2 are replaced with a 3-element resonator
   - L1 and C2 are kept as single components, L2 and C1 are replaced with a 3-element resonator
   - L1 and L2 are kept as single components, C1 and C2 are replaced with a 3-element resonator
   - L2 and C1 are kept as single components, L1 and C2 are replaced with a 3-element resonator
   - L2 and C2 are kept as single components, L1 and C1 are replaced with a 3-element resonator
   - C1 and C2 are kept as single components, L1 and L2 are replaced with a 3-element resonator
4. 6-element balun
   - L1, L2, and C1 are kept as single components, C2 is replaced with a 3-element resonator
   - L1, L2, and C2 are kept as single components, C1 is replaced with a 3-element resonator
   - L1, C2, and C1 are kept as single components, L2 is replaced with a 3-element resonator
   - L2, C2, and C1 are kept as single components, L1 is replaced with a 3-element resonator

6.1 12-Element Dual-Band Matching Balun

The theoretically perfect, without any compromise in performance, dual-band matching balun uses 12 elements; i.e., each of the 4 components in the standard single-band balun network is replaced with a 3-element resonator. One variant of the 12-element dual-band balun representations is shown in the figure below (inductor type 1 and capacitor type 1 of 3-element resonators are being applied).

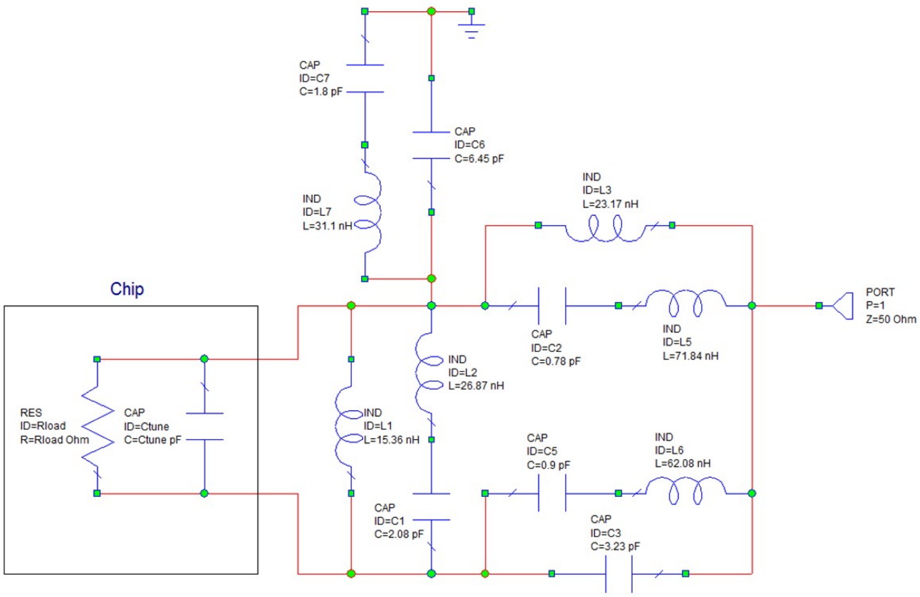

Figure 6.2. 12-Element Dual-Band Matching Balun

The simulation results are shown in the following figures. This example is tuned for 426 and 920 MHz, with Rload=125 ohms and Ctune=3.25 pF. Simulation component values are only based on the calculation of formulas shown previously.

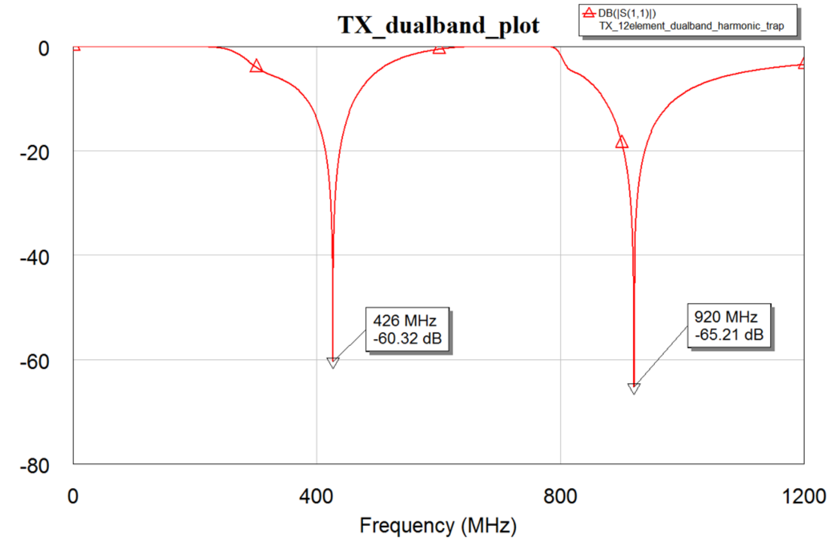

Figure 6.3. S11 of 12-Element Dual-Band Matching Balun

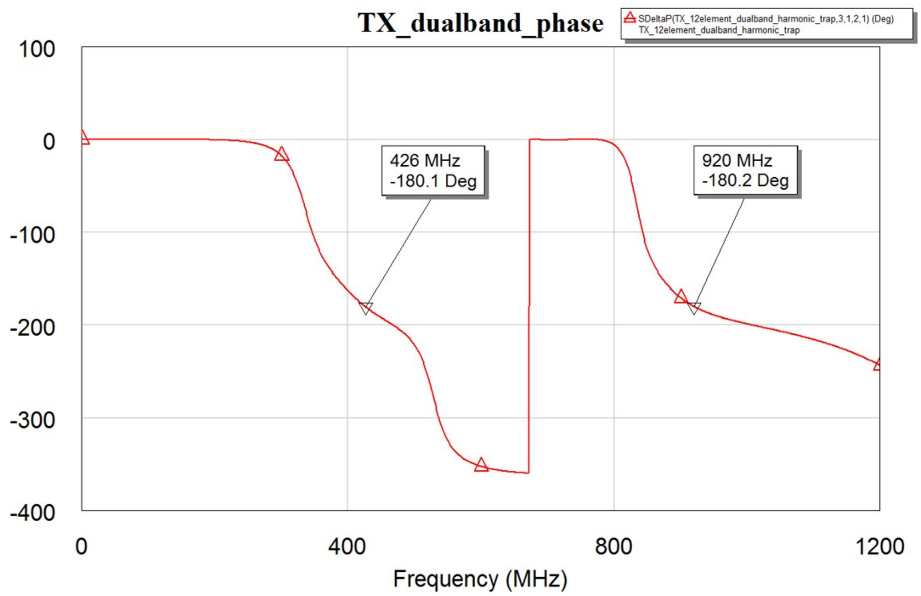

Figure 6.4. Phase Difference of 12-Element Dual-Band Matching Balun

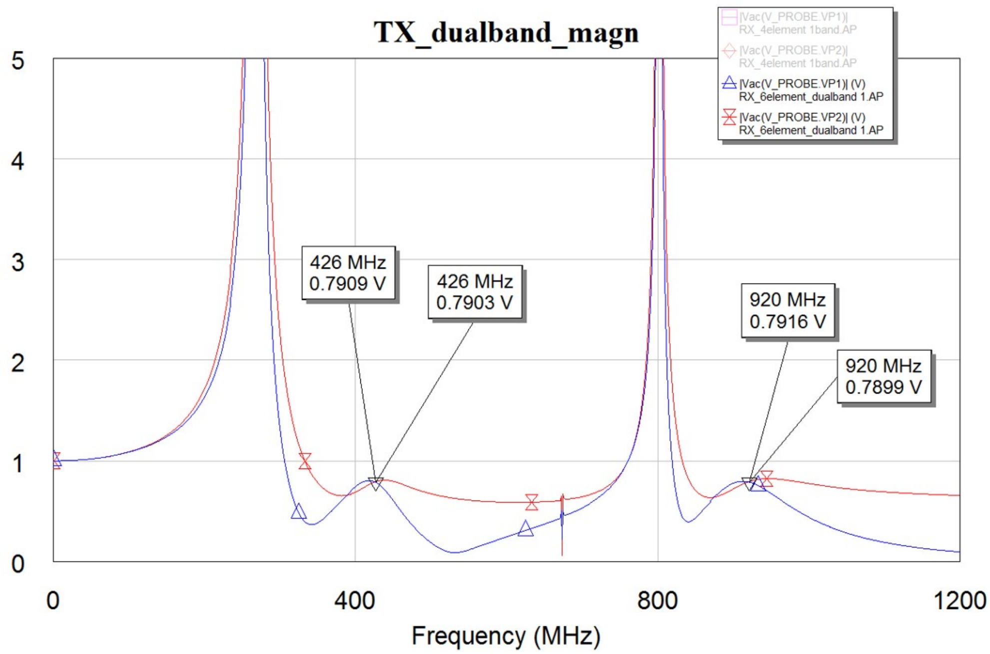

Figure 6.5. Magnitudes on the Differential Ports of 12-Element Dual-Band Matching Balun

The simulation results shown above yield excellent dual-band matching balun operation without any performance degradation expected.

6.2 6-Element Dual-Band Matching Balun

The BOM-optimized dual-band matching balun utilizes only 6 SMD components; i.e., only one 3-element resonator is being used in the 4-element matching balun network. Certainly, it requires some compromise in the RF performance. However, with equalizing the errors between the two bands and/or equalizing between the matching, phase and magnitude mismatches the overall insertion loss and matching degradation can be quite moderated in the range of about 1…2 dB (compared to the single-band optimum values).

There are obviously 4 different 6-element matching balun topologies depending on which normal element is replaced with a 3-element resonator and the rest of the 3 components are being kept as single, normal elements. Additionally, both types of 3-element resonators can be applied. For dual-band operation, at least one resonator needs to be kept in the circuitry, so the 6-element matching balun is the most BOM-optimized solution for the dual-band matching balun network, and therefore have the highest potential in practical use-case in discrete designs.

Replacing L1, the first parallel inductor between the differential ports of the standard single-band 4-element balun, with a 3-element resonator and keeping the other 3 components as normal ones, yield the best performer of the 6-element matching balun networks. The following figures show the recommended schematics for the 6-element dual-band balun networks for optimal overall performance that give good impedance matches and balun functions (phase shift and magnitudes). Circuit schematics and simulation results are also shown in the following figures. Simulation values are not being shown in the simulated schematic below, since those may require to be adjusted due to some parasitic effects (e.g., bonding wire inductance, stray capacitance, and PCB and SMD component parasitics). Bench tuned values are of course being shown in the tables below and complete dual-band TRX schematics are also provided that can cover the (426–) 434 – 868/915 MHz frequency bands (main frequencies of interest in the global ISM regions) simultaneously.

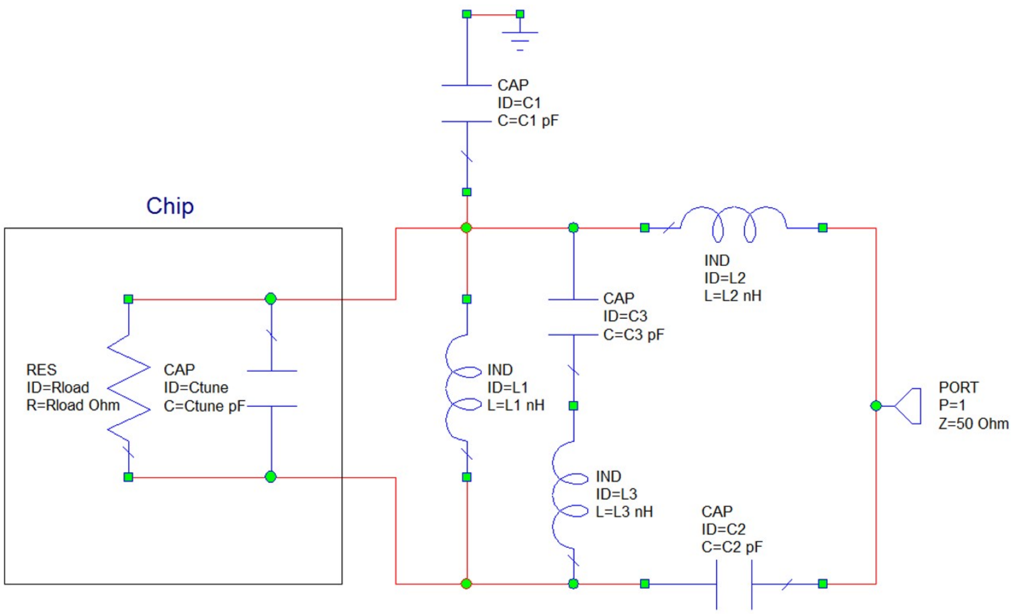

Figure 6.6. 6-Element Dual-Band Matching Balun

It has a nice S11 curve (so the impedance match is good) and the phase difference is also quite good and acceptable between the differential ports. However, it slightly sacrifices the magnitudes on the differential ports, especially in the higher frequency band.

