CC11xx 868/915 MHz RF Matching

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Keywords

- *Balun*
- *Reference design*
- *RF matching*
- *Impedance*
- *Filter*
- *CC1100*
- *CC1101*
- *CC1110*
- *CC1111*
- *CC1150*

1 Introduction

The CC11xx family consist of 5 different products; CC1100, CC1101, CC1110, CC1111 and CC1150. CC1100, CC1101, CC1110 and CC1111 are using the same RF front end. CC1150 has only the transmitter part implemented.

This design note gives a short introduction to RF matching and important aspects when designing products using the CC11xx parts. Since all the CC11xx parts have the same RF front end, the same matching network can be used between the radio and the antenna. Texas Instruments provides a reference design for all CC11xx products. These reference designs show recommended placement and values for decoupling capacitors and components in the matching network.

Three versions of the CC11xx reference design have been published and differences between these designs are described in this document.

The 868/915 MHz reference designs are designed to fulfil the ETSI EN300 220 and FCC part 15.247/15.249 requirements for operation in the European 863 – 870 MHz SRD band and the US 902 - 928 MHz ISM band respectively.

ETSI requires measurements of conducted spurious emission if an antenna connector is used. Conducted measurements with CC1101 [1] and CC1110 [2] reference designs have shown spurious emission close to 699 MHz in transmit mode. The amplitude level of this spurious emission is close to the ETSI EN 300 220 limit. This design note describes the implementation of a filter designed to attenuate this spur below the ETSI requirement.

Above 1 GHz FCC allows higher level of spurious emission if duty cycling is being used. If CC11xx is configured for maximum output power and the CC11xx reference design is used, duty cycling must be utilized when transmitting to comply with FCC requirements. Chapter 5 describes a solution which allows 100 % duty cycle and compliance with FCC when transmitting at maximum output power. Project collateral discussed in this design note can be downloaded from the following URL: http://www.ti.com/lit/zip/SWRA168.

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2 Abbreviations

AF	Averaging Factor
CC11xx	CC1100, CC1101, CC1110, CC1111 and CC1150
EM	Evaluation module
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FH	Frequency Hopping
ML	Multi Layer
PA	Power Amplifier
PCB	Printed Circuit Board
RBW	Resolution Bandwidth
RF	Radio Frequency
SE	Single Ended
SMD	Surface Mounted Device
WW	Wire Wound

3 Filterbalun Design Principles

The word filterbalun is in this document used to describe all the components necessary to implement a balun, filter and to ensure proper impedance matching between the radio and the antenna. A balun is a network that transforms from a balanced to an unbalance signal, hence the name balun. Figure 1 shows the recommended filterbalun schematic for operation at 868/915 MHz. A different topology and different component values are recommended for operation at 315 and 433 MHz. Even if this document describes the 868/915 MHz filterbalun in detail, the same principles applies to the 315 and 433 MHz filterbalun.

CC11xx has differential RF ports, RF_P and RF_N. According to the datasheet the optimum impedance seen from the chip towards the antenna is Z= 86.5 + j43 Ohm at 868/915 MHz. For each port this is equal to Z= 43 + j21.5 Ohm. The impedance at the antenna port is 50 Ohm. To transform the balanced output from the chip to a 50 Ohm unbalanced load, a balun is used together with matching components

3.1 Schematic and Layout Principles

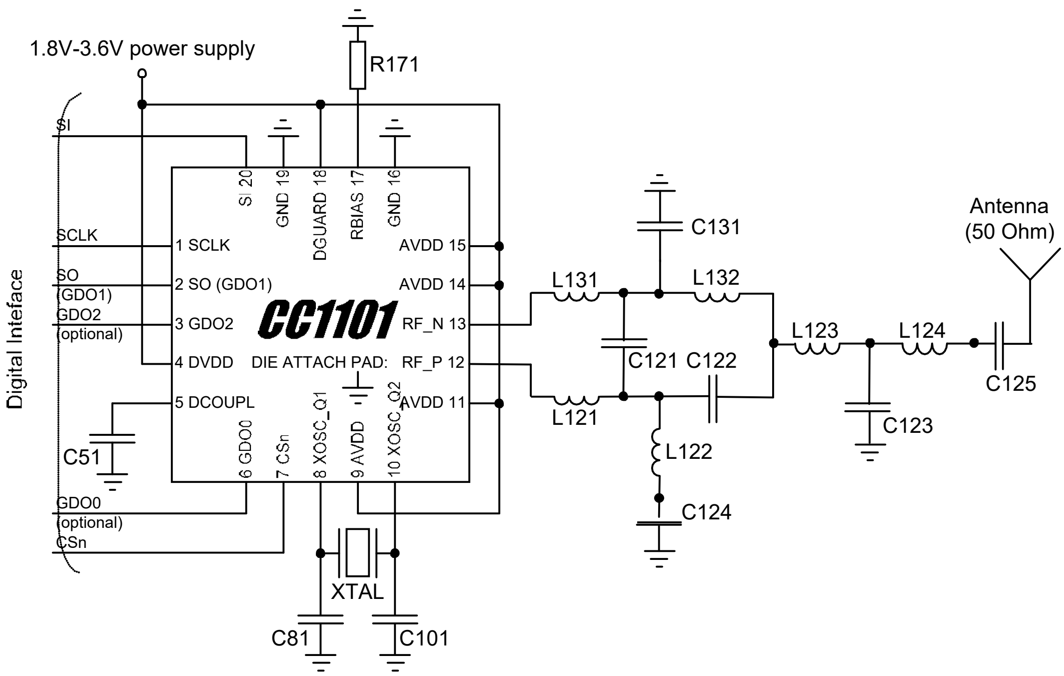

Figure 1. Schematic of 868/915 MHz Filterbalun

In TX mode the filterbalun has the following purposes:

- Provide optimum matching for lowest possible current consumption and highest possible output power.
- Fulfil ETSI (Europe) and FCC (US) regulations in terms of harmonics and spurious emissions.

