CC1310 Discrete PA Chinese AMR Reference Design Rev 1.x

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ABSTRACT

Automatic Meter Reading (AMR) automatically collects the information on the amount of water, electric or gas that has been consumed by each household. When the AMR information is received, the exact energy amount can be charged from the energy supplier company. Traditionally, this has been done by manual reading of meters, but this can now be done automatically with wireless technology.

Several countries now have laws requiring energy companies to charge for the exact amount of energy being consumed and not just a predicted energy bill. Each country has specific regulatory requirements for AMR. This application report is targeting the Chinese AMR market (470 MHz to 510 MHz) with CC1310. The reference design [3] discussed in this document can transmit up to +22 dBm with high power efficiency.

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1 Introduction

The Chinese AMR market has been allocated a frequency range of 470 MHz to 510 MHz. The maximum radiated output from the metering unit is not to exceed 17 dBm effective radiated power (ERP). The majority of meters are quite compact and require a compact antenna. The antenna efficiency is normally quite low due to the physical size so higher output power is desired to compensate for the antenna losses. The design covered in this application note is based on the CC1310 from the CC13xx family.

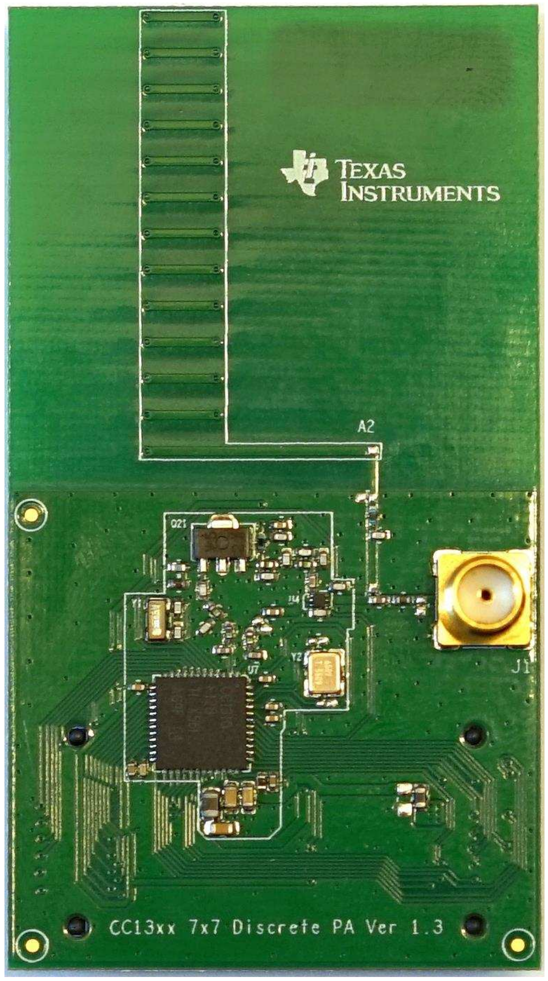

Figure 1. CC1310 7PA 4751 EM

2 Design

When designing an AMR system, the maximum range between the transmitter and receiver is one of the most important parameters that will dominate the system configuration and installation. In the AMR system, the range is critical so that all households' meters can be read otherwise this needs to be done manually which is expensive. To achieve a long range the output power can be increased to the maximum limit specified by the regulations and the data rate reduced as much as possible for the application.

The AMR system must be able to work in a noisy RF environment since the number of meters in industrial complexes or high rise buildings can be positioned very close to each other so blocking and selectivity is also a critical requirement. More information on achieving optimum radio distance and blocking/selectivity is available [1].

2.1 CC1310

The CC1310 has been specifically designed for long range, city-wide low-power networks. This is used in home automation, building automation and outdoor wide-area networks. The main advantages of CC1310 are high sensitivity (-124 dBm @ 0.625 kbps), strong co-existence (up to 80 dB blocking), and lowest power consumption (61 µA/MHz ARM Cortex M3).

CC1310 can be basically split into four low-power sections [2]:

- Main CPU with Cortex M3
- RF Core with radio controller. The RF core is a highly flexible and capable radio system that interfaces the analog RF and base-band circuitries, handles data to and from the system side, and assembles the information bits in a given packet structure.
- General Peripherals
- Sensor Controller

For more in-depth information on the CC1310 [2].