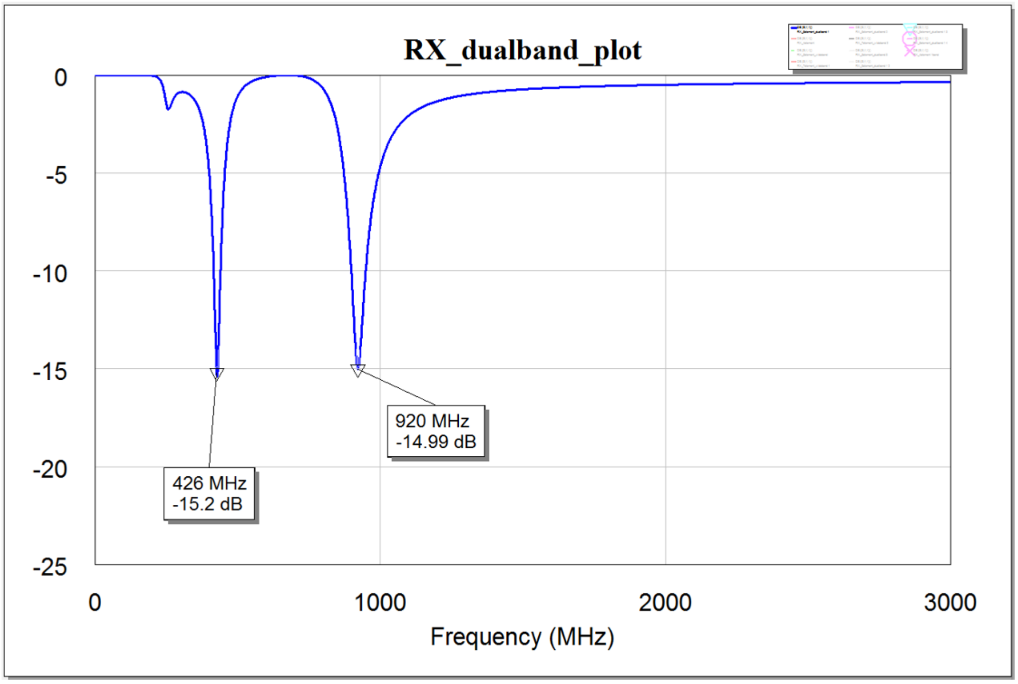

Figure 6.7. S11 of 6-Element Dual-Band Matching Balun

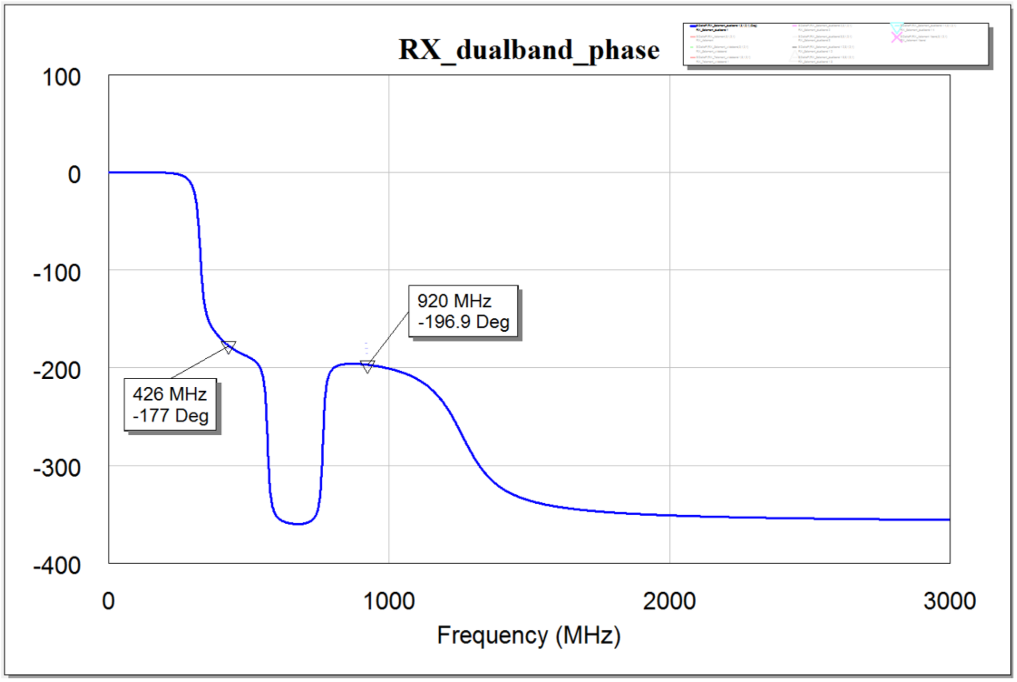

Figure 6.8. Phase Difference of 6-Element Dual-Band Matching Balun

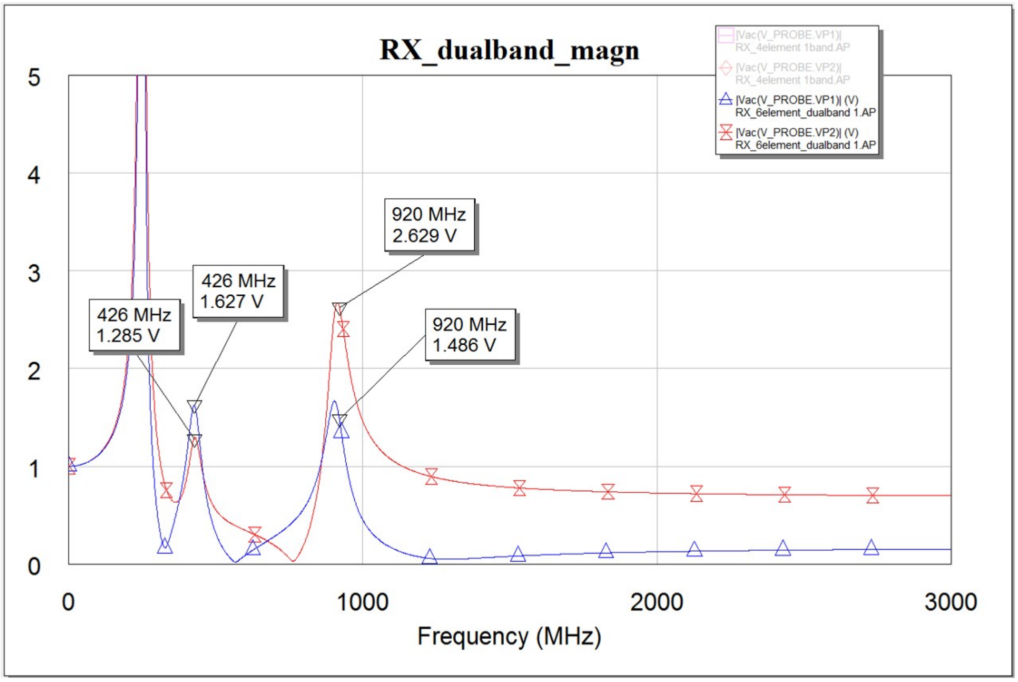

Figure 6.9. Magnitudes on the Differential Ports of 6-Element Dual-Band Matching Balun

This simulation example on the 6-element matching balun was performed between Rload=600 ohms, Ctune=1.1 pF, and 50 ohms.

6.3 Tuning Guidance of the 6-Element Dual-Band Matching Balun

The tuning of the dual-band matching balun network can be necessary for several reasons, such as different frequency bands desired, different component type (especially for inductors) applied in the circuit, and layout drawing differences. This section provides some insights on how to tune the 6-element dual-band matching balun network.

Component	Tuning Effects Description
C3	Rapidly tunes both resonances mainly in frequency
L3	Rapidly tunes the upper resonance, slight effects on the lower resonance mainly in frequency
L1	Tunes both resonances in frequency
L2	Tunes both resonances in impedance level
C2	Rapidly tunes both resonances mainly in impedance level
C1	Rapidly tunes the upper resonance

6.4 Recommended RX Dual-Band Matching Balun (6-Element)

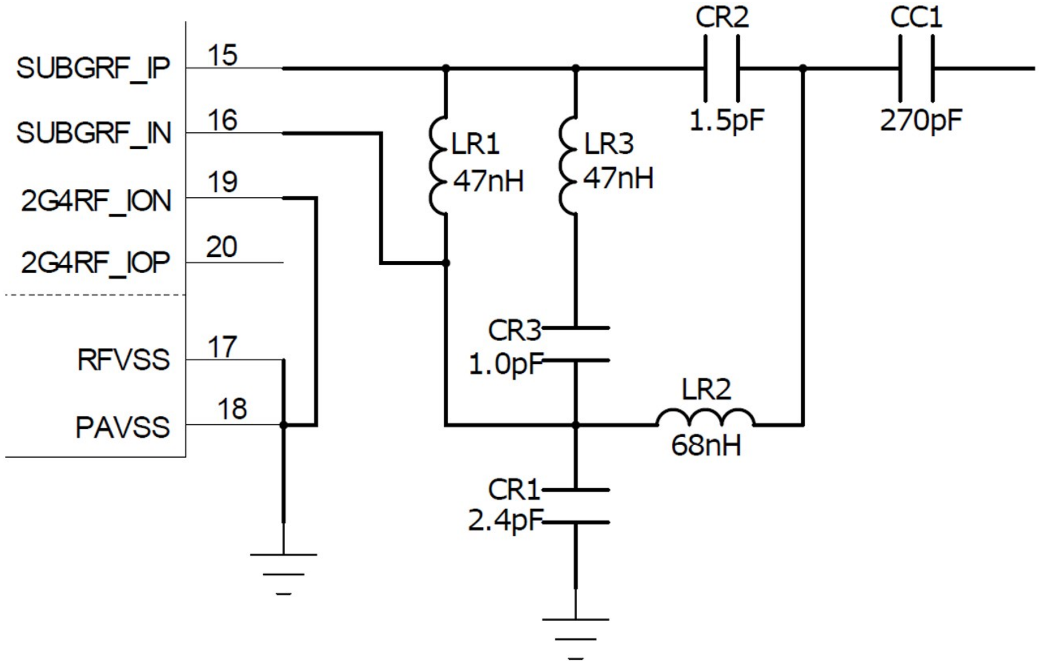

Figure 6.10. Recommended 6-Element RX Dual-Band Matching Balun

6.4.1 Measured RX Sensitivity Performance Vs. Component Values

Component Values						Sensitivity	
LR1	LR2	LR3	CR1	CR2	CR3	426 MHz	920 MHz
43 nH	68 nH	47 nH	2.4 pF	1.5 pF	1.0 pF	-107.5 dBm	-106.3 dBm
43 nH	68 nH	47 nH	2.7 pF	1.5 pF	1.0 pF	-107.8 dBm	-106.0 dBm
47 nH	68 nH	47 nH	2.4 pF	1.5 pF	1.0 pF	-107.8 dBm	-106.5 dBm

Component Values						Sensitivity [dBm]			
LR1	LR2	LR3	CR1	CR2	CR3	426 MHz	434 MHz	868 MHz	915 MHz
43 nH	68 nH	51 nH	2.4 pF	1.5 pF	1.0 pF	-108	-107.5	-106.5	-106

Note: Modulation settings: 2-FSK, DR=100 kbps, Dev=50 kHz. Sensitivity level at BER<1%. SMD 0402 wire-wound inductors used on 4-layer PCB. Measured on Silicon Labs' EVB.