In RX mode the filterbalun has the following purpose:

- Provide optimum matching for best possible sensitivity.

Basically the filterbalun can be functionally divided in different parts.

- Differential low pass filter: L121, L131 and C121
- Balun: L122, L132, C131 and C122
- Single ended low pass filter: L123, L124 and C123
- DC-block: C124 and C125

TI provides a separate reference design for all CC11xx products. The naming of the components in the filterbalun differs between the different reference designs, but the recommended values of the filterbalun components are the same for all the CC11xx products. Note that the recommended values of decoupling capacitors might be different for the different CC11xx products. All component values are provided in the reference designs which can be downloaded at http://www.ti.com/lpw.

An ideal output signal from the CC11xx products in TX mode is a square wave signal at the RF_P and RF_N pins and a sine wave at the antenna port. To achieve this, the filterbalun must reflect the harmonics back towards the RF_P and RF_N ports. The shape of the square wave pulse depends on the impedance at the different harmonics. Preferably the odd harmonics should be reflected back towards the chip with high real part of the impedance. The current consumption in TX depends on the shape of the signal at RF_P and RF_N. Lowest possible current consumption is achieved by having the odd harmonics (3rd and 5th) reflected back as described above. Unexpected high current consumption in a design may be caused by incorrect or missing reflection of harmonics. The simplest way of reflecting the harmonics towards the chip is to have a differential low pass filter between the CC11xx and the balun. Ideally the series inductors, L121 and L131, will reflect harmonics towards the chips with high real part of the impedance. The low pass filter will also lower the harmonics level into the balun and reducing the risk of having unwanted radiated power through the balun and the single ended filter.

The balun has a ±90 degrees phase shift implemented by using a low pass filter and a high pass filter. The important part is to keep the balun as symmetrical as possible. Therefore the trace length from the single ended port to each of the RF–pins should be equal to achieve best amplitude and phase balance in the balun. An unbalance in the balun causes higher harmonic level, especially at the 2nd and 4th harmonic. Another effect of having an unsymmetrical balun is reduced output power at the single ended side of the balun. Both component values and component placement is important to achieve best possible symmetry in the balun.

The single ended low pass filter presented in figure 1 is dimensioned to fulfil the ETSI requirement of harmonic emission below -30 dBm. It is recommended to use a T-type filter instead of a Pi-type filter due to unwanted radiated emission through the shunt capacitors. The filterbalun is also dimensioned to have 50 Ohm impedance between the balun and the single ended low pass filter. That means the single ended low pass filter has 50 Ohm impedance at both sides and can easily be removed or redesigned to fulfil special requirements. The balun in the 315 and 433 MHz reference design are not matched to 50 Ohm, it is only the antenna output which is matched to 50 Ohm in these designs.

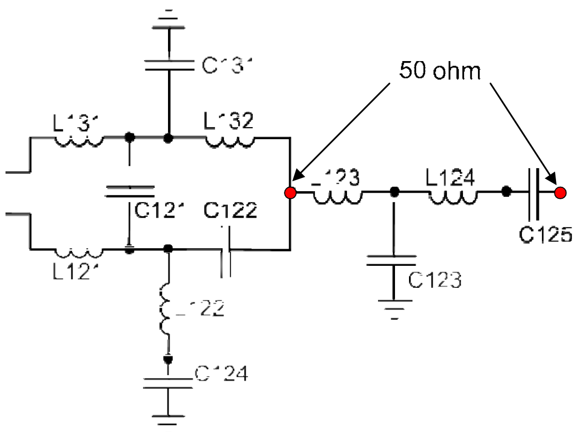

Figure 2. 50 Ohm Points in the Filterbalun

A 50 Ohm single ended solution makes it suitable for adding an external PA, LNA or SAW filter. Switches could be placed in the two 50 Ohm points shown in Figure 2 and a PA matched to 50 Ohm could be implemented in the TX path after the filter as shown in Figure 3. Note that the implementation of an external PA most likely requires additional filtering after the PA to ensure compliance with regulatory requirements.

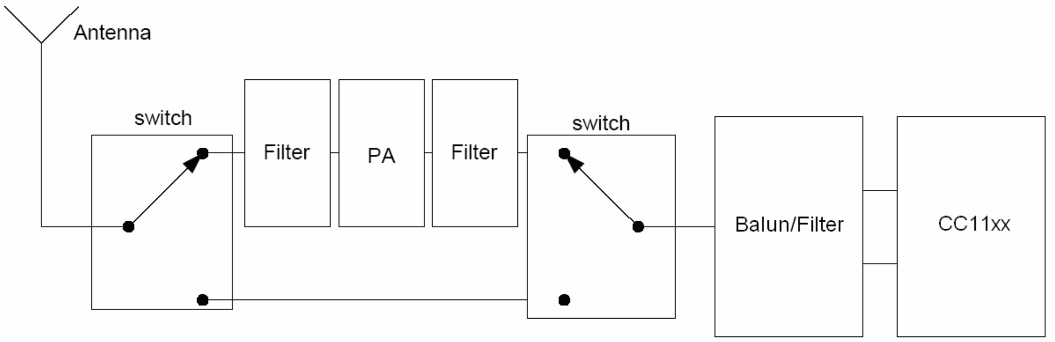

Figure 3. Implementation of External PA

In designs that only have an antenna without SMA connector and the antenna has no connection to ground, the DC-block component C125 can be skipped. The essential part is that the RF output from the chip has no DC-connection to ground.