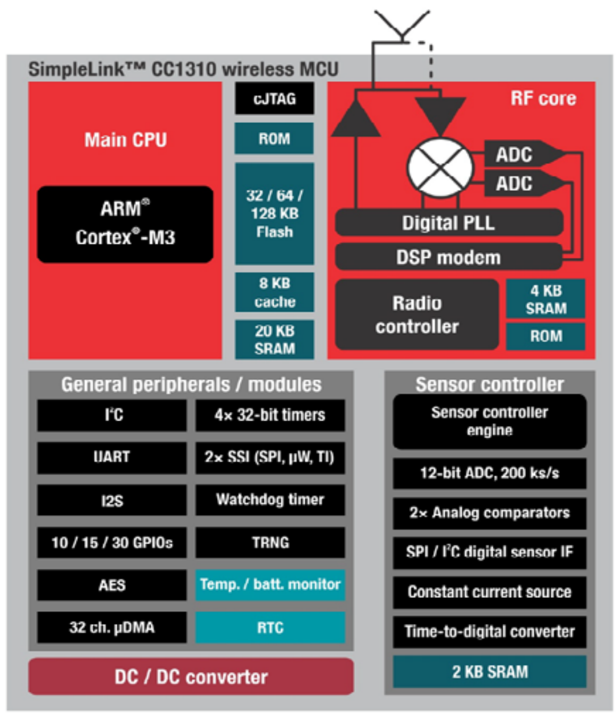

Figure 2. CC1310 Block Diagram

2.2 Schematic

The RF core is highly configurable and the radio front-end can be set to differential or single ended. With a differential output configuration, the maximum output is 14 dBm. With a single ended output, the maximum output is 11 dBm. Since many AMR customers have requested an output power up to 22 dBm, the CC1310 transmitter was configured as a single ended port (RF_N set to Tx) connected to an external MOSFET acting as an amplifier (see Figure 3). If an output power of 14 dBm is sufficient then the standard reference design for 420 MHz to 510 MHz can be used.

The power MOSFET used is from Renesas (NE5550234) [4]. This MOSFET can also be used for the other sub 1-GHz frequency ranges such as 169 MHz, 433 MHz and 868/915/920 MHz. The output power can be configured to the maximum power allowed (30 dBm) by the sub-1 GHz regulatory standards. If a different frequency than 470 – 510 MHz or higher output power (> 22 dBm) is required, then the biasing and filtering needs to be changed in the schematic shown in Figure 3.

The reference design [3] shown in Figure 3 is based upon 3.3 V supply voltage. The power gain of the MOSFET is dependent on the drain-source voltage. Increasing the voltage for the MOSFET will increase the gain and a higher output power can be achieved. Optimal supply voltage for both the radio and the MOSFET is 3.6 V.

The external biasing around the MOSFET sets the maximum output power and gain. The output power can be reduced by lowering the output power being transmitted from the CC1310. That is, reducing output power from +10 dBm from CC1310 to –15 dBm. The power added efficiency (PAE) is always the greatest at the maximum power. One main reason for choosing the Renesas MOSFET is because of the high PAE of around 60 – 70 %. The MOSFET is gate controlled by the DIO1 GPIO. DIO1 is connected both to the MOSFET and to the SPDT switch.

An alternative lower-power MOSFET to the NE5550234 is the RQA0004PXDQS [5]. This has the same pinout and footprint.

When designing an external PA it is important that the transistor can handle a mismatch load on the antenna. When the antenna is mismatched, the load current may increase. It is important that the transistor can handle this extra current. The NE5550234 can handle an open and short mismatch on the antenna without being destroyed.

Components L24 // C24 form a parallel notch filter for the second harmonic (2 x 490 MHz) and L25 // C28 form a parallel notch filter for the third harmonic (3 x 490 MHz). If the layout is changed, especially the surrounding GND distance to C24 and C28, then these two capacitors may need to be altered. C27 and C29 form additional low-pass filtering together with the parallel notch filters.

The Rx port is also configured as a single ended port (RF_P set to Rx). The biasing of CC1310 LNA can be configured as external or internal. Internal biasing was chosen to reduce the component count.

Both the Tx branch and Rx branch are connected to a SPDT switch. The SPDT switch is controlled by two GPIOs (DIO1 and DIO30) (see Example 1). The SPDT function is achieved by a low cost switch from Skyworks (SKY13323-378LF) [6]. There are other low cost SPDT switches available on the market that can provide the same function such as Peregrine (PE4259SCBECT-Z) [7]. The main reason for choosing the Skyworks (or Peregrine) SPDT was due to the low price ($0.07).

Example 1. Truth Table for SKY13323-378LF

```
DIO_1 (VCTRL1) : LOW & DIO_30 (VCTRL2)  : HIGH -> Rx (OUT2)
DIO_1 (VCTRL1) : HIGH & DIO_30 (VCTRL2) : LOW  -> Tx (OUT1)
```

The antenna/ SMA are connected to the single pole side of the SPDT switch. The antenna is chosen by assembling the 100 pF capacitor at position C63. Discrete components ANT1, ANT2 and ANT3 are dedicated for antenna matching purposes. The SMA connector can be chosen instead of the integrated antenna by assembling the 100 pF capacitor at position C52.