6.4.2 Measured S11 Impedance Plot

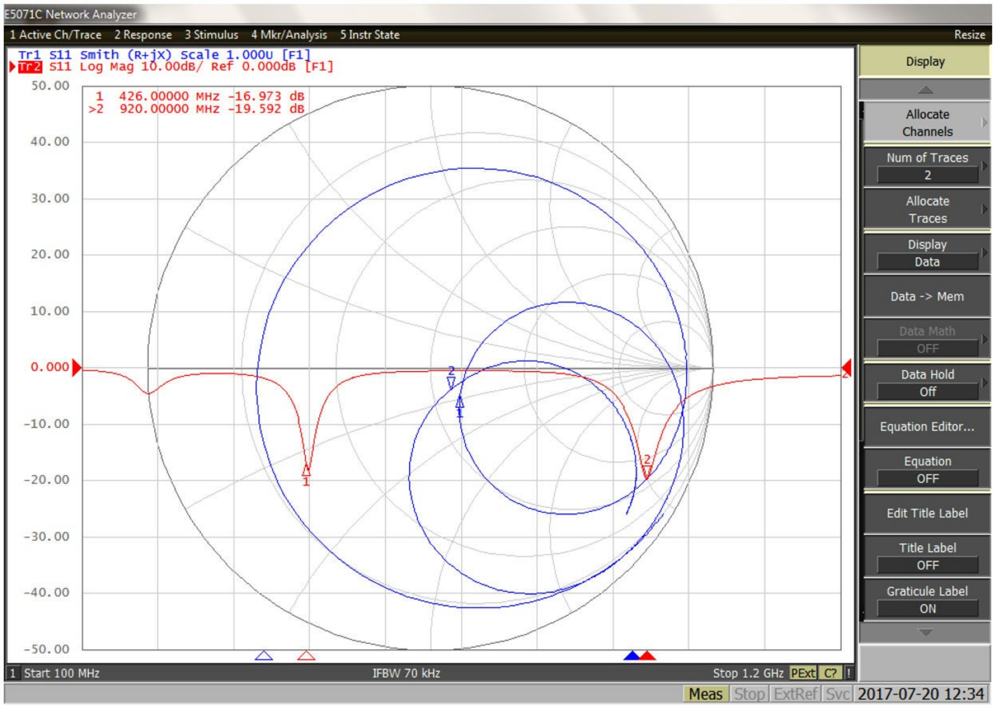

Figure 6.11. Measured S11 of 6-Element RX Dual-Band Matching Balun

Note: Measured impedance plot with the following component values: LR1=47 nH; LR2=68 nH; LR3=47 nH; CR1=2.4 pF; CR2=1.5 pF; CR3=1.0 pF. Measured on Silicon Labs' EVB.

6.5 Recommended TX Dual-Band Matching Balun (6-Element)

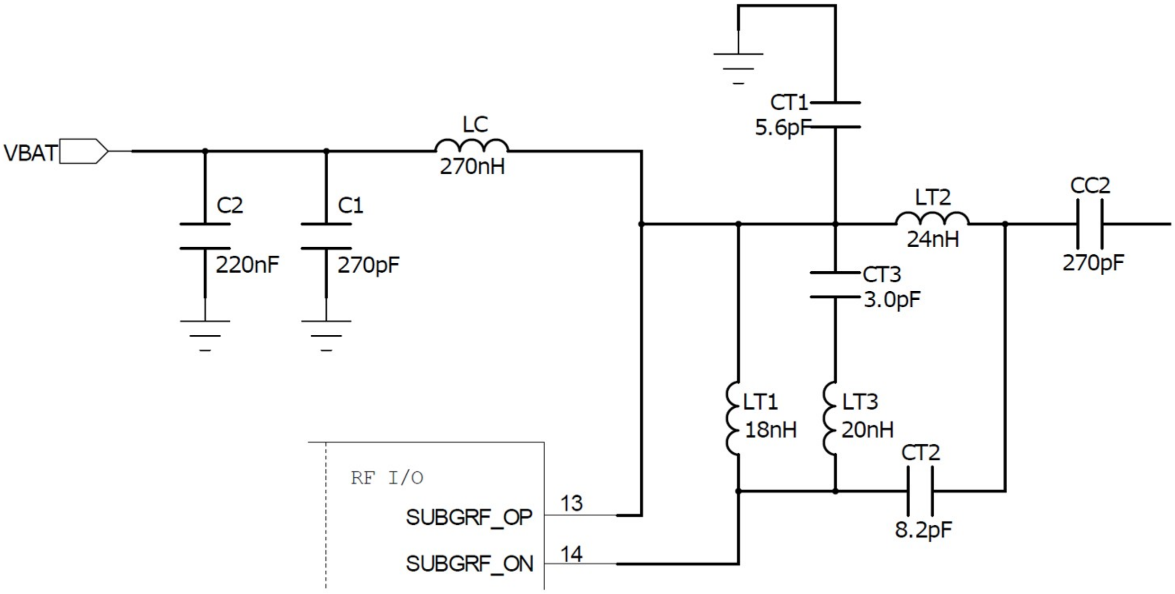

Figure 6.12. Recommended 6-Element TX Dual-Band Matching Balun

6.5.1 Measured TX Power Vs. Component Values

Component Values						TX Power	
LT1	LT2	LT3	CT1	CT2	CT3	426 MHz	920 MHz
15 nH	24 nH	20 nH	5.6 pF	8.2 pF	3.0 pF	19.8 dBm	19.8 dBm
15 nH	24 nH	20 nH	6.8 pF	8.2 pF	3.0 pF	20.2 dBm	19.6 dBm
15 nH	24 nH	20 nH	8.2 pF	8.2 pF	3.0 pF	20.5 dBm	19.3 dBm
18 nH	24 nH	20 nH	5.6 pF	8.2 pF	3.0 pF	20.4 dBm	20.0 dBm

Component Values						TX Power [dBm]			
LT1	LT2	LT3	CT1	CT2	CT3	426 MHz	434 MHz	868 MHz	915 MHz
20 nH	24 nH	20 nH	5.6 pF	8.2 pF	3.0 pF	20.7	20.8	20.0	20.0

Note: SMD 0402 wire-wound inductors used on 4-layer PCB. Measured on Silicon Labs' EVB.

6.6 Recommended Complete TRX Dual-Band Matching Network #1

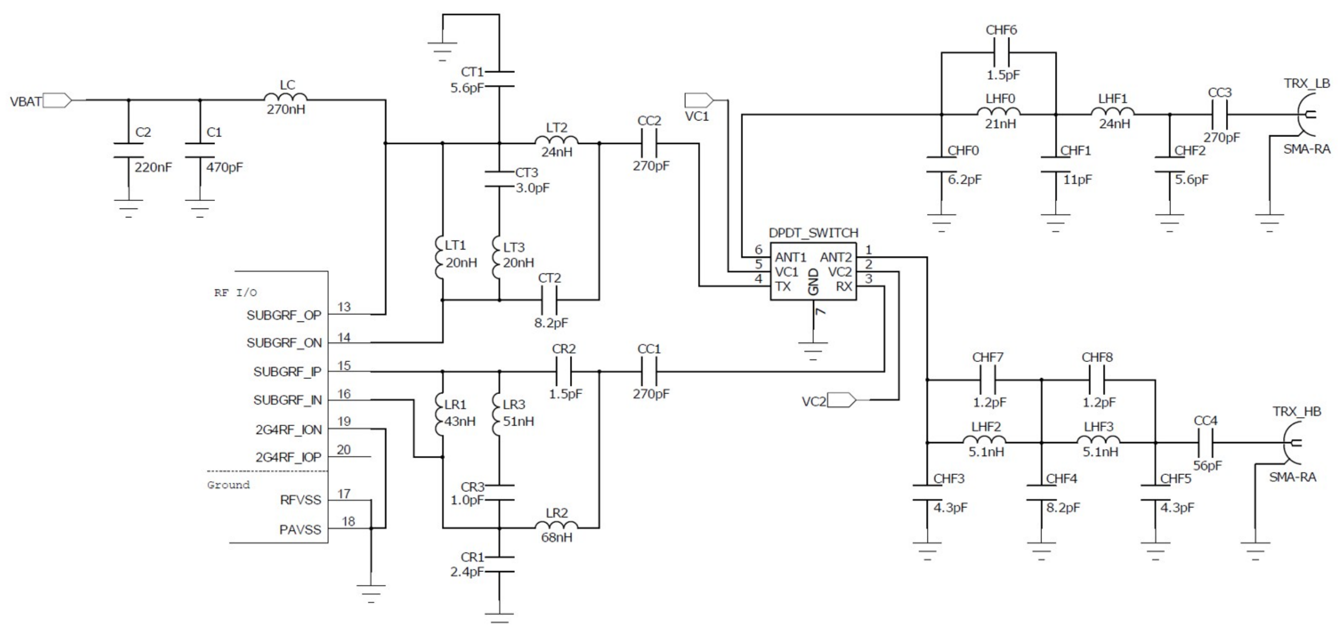

Figure 6.13. Recommended Complete Dual-Band Match RF Schematic #1

Component values shown above are tuned on Silicon Labs' EVB with SMD 0402 wire-wound inductors.

6.6.1 Measured Performance Results Vs. Component Values

Frequency (MHz)	TX Power (dBm)	TX Harmonics (dBm)		Sensitivity (dBm)	Notes *BOM Changes
		2nd	3rd...10th		
426	+20.0	-45	< -45	-106.5	Recommended complete RF schematic (1) as-is
434	+20.1	-44	< -45	-106.3	
868	+19.2	-41	< -50	-105.3	
915	+18.8	-50	< -50	-104.5	
426	+20.0	-45	< -45	-106.5	*CHF3 = 5.1 pF *LHF3 = 6.2 nH *CHF8 = N.M.
434	+20.1	-44	< -45	-106.3	
868	+19.2	-34	< -50	-105.5	
915	+19.0	-40	< -50	-105.0	
426	+20.0	-45	< -45	-106.5	*CHF3 = CHF5 = 3.0 pF *CHF4 = 5.6 pF *LHF2 = LHF3 = 7.5 nH *CHF7 = CHF8 = 0.8 pF
434	+20.1	-44	< -45	-106.3	
868	+19.3	-37	< -50	-105.0	
915	+19.1	-50	< -50	-105.3	

Note: Modulation settings: 2-FSK, DR=100 kbps, Dev=50 kHz. Sensitivity level at BER<1%. SMD 0402 wire-wound inductors used on 4-layer PCB. Measured on Silicon Labs' EVB.

Note: It is recommended to follow the schematic structure #1 shown above when separate single-band antennas are intended to use in the different frequency bands.

6.7 Recommended Complete TRX Dual-Band Matching Network #2

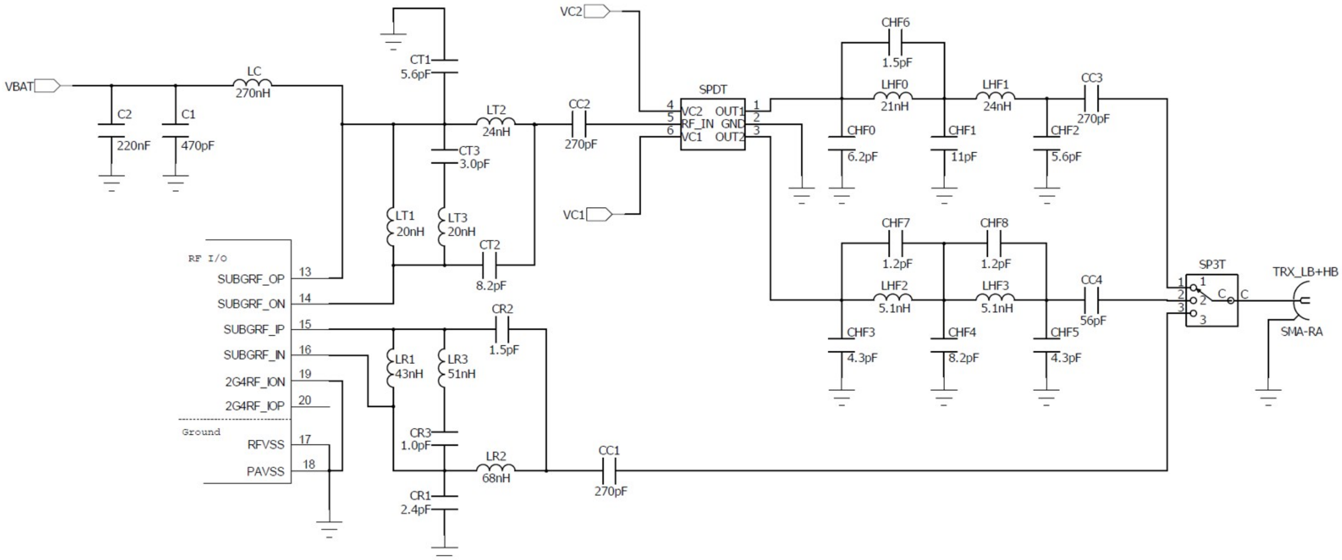

Figure 6.14. Recommended Complete Dual-Band Match RF Schematic #2

SPDT switch can be replaced by a diplexer, if desired.