All CC11xx chips are characterized on a reference design using multilayer type SMD inductors. These reference designs can be downloaded from http://www.ti.com/lpw and contains description of component types and values. Approximately 2 dB higher output power and reduction of harmonic emission, above 5 GHz, with more than 10 dB can be achieved by replacing the Multi Layer (ML) type inductors with Wire Wound (WW) inductors. The tradeoff is that WW inductors are more expensive than ML. See section 5 for more information about how the inductor type affects the performance.

Component placements should be done according to reference design. Deviation in the symmetrical filter and balun may cause reduced output power, higher harmonics level, higher TX current consumption and reduced sensitivity. The layout of the single ended filter towards the antenna is not that critical as long as the impedance is approximately 50 Ohm. A solid ground plane should be implemented beneath the RF circuitry. It is recommended that the distance between layer 1, having the RF circuitry, and ground is around 0.8-1.0 mm. Shorter or longer distance may degrade the performance since it will influence the impedance of the traces in the filterbalun. Changing the thickness of the board will also change the inductance of the vias. A change of inductance in series with the decoupling capacitors could affect the performance. The reference design is implemented on a FR4 substrate and it is recommended to use the same type since the substrate will affect the impedance of the PCB traces. If a different substrate type or board thickness are used it might be necessary to tune the value of the filterbalun components to achieve the optimum performance.

Vias should be placed close to all decoupling capacitors to ensure a good connection to the solid ground plane below. The CC11xx reference designs uses 0402 components. Using 0603 component size instead of 0402, the components must be placed as close to each other as possible and with the same layout as in the CC11xx reference designs. The suppression of harmonics may differ from a 0402 solution due to component parasitics. Components from different vendors have slightly different performance. Inductors and capacitors from Murata are used in the CC11xx reference design. Thus, using components from different vendors or different component size than in the reference design might require additional tuning of component values to achieve optimum performance and sufficient suppression of harmonics.

The optimum impedance for RX and TX is slightly different on the CC11xx products. CC1150 is a pure transmitter and has no receiver capabilities. It is therefore possible to achieve around 1 dB higher output power by tuning the filters, but the current consumption will increase with approximately 3 mA. Tuning for maximum output power will increase the return loss at the antenna input and will therefore reduce the sensitivity for the transceivers.

3.2 Simulation Results

The results presented in this chapter are based on simulation of PCB layout and component models. The PCB layout is electromagnetic (EM) simulated using IE3D from Zeland. The advantage of using an EM simulator is that PCB effects such as trace length, width, pads, grounding and coupling will be taking into account. The SMD components are represented by s-parameters which are provided by the component vendor. The layout model and components are joint-simulated in a linear s-parameter simulator, Microwave Office (MWO-100). Since this simulation setup gives a more realistic representation of the filterbalun, the result will differ from an ideal simulation using only the ideal component values. A zip file with s-parameters describing the CC11xx 868/915 MHz filterbalun can be downloaded from the web [3]. A readme file which describes how to interpret the s-parameters is included in this zip file.