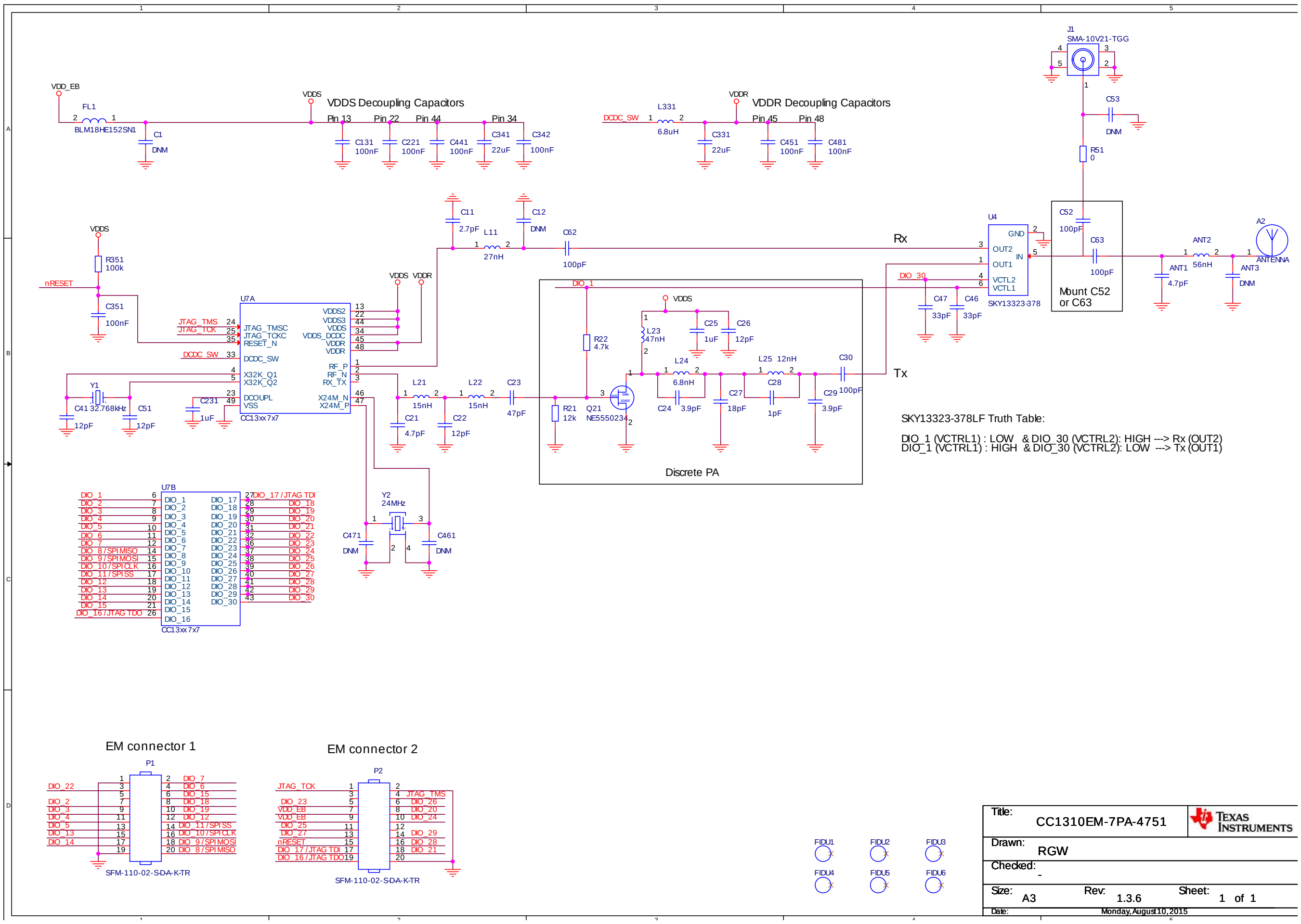

Figure 3. CC1310EM-7PA-4751 Schematic (Rev 1.3.6)

2.3 Layout

The design note [3] is based upon a 0.8 mm thick, two-layer PCB. The top layer and bottom layer is shown in Figure 4. All components are positioned on the top layer apart from the evaluation module (EM) connectors. The CC1310 is based upon the 7x7 QFN but this is also available in 5x5 QFN and 4x4 QFN packages as well.