6.7.1 Expected Performance Results Vs. Component Values

Frequency (MHz)	TX Power (dBm)	TX Harmonics (dBm)		Sensitivity (dBm)	Notes *BOM Changes
		2nd	3rd...10th		
426	+20.0	-45	< -45	-107.7	Recommended complete RF schematic (2) as-is
434	+20.1	-44	< -45	-107.3	
868	+19.2	-41	< -50	-106.3	
915	+18.8	-50	< -50	-105.7	
426	+20.0	-45	< -45	-107.7	*CHF3 = CHF5 = 3.0 pF
434	+20.1	-44	< -45	-107.3	*CHF4 = 5.6 pF
868	+19.3	-37	< -50	-106.3	*LHF2 = LHF3 = 7.5 nH
915	+19.1	-50	< -50	-105.7	*CHF7 = CHF8 = 0.8 pF

Note: Modulation settings: 2-FSK, DR=100 kbps, Dev=50 kHz. Sensitivity level at BER<1%. SMD 0402 wire-wound inductors used on 4-layer PCB.

Note: It is recommended to follow the schematic structure #2 shown above when a common, dual-band antenna is intended to use for both frequencies and TX-RX functions.

7. Multi-Band Matching Balun Network

This section will provide a multi-band matching balun solution that is bench-tuned for the receiver side of the EFR32 Series 1 chip family. The main matching goal is to cover the following Industrial, Scientific, and Medical (ISM) frequency bands with the multi-band RX balun circuits: 310–434 and 868–928 MHz. Certainly, it also requires some more compromise in the RF performance due to the multi-band and/or wideband operation. Also, the focus and priority are to satisfy the impedance matching requirements. The overall insertion loss and matching degradation can be quite moderated in the range of about 2…3 dB (compared to the single-band optimum values).

The dual-band balun networks discussed in the previous chapters have two resonances that can cover two frequency bands of interest. The multi-band matching balun circuits provided in this section will have three separate resonances and thus, those are able to cover more frequency bands.

The 7-element variants of multi-band matching balun networks are shown in the following figures. They are composed by the 6-element dual-band balun network together with an additional inductor (L4) coupled between PORT 1 and an internal node of the 3-element frequency-dependent resonator. The addition of inductor L4 creates another 4-element balun that includes L4, L3, C2 and C3xC1 (in series to GND) and thus, the 7-element balun networks can have 3 resonances.

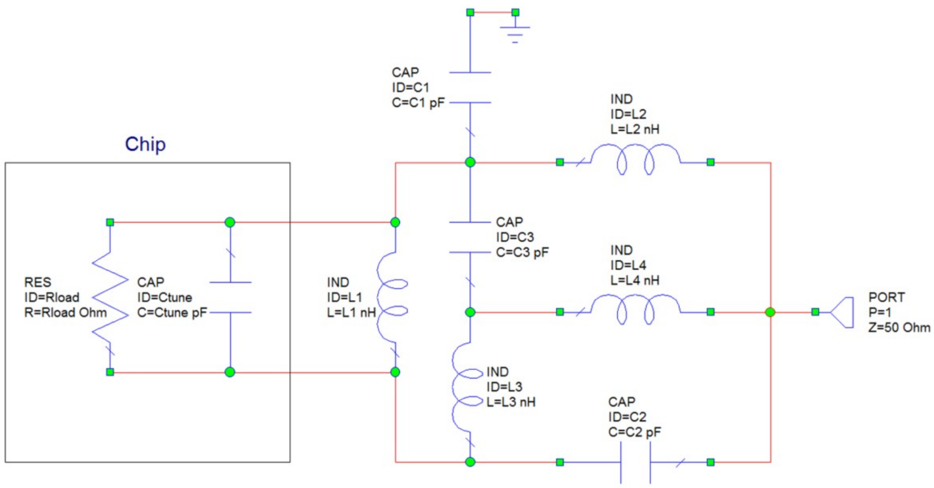

Figure 7.1. 7-Element Multi-Band Matching Balun #1

The other variant of 7-element multi-band matching balun networks is also shown in the following figure where the 3-element resonator is utilized by the dual-type of frequency-dependent inductor of 3-element resonator.

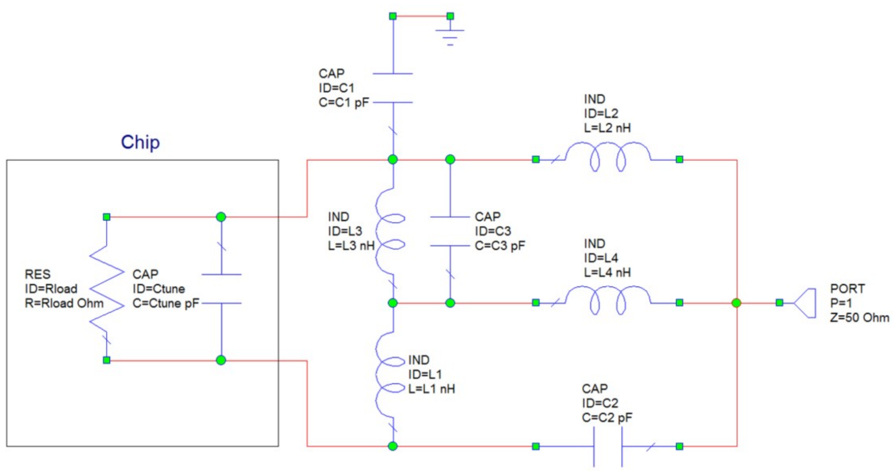

Figure 7.2. 7-Element Multi-Band Matching Balun #2

The 7-element multi-band matching balun networks can even be more simplified while they keep their three resonances. The simplification of these networks will yield a 5-element multi-band matching balun circuit which is the most BOM-optimized variant of these kind of multi-band networks. The schematic structure of the 5-element multi-band matching balun network is shown in the figure below.

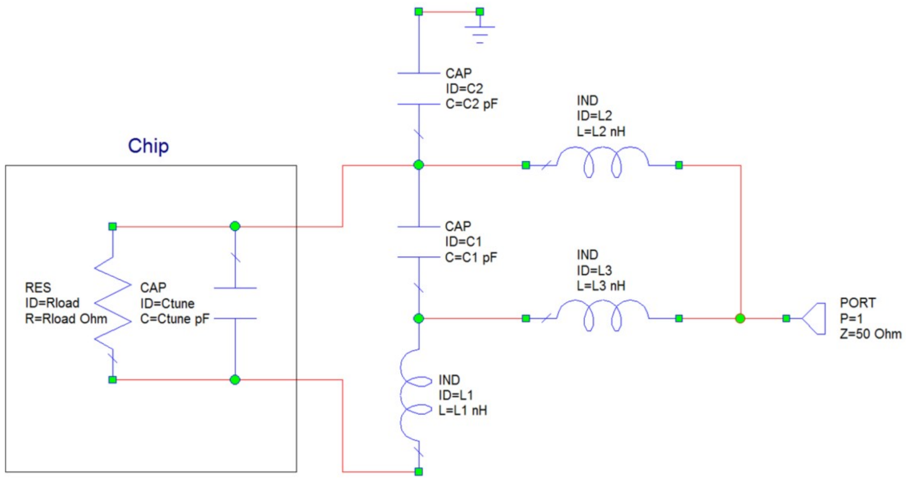

Figure 7.3. 5-Element Multi-Band Matching Balun

The 5-element multi-band matching balun represents an optimized version (fewer components or elements, for a lower-count/lower-cost bill of materials) of the 7-element multi-band matching balun network described above. Thus, the 5-element multi-band matching balun does not include any true 3-element frequency-dependent resonators. The resonators in 5-element multi-band matching balun, however, are cross-coupled to each other, and one element or component is part of more than resonators (for example, L1 – L2+L3 – C1; L2 – L3 – C1; and C2 – L2+L3 – C1). Note further that 5-element multi-band matching balun represents 3 resonances, where L2 and C2 components are mostly responsible for the lower frequency resonances, while L1, L3, and C1 elements give rise to the upper frequency resonance.

7.1 Simulation and Measured S11 Results of Multi-Band RX Matching Balun Network

The S11 simulation results of the 5- and 7-element multi-band RX matching balun networks with EFR32 are shown in the first figure below. The two lower frequency resonances are tuned close to each other in order to satisfy the matching goal in the frequency range of 310–434 MHz. The third resonance is responsible to cover the higher frequency band of 868–928 MHz.

Based on the BOM cost versus performance consideration, Silicon Labs recommend going with and utilize the 5-element multi-band matching balun network for multi-band design solutions.

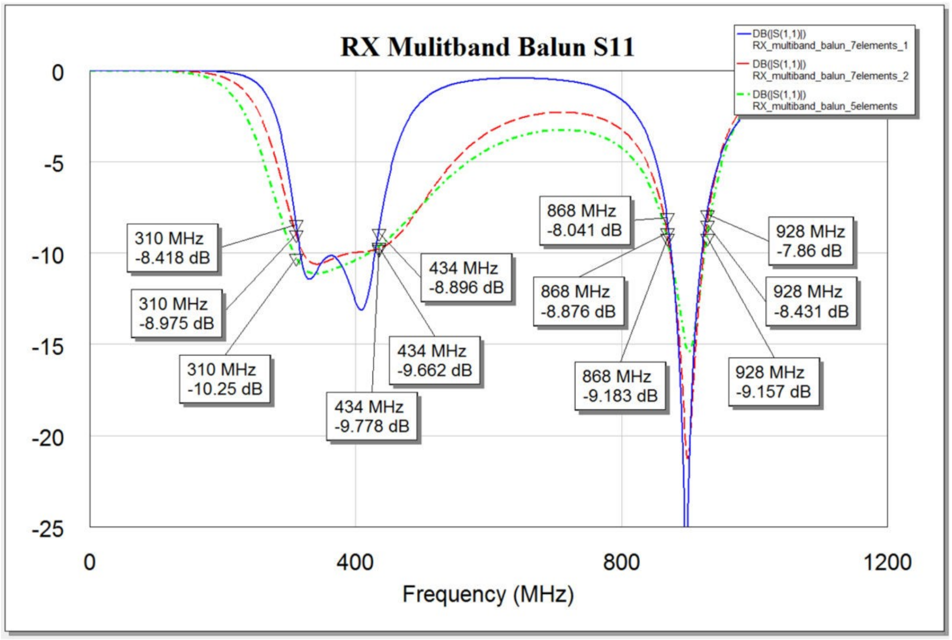

Figure 7.4. Simulated S11 of 5- and 7-Element Multi-Band EFR32 Matching Balun Networks

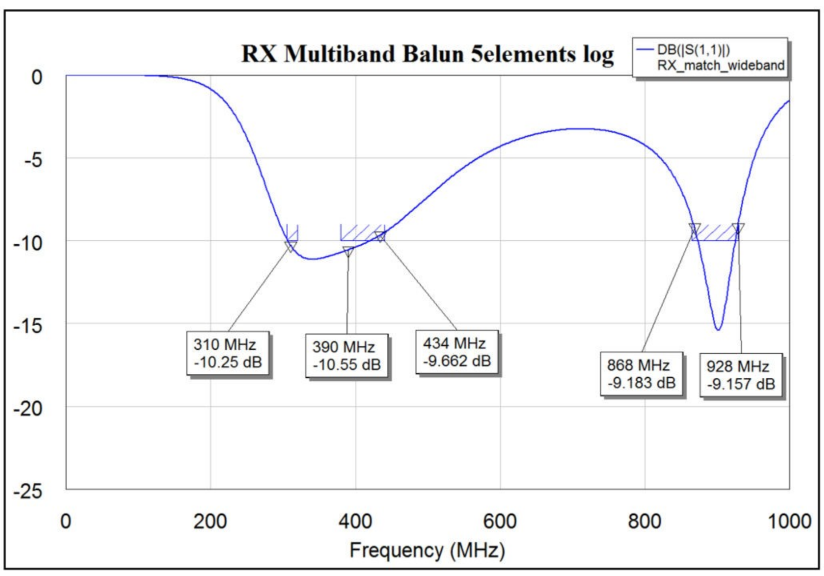

Figure 7.5. Simulated S11 of 5-Element Multi-Band EFR32 Matching Balun Network

The measured S11 of the 5-element multi-band RX balun network with EFR32 is shown in the figure below.