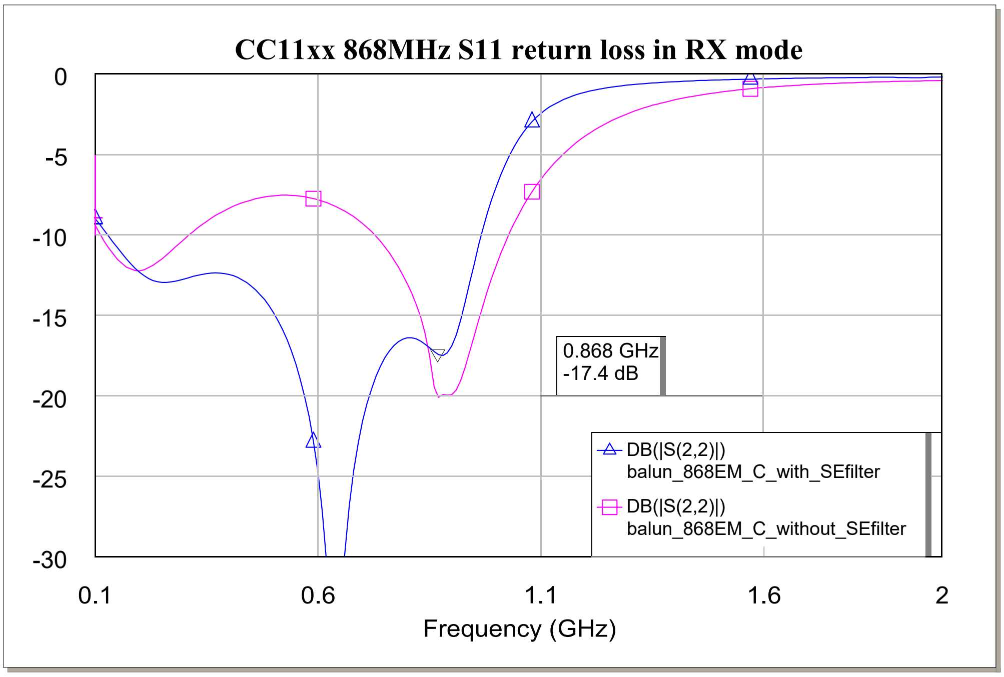

Figure 4. Return Loss at the Antenna Port

Figure 4 shows the Return Loss (RL) at the antenna port. A low RL in the frequency band of operation is important to achieve good sensitivity. The blue trace (balun_868EM_C_with_SEfilter) is the simulation results of the filterbalun, shown in Figure 1. The pink trace (balun_868EM_C_without_SEfilter) is a similar simulation where the single ended low pass filter is removed, see Figure 5. Both simulations show low and similar RL for the 868/915 MHz frequency band. This indicates that the impedance is very close to 50 Ohm at both sides of the single-ended filter.

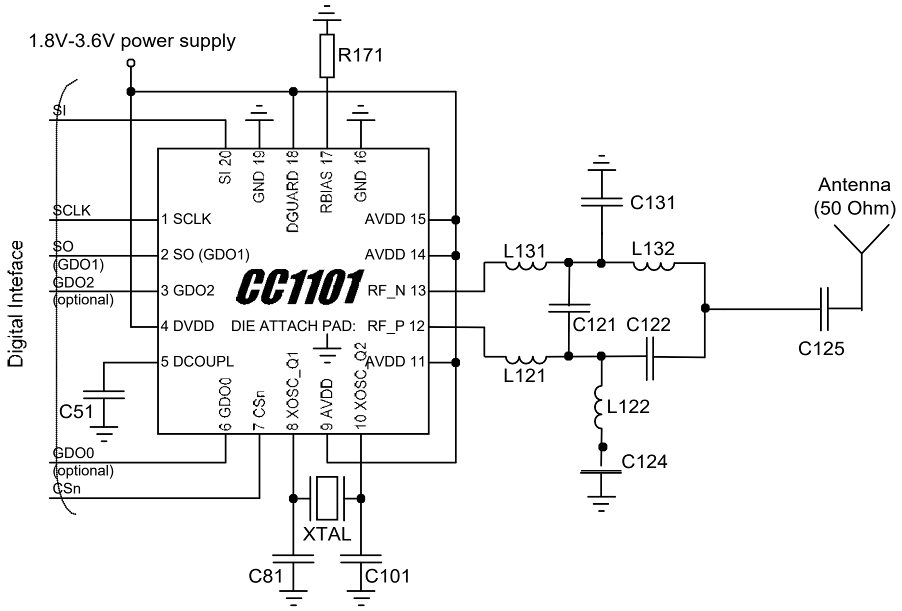

Figure 5. Schematic 868/915MHz without Single-Ended Filter

Figure 6 shows the insertion loss for the filterbalun with and without single-ended low pass filter. The red trace, which is the simulation results of the filterbalun without the single-ended low pass filter, has 0.35 dB lower loss compared to the filterbalun with the single ended low pass filter (black trace). This shows that the design is closely matched to 50 Ohm at both sides of the filter. Figure 6 also show how the filter attenuates signals above 1 GHz.

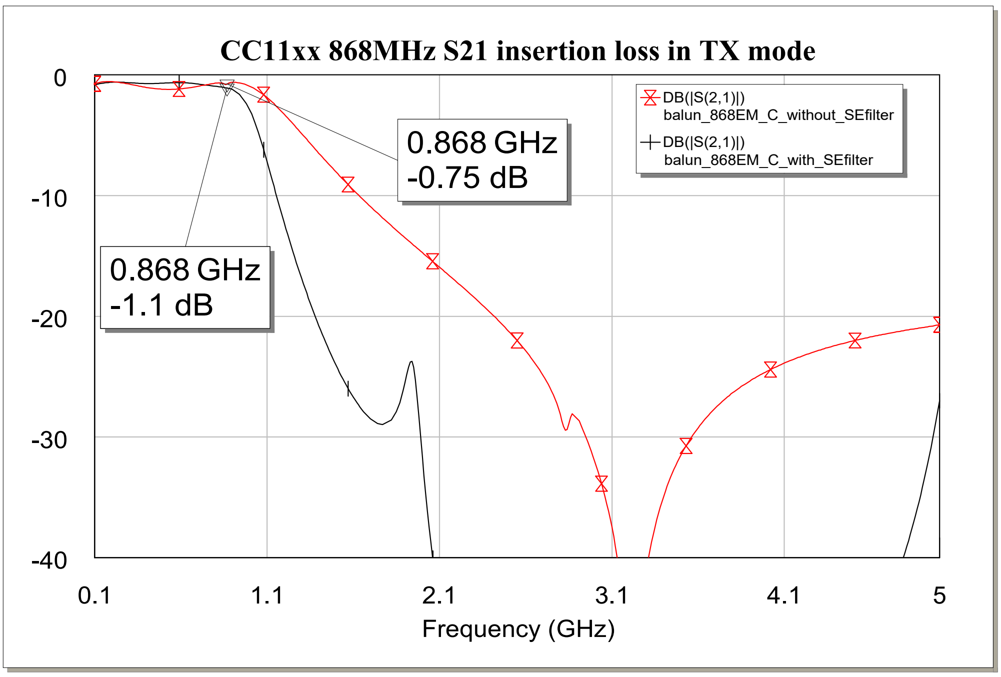

Figure 6. Insertion Loss

Figure 7 and Figure 8 shows the amplitude and phase of the differential output signal respectively. The simulation is performed by applying a signal to the single ended port, port 2, and plotting the amplitude and phase at the differential ports, port 1 and 3. At 868 MHz the simulated amplitude difference is 1.2 dB and the simulated phase difference is 187.5°.