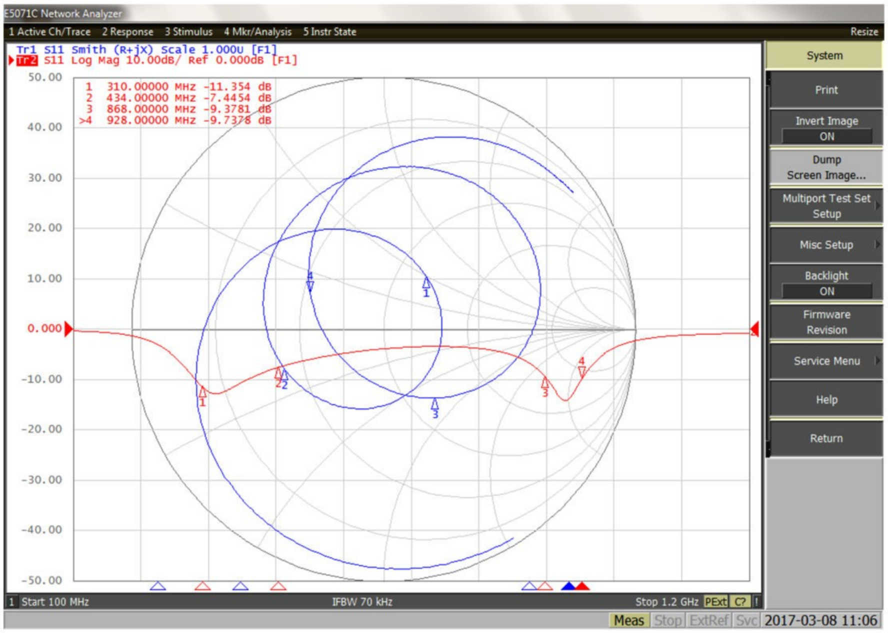

Figure 7.6. Measured S11 of 5-Element Multi-Band EFR32 Matching Balun Network

7.2 Recommended Multi-Band RX Matching Network

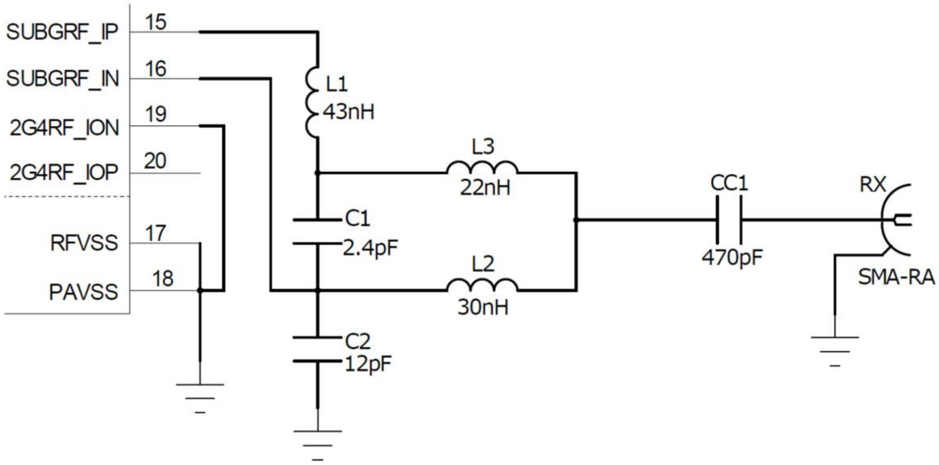

Figure 7.7. Recommended 5-Element Multi-Band RX Matching Schematic for EFR32

Table 7.1. Measured Performance Results Vs. Component Values

Component Values					Sensitivities (dBm) at Different Frequencies (MHz)				
L1 (nH)	L2 (nH)	L3 (nH)	C1 (pF)	C2 (pF)	315	390	434	868	915
43	39	27	2.7	5.6	-106.8	-105.5	-105	-105	-105.5
43	39	24	2.7	6.8	-106.5	-106	-105.5	-104.8	-105
43	33	27	2.7	5.6	-108	-105.5	-104.5	-105	-105.3
43	27	27	2.7	5.6	-109.5	-105.3	-103.8	-105.3	-105.3
51	30	30	1.8	5.6	-109.5	-107	-105	-103	-103.8
51	27	30	1.8	10	-109	-108	-105.3	-103.5	-103.3
43	30	22	2.4	12	-107.8	-107.5	-106.5	-104	-104.3
Note: Modulation settings: 2-FSK, DR=100 kbps, Dev=50 kHz. Sensitivity level at BER<1%. SMD 0402 wire-wound inductors used on 4-layer PCB. Measured on Silicon Labs' EVB.									

7.3 Tuning Guidance of the 5-Element Multi-Band Matching Balun

The tuning of the multi-band matching balun network can be necessary for several reasons such as different frequency bands desired, different component type (especially for inductors) applied in the circuit, layout drawing differences. This section provides some insights on how to be able to tune the 5-element multi-band matching balun network.

Component	Tuning Effects Description
C1	Rapidly tunes the upper resonance but affects each resonance
L3	Rapidly tunes mainly the upper resonances
L1	Rapidly tunes the upper resonance
L2	Tunes mainly the lower resonances
C2	Mainly tunes the lower resonances in impedance level

8. Dual-Wideband Matching Balun Network

Silicon Labs provides discrete matching network designs for dual-wideband frequency coverage based on the dual- and wideband discrete matching balun designs discussed above. The matching network utilizes SMD components only and is tuned for two frequency bands that are falling relatively far from each other and with large bandwidth in both frequency regions. There is a single-BOM matching network recommended and presented in this application note that can cover the following ISM frequency bands, e.g. from 315 MHz up to 510 MHz and from 780 MHz up to 928 MHz.

The dual-wideband matching network is based on utilizing the 3-element resonators together with Youla wideband matching technique.

8.1 Design Details of Discrete Dual-Wideband Matching Balun Network

This section summarizes the design steps of a discrete dual-wideband matching balun network for the frequency coverage of 310–510 and 780–930 MHz, applicable for EFR32 Series 1 receiver path.

8.1.1 Step 1: Designing the Separate Wideband Matches

The first step is to design the wideband matching balun networks separately for 310–510 MHz and then for 780–930 MHz, based on the discrete wideband matching balun design description as shown earlier in this application note. The receiver-only part of the discrete wideband match consists of a 3-element differential-to-differential match, that utilizes the wideband Youla technique between differential impedances of around 500 and 125 ohms, and a single-band standard 4-element matching balun circuit between a differential 125 and single-ended 50 ohms. I.e. the impedance conversion is being done in two steps which lowers the matching Q while increasing the frequency bandwidth, also the standard 4-element matching balun has big enough frequency bandwidth if the impedance is transformed between 125 and 50 ohms (i.e., it is a low-Q requirement for the that part of the match).

Discrete wideband matching balun for the lower frequency band is shown in the following figure.

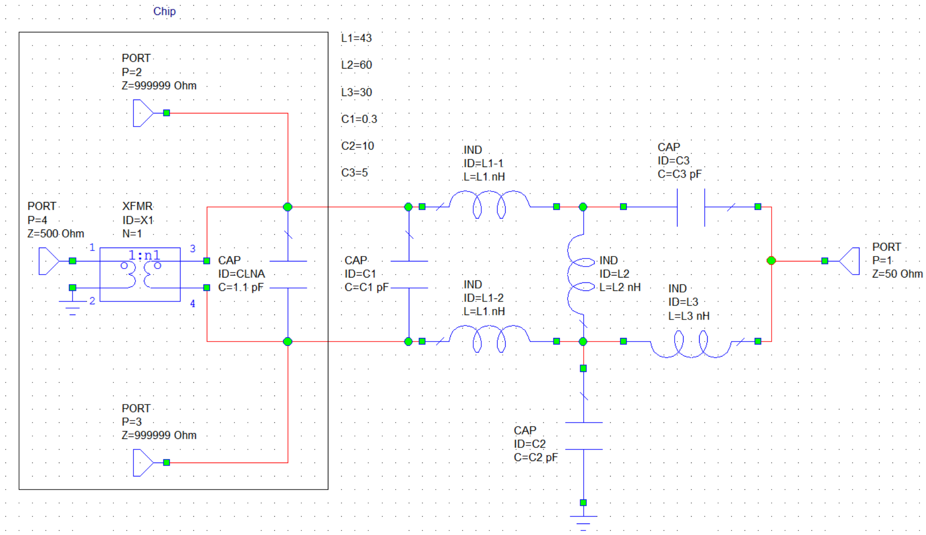

Figure 8.1. Low-Band Wideband RX-Only Matching Balun Network

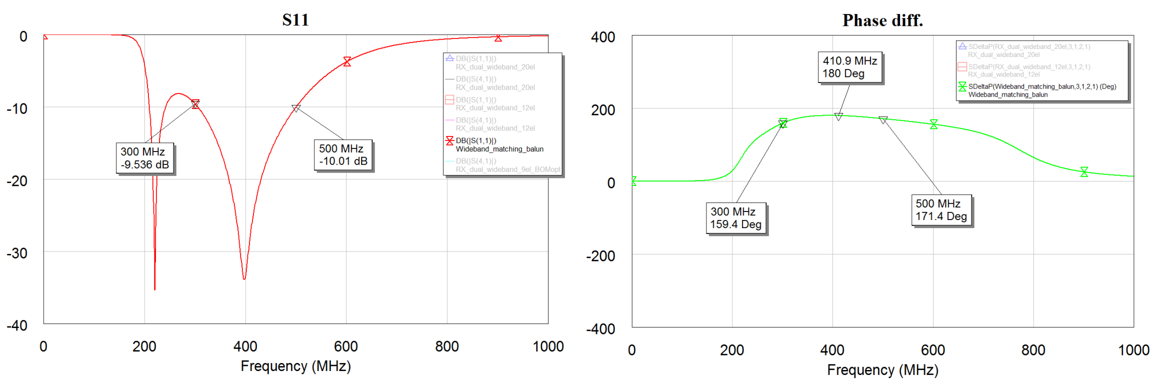

Figure 8.2. Simulated S11 and Phase Difference of Low-Band Wideband RX-Only Matching Balun

Discrete wideband matching balun for the higher frequency band is shown in the following figure.

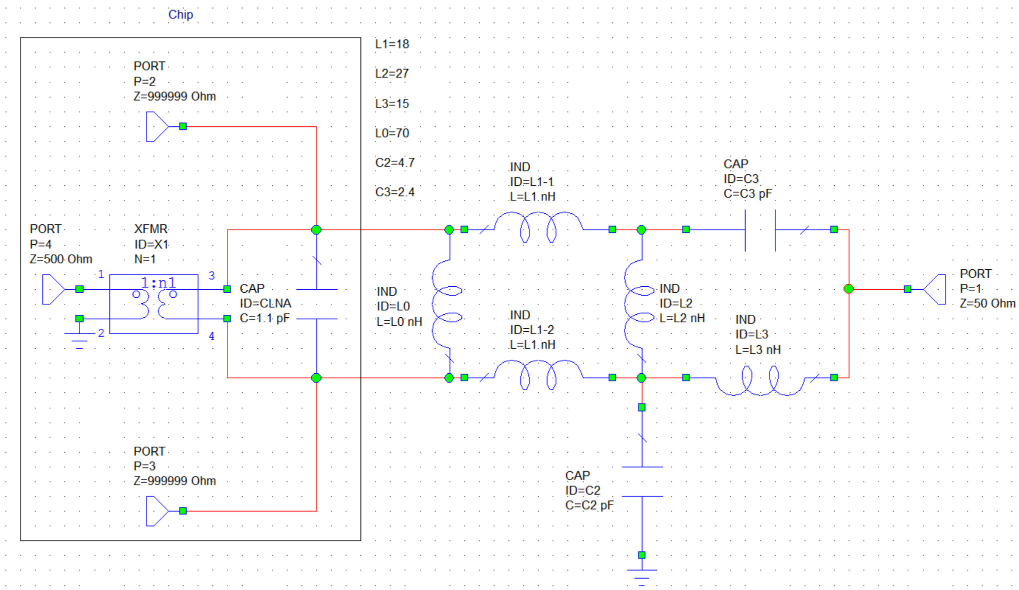

Figure 8.3. High-Band Wideband RX-Only Matching Balun Network

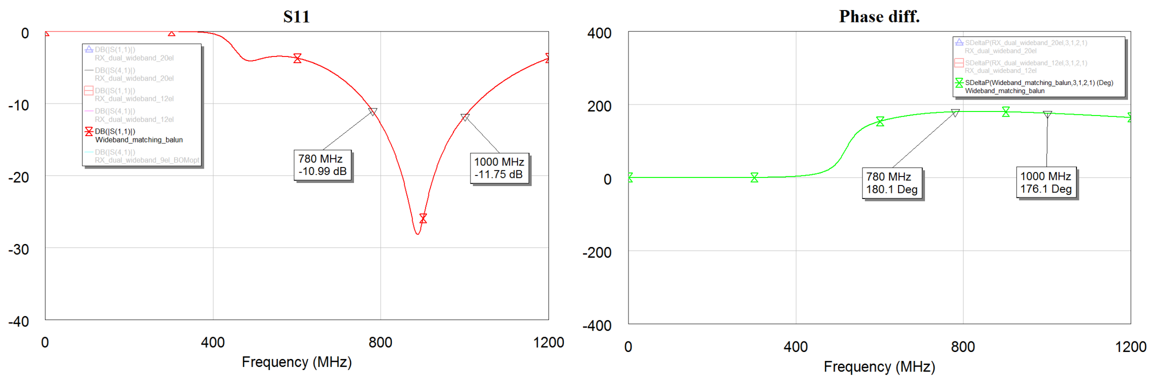

Figure 8.4. Simulated S11 and Phase Difference of High-Band Wideband RX-Only Matching Balun

8.1.2 Step 2: Unify the separate wideband matches for dual-wideband operation

Based on the dual-band and wideband matching solutions, the dual-wideband matching topology can be put together, by calculating the two separate single wide-band matching component values for both low- and high-frequency bands + replacing each component with a proper 3-element resonator to show the different required element values for the given components in the matching circuit. Excluding the first parallel component between the differential RF ports of the radio chip in the separate wideband matching balun networks shown in Figures 8.1 and 8.3, the matching network structure is the same and each component can be replaced with a proper 3-element resonator. That first parallel component exception is a capacitor for the low-band while an inductor for the high-band matching balun circuit. Given this, a series LC load needs to be applied in the dual-wideband matching balun structure to have the proper frequency response required separately in the low- and high-bands.