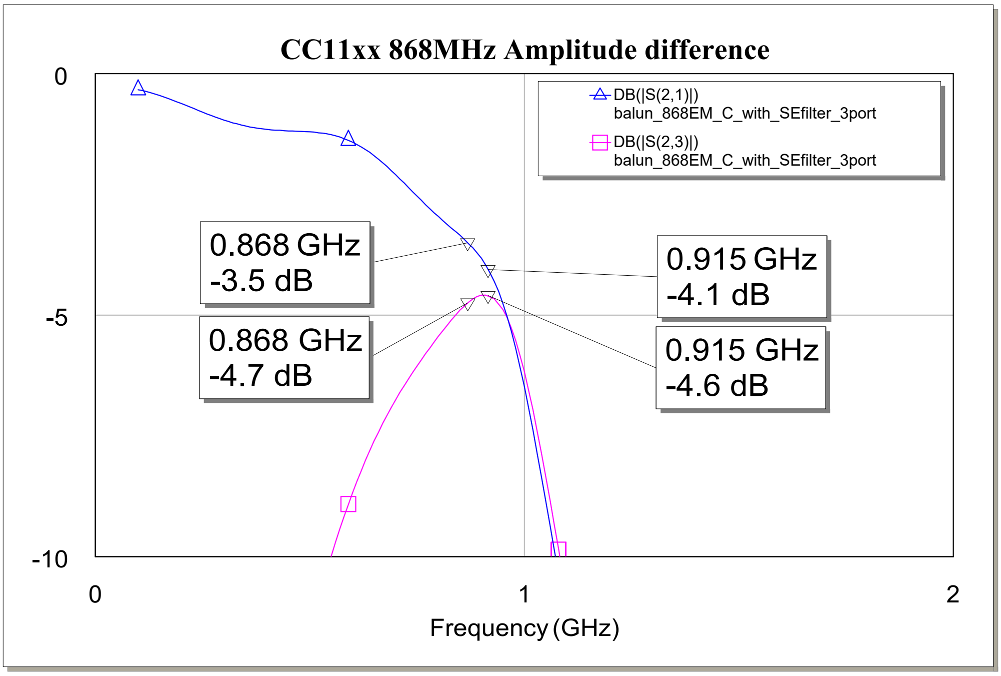

Figure 7. Amplitude Difference

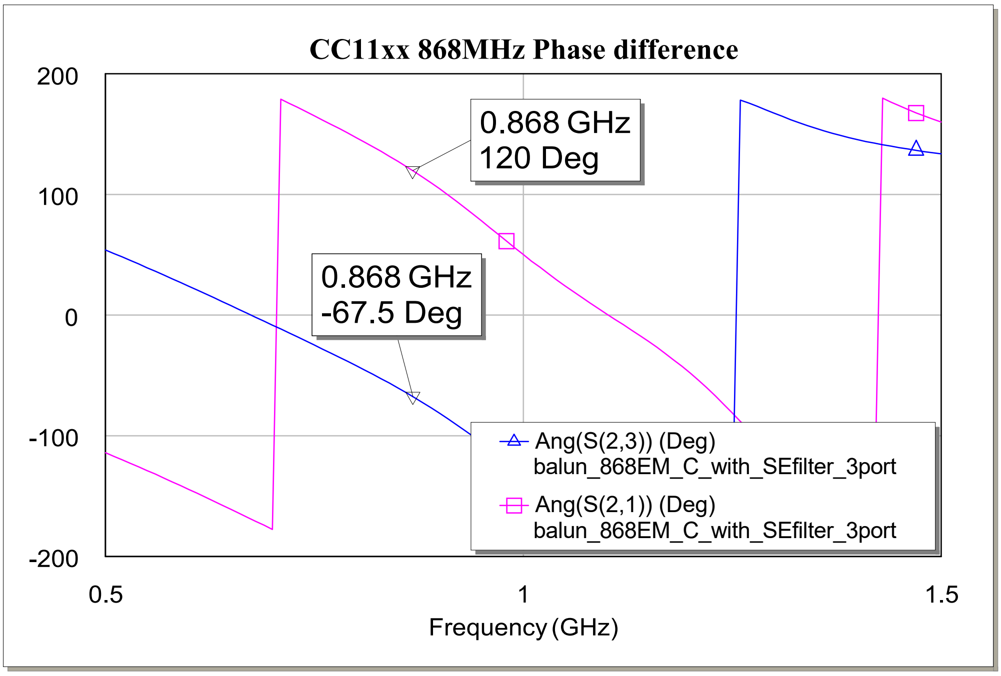

Figure 8. Phase Difference

3.3 CC11xx Reference Design History

Three different versions of the reference design have been published, see Figure 9, Figure 10 and Figure 11. The first version had too high harmonic emission, mainly radiating from the PCB. Therefore the filtering was improved by adding inductors in series with the RF pins and a capacitor in parallel, see Figure 10. When CC11xx is programmed for output power levels between 3 and 7 dBm, the harmonic emission can be higher than when using the 10 dBm setting. To ensure compliance with ETSI when using the power settings between 3 and 7 dBm, an additional pole was added in the single-ended filter. This is shown in Figure 9. It is recommended to follow the newest reference design when making new designs because this gives the best attenuation of harmonic emission and the performance stated in the data sheet.