The figure below shows the 20-element, ideal dual-wideband matching balun circuit. The series LC load in red in the figure is an exception, so this part does not use a 3-element resonator, since the required single component here for the one-band operation is different in the two bands (capacitor in low-band, but inductor in high-band) as it can be seen in the previous section. This is the case at around these sub-GHz frequency regions and impedance conditions (mentioned in section 1, 50 ohms to ~500 ohms). However, if it was the case (due to specific frequency and impedance conditions, for instance) that both low- and high-band solutions required the same component (capacitor or inductor), then it would also use a 3-element resonator in the place of that series LC load in red in the figure below – which would finally result a 21-element dual-wideband balun circuit. The circuit part in green is using the differential-to-differential match based on the Youla impedance matching method between the impedances of 500 and 125 ohms, and the series inductors are replaced by 3-element resonators to make the proper matching in the low- and high-bands as well. The purple part of the match is the 12-element dual-band balun (as shown in an earlier section) between the impedances of 125 and 50 ohms.

When replacing the components by 3-element resonators, both type of the resonators can be utilized for both capacitor and inductor component as shown in Figure 5.1 Frequency-Dependent 3-Element Resonators on page 19.

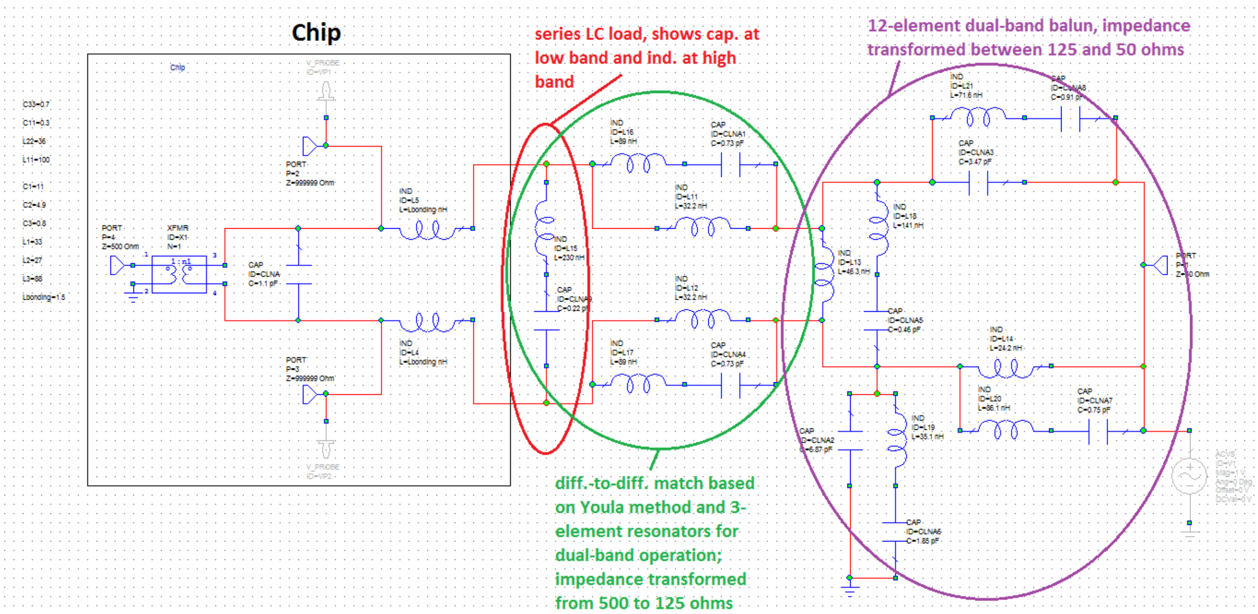

Figure 8.5. 20-Element Dual-Wideband RX-Only Matching Balun Network

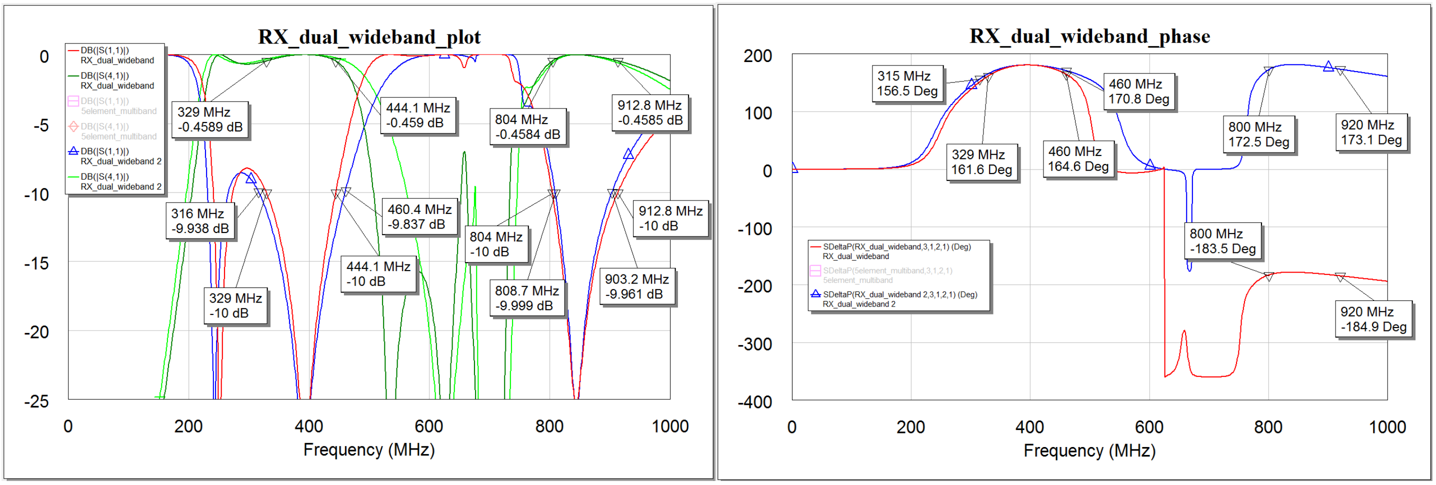

Figure 8.6. Simulated S11 and Phase Difference of 20-Element Dual-Wideband RX-Only Matching Balun

8.1.3 Step 3: BOM optimization

The 20-element dual-wideband balun shown above can be simplified and the required BOM count can be reduced while keeping an acceptable level of performance. Here is the list below about the possible BOM-reduced solutions (it can be applied on the 20-element circuit in any combination of these below):

- The purple section of circuit, i.e. 12-element dual-band balun part, can be reduced to use 10, 8 or 6 elements as the dual-band balun variants, as discussed in an earlier section. This part of the schematic can also be replaced with a wideband coil balun.
- The purple section of circuit, i.e. 12-element dual-band balun part, can even be reduced to use the standard 4-element (as shown in Figure 1.1) or 3-element (shown later below, or in AN643, for instance) discrete matching balun circuit.
- The series LC load in red can also entirely be eliminated from the design with some acceptable compromise in performance.

The figure below shows a BOM-reduced dual-wideband matching balun circuit, where the 12-element dual-band balun part is replaced by a 6-element dual-band balun but the other parts are kept as shown in the schematic of 20-element dual-wideband balun variant. This gives a 14-element dual-wideband balun circuit, for instance.

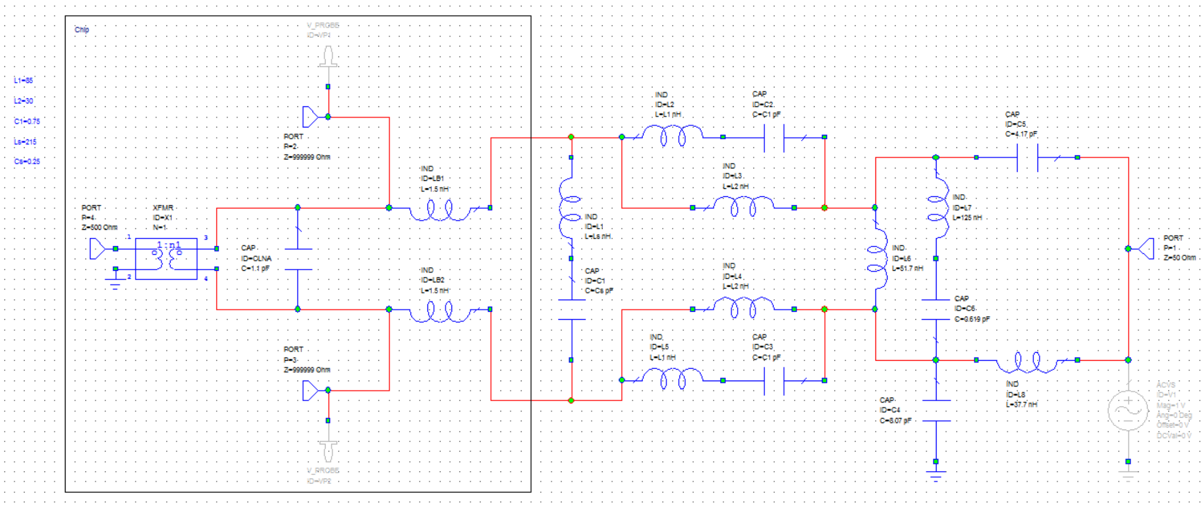

Figure 8.7. 14-Element Dual-Wideband RX-Only Matching Balun Network

The next figure below shows the most BOM-optimized dual-wideband matching balun circuit, where the 12-element dual-band balun part is replaced by a standard 3-element balun, the series LC load is eliminated, while the 3-element resonators are kept for the series inductors in the differential matching part as shown in the schematic of 20-element dual-wideband balun variant (circled by green), but with the other type of 3-element resonator for the inductor being used since this type apparently had more robust component values under our sub-GHz frequency and impedance load conditions, and also the series bonding wire and PCB trace inductance can more easily be compensated by this structure. This finally yields a 9-element dual-wideband balun circuit.