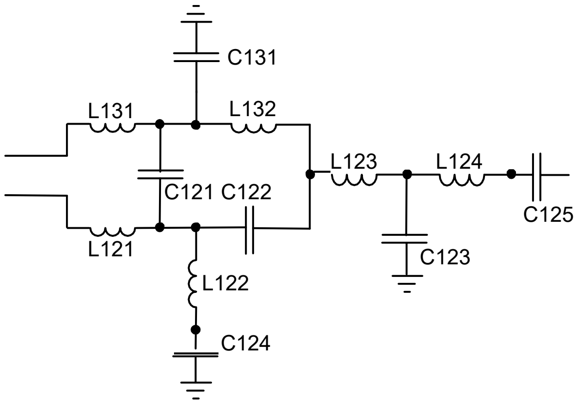

Figure 9. Newest Reference Design. Recommended

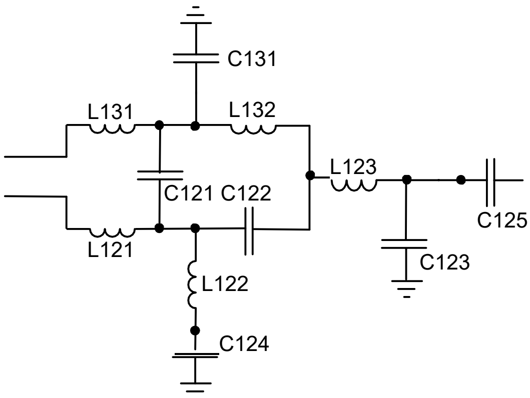

Figure 10. Second Version of the Reference Design. Not recommended

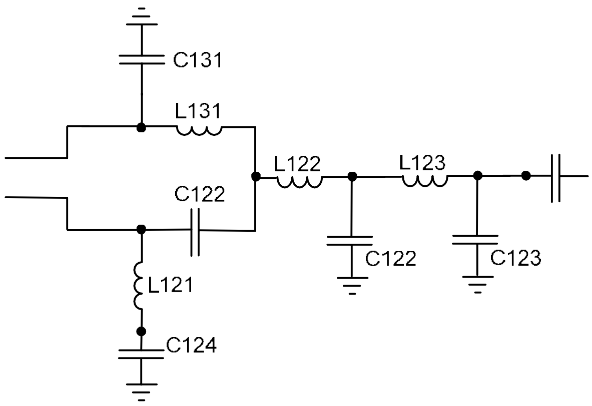

Figure 11. First Version of the Reference Design. Should not be used

4 Suppressing Spur at 699 MHz

To be allowed to sell a product intended for operation in the 868 MHz frequency band in Europe, compliance to EN 300 220 must be proven. EN 300 220 requires conducted measurements of spurious emission if the device uses an antenna connector. For devices using an integrated antenna, it is sufficient to perform radiated measurements of spurious emission. Conducted measurements of CC11xx show a spurious emission above -54 dBm at

699 MHz. This spurious emission shall be measured with the transmitter outputting an unmodulated carrier and a spectrum analyzer using quasi-peak detector and resolution bandwidth (RBW) of 100 kHz. At 699 MHz, EN 300 220 states that the spurious emission shall be below -54 dBm. To comply with this requirement a notch filter could be used. Implementation of such a filter is described in the next section.

4.1 699 MHz Notch Filter

The schematic for the notch filter is shown below in Figure 12 and requires only two additional components compared to the filterbalun in the CC11xx reference design. The recommended component values for the notch filter are listed in Table 1. The rest of the components should use the values found in the CC11xx reference design. For applications that do not use an antenna connector or doesn't require compliance with ETSI EN 300 220, the filter can be left out.

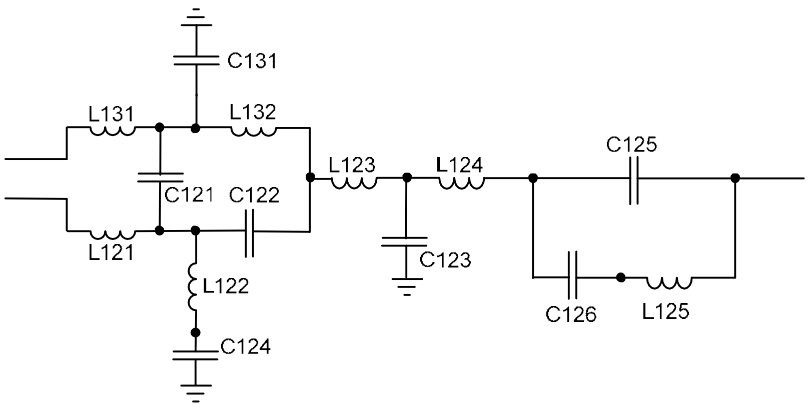

Figure 12. The Notch Filter Schematic

Component	Value
C125	12 pF
C126	47 pF
L125	3.3 nH

Table 1. Component Values for the Notch Filter

The layout of the notch filter is not critical. Figure 13 shows an example on how the filter could be implemented.

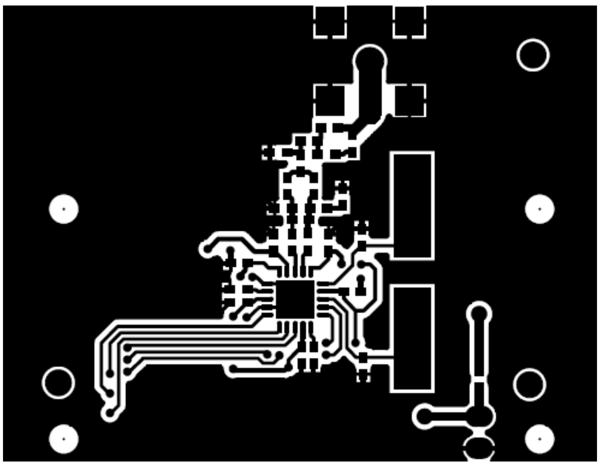

Figure 13. Layout of the Notch Filter

4.2 Measurement Results

Measurements with the notch filter have been performed with CC1101 and CC1110. Table 2 shows a comparison of the results from measurements with and without the notch filter. The measurements were performed on 3 samples at 3.0 V, 25°C and with 10 dBm output power (PA value 0xC2).

	CC1101		CC1110	
	Without filter	**With filter**	**Without filter**	**With filter**
Spurious emission at 699 MHz	-52.2 dBm	-57.3 dBm	-50.6 dBm	-57.1 dBm
Output power	10.5 dBm	9.9 dBm	10.6 dBm	9.4 dBm
TX current consumption	32.2 mA	30.2 mA	36.0 mA	33.5 mA
Sensitivity at 250 kbps	-93.4 dBm	-93.9 dBm	-92.4 dBm	-92.5 dBm

Table 2. Measurement Results

The ETSI limit for spurious emission at 699 MHz is -54 dBm. It can be seen from the measurements results that the filter can be used to obtain compliance with EN 300 220 for both the CC1101 and the CC1110. when using an antenna connector.

5 Inductor Types

The type of inductors being used in the filterbalun impacts the performance. There are mainly two types of inductors to choose from, Wire Wound inductors (WW) and ceramic Multi Layer (ML) inductors. ML inductors are cheaper than WW inductors. To achieve lowest possible BOM, ML inductors are being used on all CC11xx evaluation boards. WW inductors have less loss than ML and perform better at high frequencies, but the drawback is increased cost.

The choice of inductor type will affect the performance in terms of output power and sensitivity, but it will also affect the suppression of harmonic emission. Measurements have been performed to check how different inductor types affect the performance. The inductor types used in the testing described in section 5.1 and 5.2 are listed in Table 3. All testes were performed with conducted measurements on three samples at, 3.0 V, 915 MHz and with power setting 0xC0. Radiated measurements will be affected by the antenna, but will show a similar trend. Operation at 868 MHz will give similar results, but changing the power setting will affect the output power, current consumption and harmonic emission. See DN012 [4] and DN013 [5] for more information about output power programming of CC1100, CC1150 and CC1101.

Inductor Type	Manufacturer	Series	Tolerance
Multi Layer	Murata	LQG15H	± 5 %
Wire Wound	Murata	LQW15A	± 2 %

Table 3. Inductors Used for Testing

5.1 Performance

Since WW inductors have less loss than ML type there will be less loss in the filterbalun and thus higher output power and increased sensitivity. The increased output power will also result in a slight increase in the current consumption in transmit mode. Table 4 shows that it is possible to achieve more than 2 dB higher output power and approximately 1 dB improved sensitivity by using WW inductors.

	All inductors ML	All inductors WW
TX Current consumption	33.6 mA	35.0 mA
Output power	9.8 dBm	12.0 dBm
Sensitivity 250 kbps	-93.7 dBm	-94.6 dBm

Table 4. Measured Performance with WW Inductors

5.2 ETSI and FCC Compliance

WW inductors perform better than ML at high frequencies. By using WW instead of ML in the filterbalun is it therefore possible to achieve better suppression of harmonic emission. Figure 14 shows how the PA settings and inductor types affect the level of the harmonic emission. The numbers in Figure 14 and Table 5 are based on conducted measurements. Radiated results are listed in Table 6. These measurements were performed with the CC1101EM plugged in SmartRF04EB and with power setting 0xC2.

ETSI

ETSI EN 300 220 requires spurious emission above 1 GHz to be below -30 dBm. When using ML inductors, the highest PA setting which ensures compliance with ETSI is 0xC2. Using 0xC0 which is the CC11xx PA setting resulting in maximum output power will result in a level of 2nd harmonic which is at the ETSI limit. It is therefore recommended to use WW inductors in the filterbalun to achieve highest possible output power when seeking compliance with ETSI EN 300 220.

FCC

FCC part 15.247 allows for up to 1 W output power if Frequency Hopping (FH) or digital modulation is used. Maximum output power for CC11xx is 10 dBm. DN006 [6] describes how CC11xx can be configured to comply with FCC 15.247 without using FH. Part 15.247 requires the spurious emission to be 20 dB below the intentional radiator except inside restricted bands which are defined in part 15.205. The 2^{nd} and 7^{th} harmonic is the only harmonics below 10 GHz which doesn't fall within any restricted bands when operating in the 902-928 MHz ISM band. The spurious emission limit is -41.2 dBm inside the restricted bands, but FCC allows for up to 20 dB higher emission if duty cycling is being used. The maximum TX on time must be less than 100 ms to get a benefit from this rule. By using Equation 1 and the maximum on time of the application, it is possible to calculate the Averaging Factor (AF). The spurious level accepted by FCC would then be -41.2 dBm + AF, and maximum -21.2 dBm

$$AF = -20LOG\left(\frac{MAX\ TX\ ON\ TIME\ ms}{100ms}\right)$$

Equation 1. Averaging Factor

FCC spurious emission limits are plotter in Figure 14 together with harmonic measurements. Both the limit for maximum AF and no AF are plotted. At the 2^{nd} and 7^{th} harmonic the limit is plotted at -10 dBm since CC11x has maximum output power of 10 dBm and the requirement is 20 dB below maximum radiation.