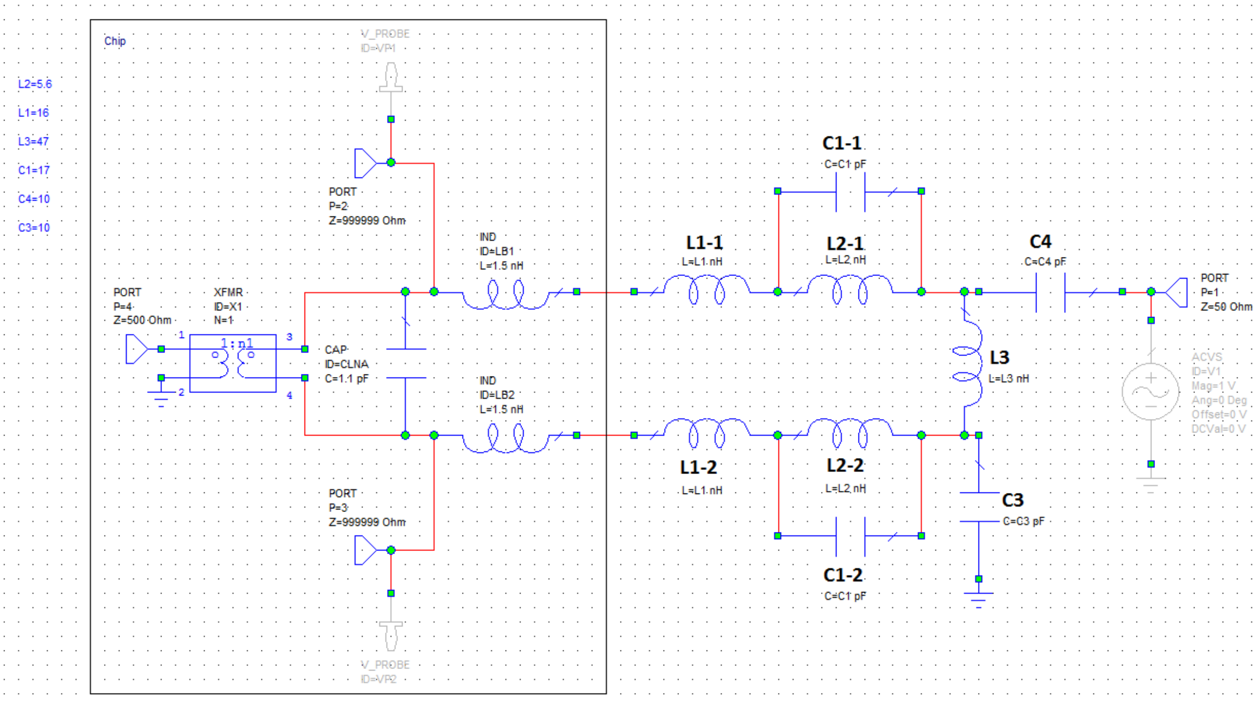

Figure 8.8. BOM-Optimized 9-element Dual-Wideband RX-Only Matching Balun Network

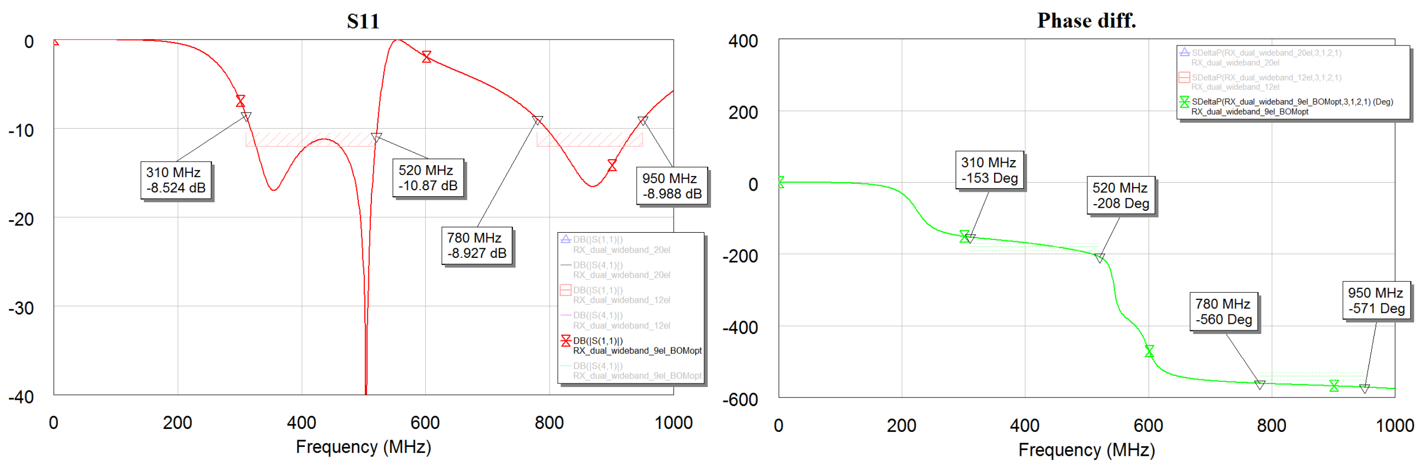

Figure 8.9. Simulated S11 and Phase Difference of 9-Element Dual-Wideband RX-Only Matching Balun

The design steps of the discrete dual-wideband matching balun network have been shown in this section above and demonstrated with the RX-only part of the match. For TX implementations the same schematic structure can be applied but with different component values due to the different load impedance conditions. During the BOM optimization and simulation it also turned out that the best performer of TX design variants is the 10-element dual-wideband matching balun which contains of an additional inductor between the 50-ohm single-ended port and the common port of components L3 and C3 in Figure 8.8 (i.e., the last purple section of the 20-element dual-wideband matching balun is replaced by a standard 4-element matching balun network). Also, the 3-element inductor-type resonator in the differential part of the match uses the dual representation compared to what is used in the RX dual-wideband match, since it yields better performance over component spreading on the TX-side matching path, confirmed by circuit simulations.

8.2 Recommended Schematic Structure of Discrete Dual-Wideband Matching Balun Network

The figure below shows the recommended schematic structure for both 9-element RX and 10-element TX dual-wideband matching balun circuits (CC1 and CC2 components are RF bypass capacitors). Since this solution is not available in direct-tie configuration Silicon Labs recommends utilizing it in split topology or with RF switch. This example shown below utilizes an DPDT RF switch, where the dual-wideband TX and RX matching networks are placed between the EFR32 and RF switch, while after the RF switch to the antenna port separate LPF sections can be mounted to separate the RF paths in frequency and ensure the desired harmonic suppression performance.

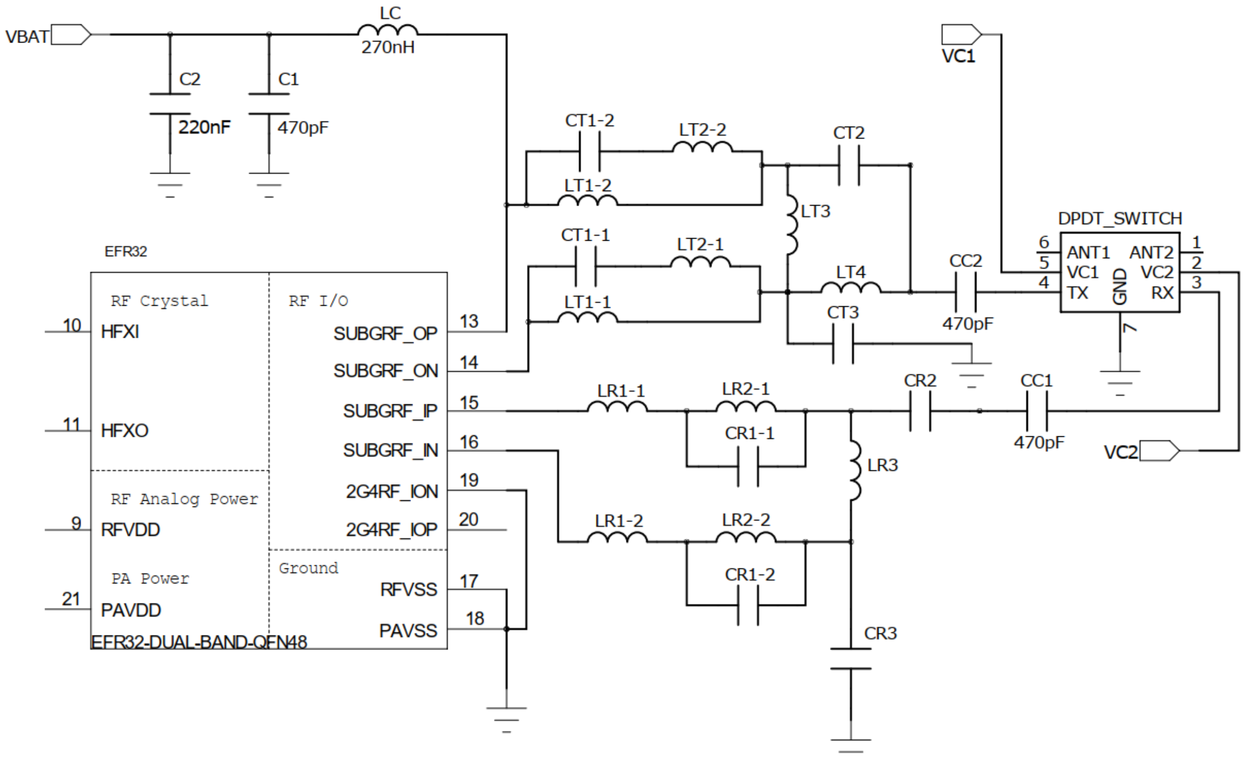

Figure 8.10. Recommended 9-Element RX and 10-Element TX Dual-Wideband Matching Balun Networks

8.3 Recommended Component Values and Measurement Results

The recommended component values are shown in Table 8.1 below for both 9-element RX and 10-element TX dual-wideband matching balun networks for the frequency band coverage of 315 – 510 and 780 – 930 MHz.

LR1= LR1-1= LR1-2; LR2= LR2-1= LR2-2; CR1= CR1-1= CR1-2; LT1= LT1-1= LT1-2; LT2= LT2-1= LT2-2; CT1= CT1-1= CT1-2.

Table 8.1. Recommended Component Values

LR1	LR2	LR3	CR1	CR2	CR3	LT1	LT2	LT3	LT4	CT1	CT2	CT3
20 nH	4.3 nH	51 nH	18 pF	15 pF	5.1 pF	5.6nH	37 nH	43 nH	24 nH	1.8 pF	6.8 pF	18 pF

The measurement results are summarized in the following table below for both TX and RX matching paths. Each RF paths have been measured at the single-ended 50-ohm point of the dual-wideband discrete matching balun networks without any additional LPF section placed after them.

Table 8.2. Measurement Results

Frequency [MHz]	315	390	434	460	490	510	780	830	868	915	930	950
TXP [dBm]	21.2	20.5	20.3	20.0	19.7	19.3	18.6	18.9	19.1	19.0	18.9	18.9
Sensitivity [dBm]	-107.2	-107.3	-106.6	-106.8	-107.2	-106.5	-104.3	-105.8	-106.3	-105.5	-105.2	-104.8
Note: Modulation settings: 2-FSK, DR=100 kbps, Dev=50 kHz. Sensitivity level at BER<1%. SMD 0402 wire-wound inductors used on 4-layer PCB. Measured on Silicon Labs' EVB.												

The figure below shows the measured input impedance of the discrete dual-wideband RX matching network with EFR32 Series 1.

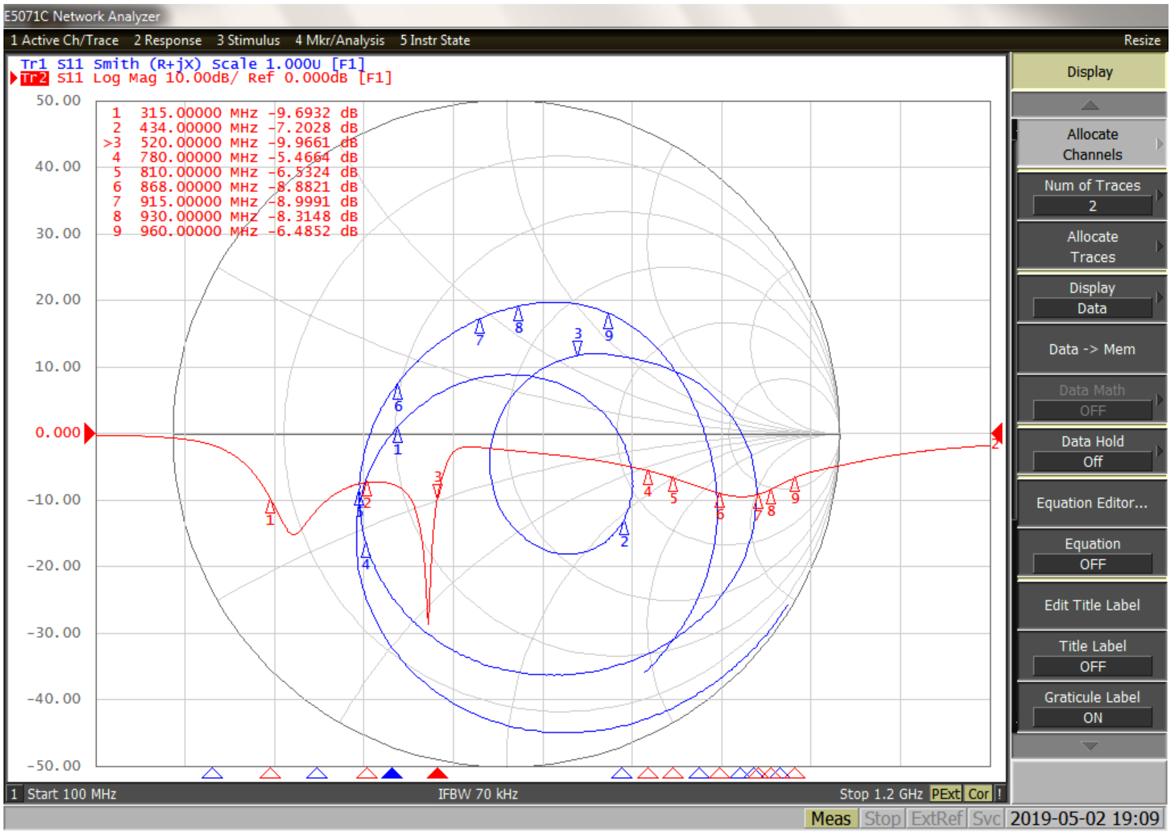

Figure 8.11. Measured Input Impedance of 9-Element Dual-Wideband RX-Only Matching Balun

8.4 Tuning Guidance of the Dual-Wideband Matching Balun

The tuning of the dual-wideband matching balun network can be necessary for several reasons, such as different frequency bands desired, different component type (especially for inductors) applied in the circuit, layout drawing differences. This section provides some in-sights on how to be able to tune the 9- and 10-element dual-wideband matching balun networks.