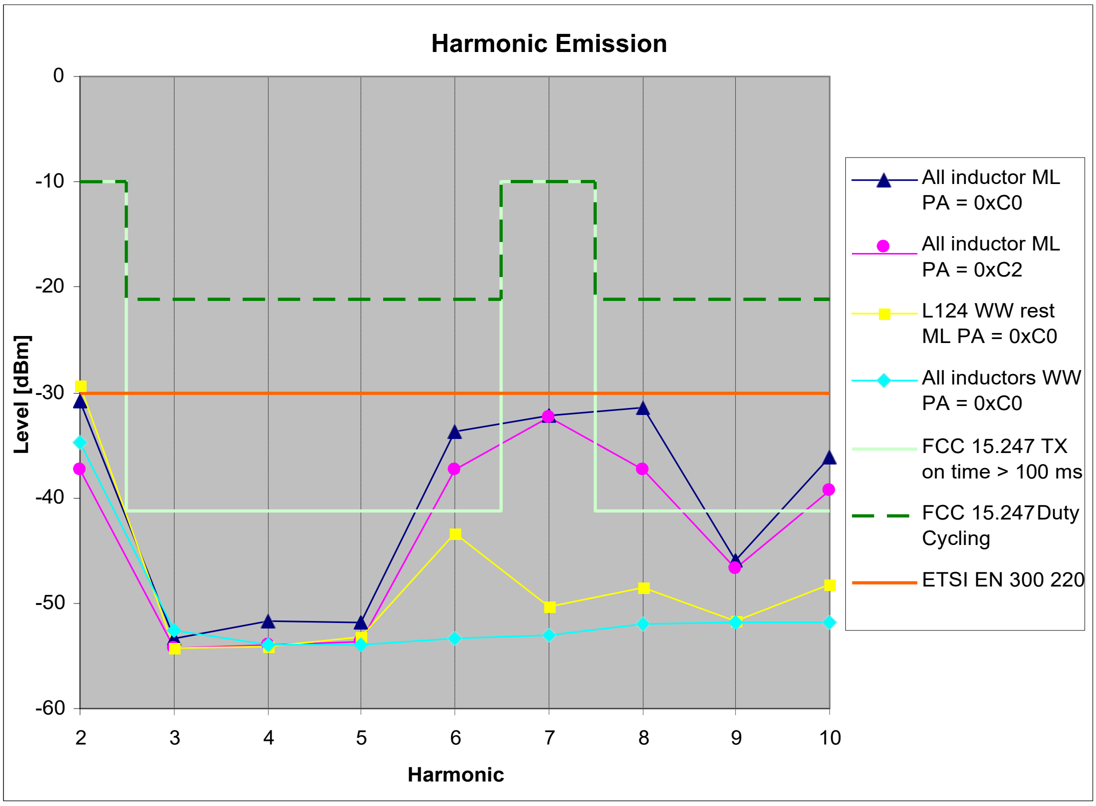

Figure 14. Conducted Harmonic Emission

Table 5 shows which combinations of output power settings and inductors types that can be used to comply with FCC part 15.247 and ETSI EN 300 220.

Graph	(magenta)	(navy)	(yellow)	(cyan)
Inductor types	**All inductor ML**	**All inductor ML**	**L124 WW rest ML**	**All inductors WW**
PA setting	**PA = 0xC2**	**PA = 0xC0**	**PA = 0xC0**	**PA = 0xC0**
TX Current consumption	30.4 mA	33.6 mA	32.9 mA	35.0 mA
Output power	9.3 dBm	9.8 dBm	9.8 dBm	12.0 dBm
2nd Harmonic	-37.3 dBm	-30.8 dBm	-29.3 dBm	-34.8 dBm
Sensitivity	-93.7 dBm	-93.7 dBm	-94.0 dBm	-94.6 dBm
Complies with FCC	Requires duty cycle	Requires duty cycle	Yes	Yes
Complies with ETSI	Yes	No margin	No	Yes

Table 5. Conducted Performance with All ML and One WW Inductor

Harmonic	**One WW**	**All WW**	**RBW**
2nd	-39,9	-42,5	1 MHz
3rd	No Signal	-46,5	1 MHz
6th	-41,9	No Signal	1 MHz
7th	-44,8	No Signal	100 kHz
8th	-39,0	No Signal	100 kHz
10th	No Signal	-44,3	100 kHz

Table 6. Radiated Harmonic Emission

6 References

[1] CC1101EM 868-915MHz Reference Design (swrr045.zip)
[2] CC1110EM 868-915MHz Reference Design (swrr048.zip)
[3] CC11xx 868/915MHz RF matching S-parameters (swra168.zip)
[4] DN012 Programming Output Power on CC1100 and CC1150 (swra150.pdf)
[5] DN013 Programming Output Power on CC1101 (swra151.pdf)
[6] DN006 CC11xx Settings for FCC 15.247 Solutions (swra123.pdf)

7 Document History

Revision	Date	Description/Changes
SWRA168A	2008.03.31	Updated reference [3]. Added radiated measurement results.
SWRA168	2008.02.01	Initial release.