Component	Tuning Effects Description
LR1	Rapidly tunes the full upper wideband region
LR2	Rapidly tunes mainly the higher frequencies of the lower wideband region
LR3	Rapidly tunes mainly the lower frequencies of the lower wideband region
CR1	Tunes the higher frequencies of the lower wideband and full upper wideband regions
CR2	Tunes both full wideband regions
CR3	Tunes the lower frequencies of the lower wideband and full upper wideband regions
LT1	Tunes both wideband regions but tunes faster the full upper wideband region
LT2	Affects mainly the higher frequencies of the lower wideband region and the lower frequencies of the upper wideband region
LT3	Tunes mainly the full lower wideband region
LT4	Tunes both full wideband regions mainly in impedance level
CT1	Tunes both full wideband regions mainly in frequency
CT2	Tunes both full wideband regions mainly in impedance level in an opposite way in the lower and upper wideband regions
CT3	Tunes both full wideband regions mainly in impedance level

8.5 Summary of the Dual-Wideband Matching Network

- BOM-optimized, cost-effective simple network design
  - Apply (from 20 down to) only 9 external SMD discrete components
  - No tunable or variable components required
  - Apply only 1 RF branch for the dual-wideband operation
- Three wide-band resonances composed by the network
  - Tunable by modifying the component values
- Robust component values
  - Fairly immune against component spreading and/or PCB parasitics
  - And thus, small board-to-board variation in performance
- Good TX/RX performance across the entire frequency bands
  - As a maximum of 2 dB performance hit measured with EFR32 Series 1 compared to the single-band optimum values
- In comparison with other presented dual-, multi- or wideband matching solutions:
  - Much wider frequency bandwidths in both bands compared to the dual-band balun design
  - Dual band operation of the single wideband balun design
  - Phase error improved and frequency bandwidth increased (but with slightly higher BOM) competitor of the multi-band balun

9. Layout Suggestions and Design Files

It is generally recommended to follow the generic RF layout design guidelines, as documented in several application notes available at www.silabs.com: AN629, AN910, and AN928.

The resonator load circuit mounted right after the RF chip is one of the most sensitive parts of the matching network, so it is strongly recommended to place the matching components close to the RF chip pins and to each other in order to avoid any de-tuning effects and thus performance degradation (e.g., minimize the trace lengths between the RF chip and matching components).

The design package, including schematics, BOM, layout CAD and Gerbers file, is available. See the links listed below to download the zipped packages of the virtual (i.e., non-orderable) reference design files:

- Single-band match: https://www.silabs.com/documents/public/schematic-files/EFR32xG1x_DISC_REF_DES_A00.zip
- Wideband match: https://www.silabs.com/documents/public/schematic-files/EFR32xG1x_DISC_WIDEBAND_REF_DES_A00.zip
- Dual-band match: https://www.silabs.com/documents/public/schematic-files/EFR32xG1x_DISC_DUALBAND_REF_DES_A00.zip
- Multi-band match: https://www.silabs.com/documents/public/schematic-files/EFR32xG1x_DISC_MULTIBAND_REF_DES_A00.zip
- Dual-wideband match: https://www.silabs.com/documents/public/schematic-files/EFR32xG1x_DISC_DUAL-WIDEBAND_REF_DES_A00.zip

10. Appendix: Multi-Band RX Matching Balun Network for Si4x6x

This section provides an additional example for the 5-element multi-band matching balun when it is applied with the EZRadioPRO Si4x6x chip family. The required impedance transformation from 50 ohms to the high-impedance differential load is lower since the Si4x6x RF chips have lower LNA input impedance compared to the EFR32 Series 1 chip family. Therefore, the Q of the matching network will be lower and thus the impedance bandwidth will be larger when utilizing the same-structured matching network with the Si4x6x chip family, but of course, with different tuned component values.

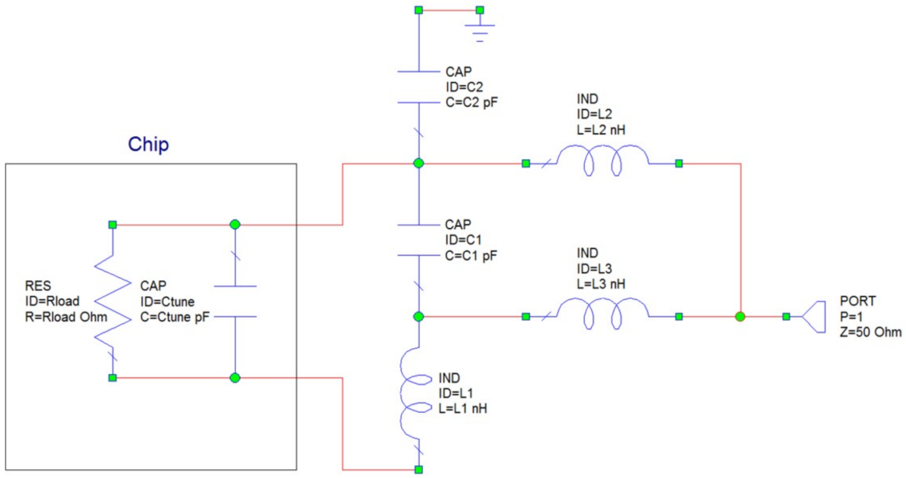

Figure 10.1. 5-Element Multi-Band Matching Balun

10.1 Simulation and Measured S11 Results of Multi-Band RX Matching Balun Network for Si4x6x

The S11 simulation result of the 5-element multi-band RX matching balun network applied with EZRadioPRO Si4x6x radios is shown in the figure below. The three resonances of the network are clearly shown on the plot. Due to the lower RX impedance of Si4x6x, the matching can be done in a wider BW.

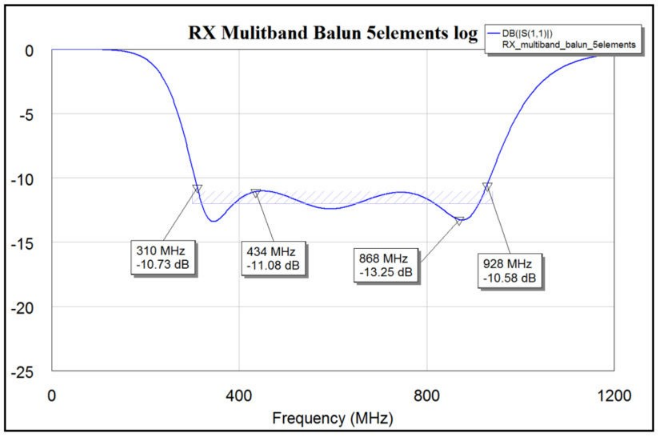

Figure 10.2. Simulated S11 of 5-Element Multi-Band Matching Balun Network for Si4x6x

The measured S11 of the 5-element multi-band balun network with Si4x6x is shown in the following figure.

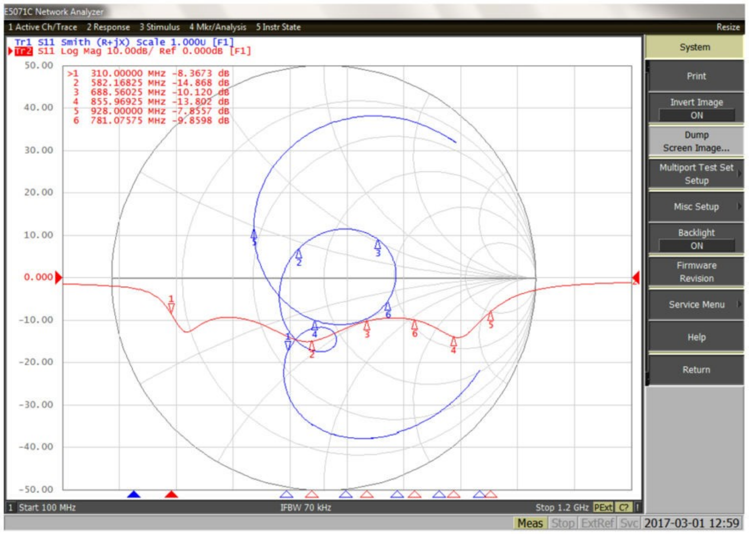

Figure 10.3. Measured S11 of 5-Element RX Multi-Band Si4x6x Matching Balun Network

10.2 Recommended Multi-Band RX Matching Network for Si4x6x

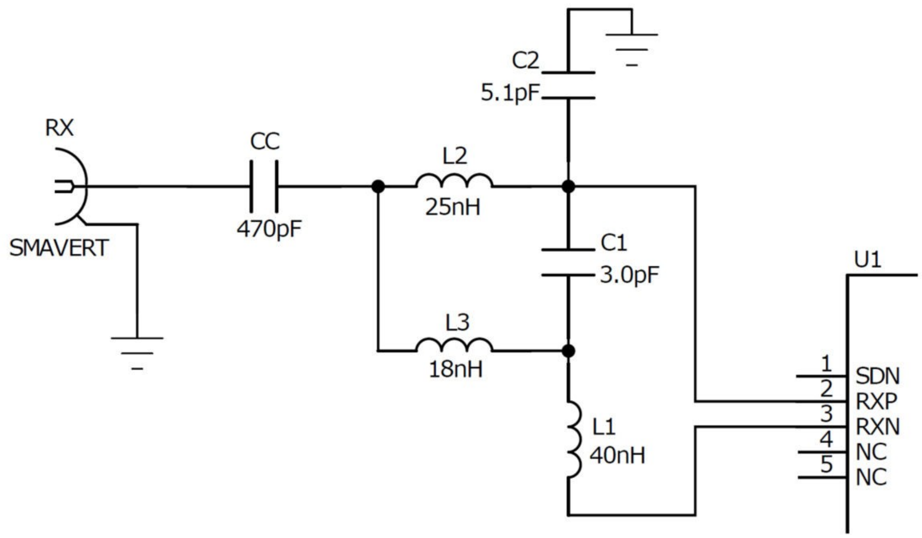

Figure 10.4. Recommended 5-Element Multi-Band RX Matching Schematic for Si4x6x

10.3 Measured Performance Results Vs. Component Values with Si4x6x

Component Values					Sensitivities (dBm) at Different Frequencies (MHz)				
L1 (nH)	L2 (nH)	L3 (nH)	C1 (pF)	C2 (pF)	315	390	434	868	915
40	25	18	3	5.1	-104.5	-103.5	-103.6	-106	-104.5
Note: Modulation settings: 2-FSK, DR=100 kbps, Dev=50 kHz. Sensitivity level at BER<1%. SMD 0402 wire-wound inductors used on 4-layer PCB. Measured on Silicon Labs' EVB.									

11. References

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8. AN629: https://www.silabs.com/documents/public/application-notes/AN629.pdf
9. AN928: https://www.silabs.com/documents/public/application-notes/an928.1-efr32-series1-layout-design-guide.pdf

12. Revision History

Revision 0.4

June, 2022

- Added 610 MHz single-band discrete matching network.

Revision 0.3

November, 2020

- Added download links for the associated virtual reference design packages.

Revision 0.2

September, 2020

- Renamed the application note to AN1180: EFR32 Series 1 sub-GHz Discrete Matching Solutions.
- Added the discrete single-band, wideband and dual-wideband matches.
- Made the application note public.

Revision 0.1

November, 2018

- Initial release of AN1180 NDA application note including the dual- and multi-band matching solutions.

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