A PCB helical antenna is incorporated in the EM design. The antenna is routed on both the top and bottom layers. It is important to incorporate the matching components (ANT1, ANT2 and ANT3,) as well if the antenna structure is to be copied to another design.

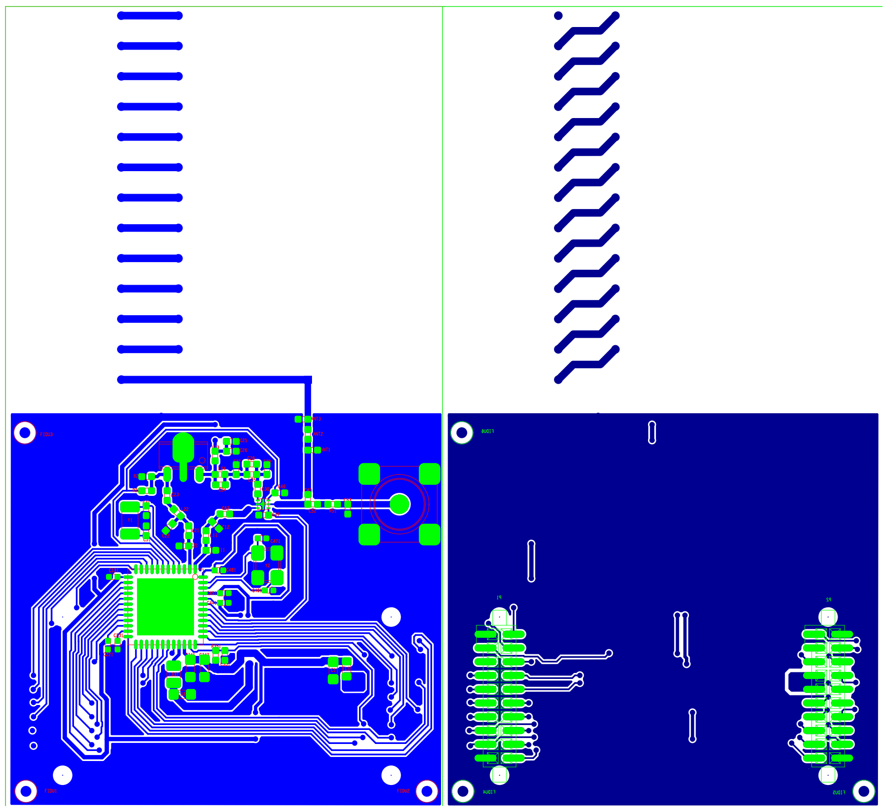

Figure 4. CC1310EM-7PA-4751 Layout (top view shown on left, bottom view on the right side)

2.4 SmartRF™ Studio

To evaluate the reference design, it is recommended to use the EM on the SmartRF06EB with SmartRF Studio software. The supported functions are continuously being updated and the software can be downloaded from www.ti.com [9].

Apart from the standard radio setup, to control the discrete PA (MOSFET) and SPDT, the DIOs (DIO1 and DIO30) must be configured.

3 Measurement Results

All measurements results were performed on the CC1310-7PA-4751 EM mounted on the SmartRF06EB. The V_{USB} power source is nominally 3.3 V on the SmartRF06EB and this drops to about 3.2 V on the EM when the output power is set to maximum. Ideally, the power regulator should be placed closer to the CC1310 and MOSFET to avoid any unnecessary voltage drops. Software control is based upon SmartRF Studio 2.1.0.

3.1 Spurious Emission

The ERP requirements set by the regulation requirements is 17 dBm_max. Note that the EIRP = ERP + 2.15 dB. Therefore, the peak EIRP should not exceed 19.15 dBm. For Tx: the emissions should not exceed -36 dBm for 30 MHz - 1GHz and -30 dBm for 1 GHz – 12.75 GHz. For Rx: the emissions should not exceed -57 dBm for 30 MHz - 1GHz and -47 dBm for 1 GHz – 12.75 GHz.

As can be seen in Figure 5, even with a slightly higher output power of 21 dBm peak EIRP, the design is still compliant to the Tx harmonic spurious emission requirements. This is ideal if the output power needs to be increased to compensate for any external conducted losses (due to large installations and distances from the antenna to the radio) and still be compliant with the harmonics. The measurement shown in Figure 5 is measured with a large whip antenna with good efficiency (approximately 80 % efficiency, 1 dB loss). The conducted output power level is the same for both Figure 5 and Figure 6.

In Figure 6, the peak EIRP is lower than shown in Figure 5 due to the compact integrated PCB antenna is used instead (approximately 4 dB loss) of the large whip antenna (approximately 1 dB loss). Figure 6 shows full compliancy towards the regulatory standards with good margins.

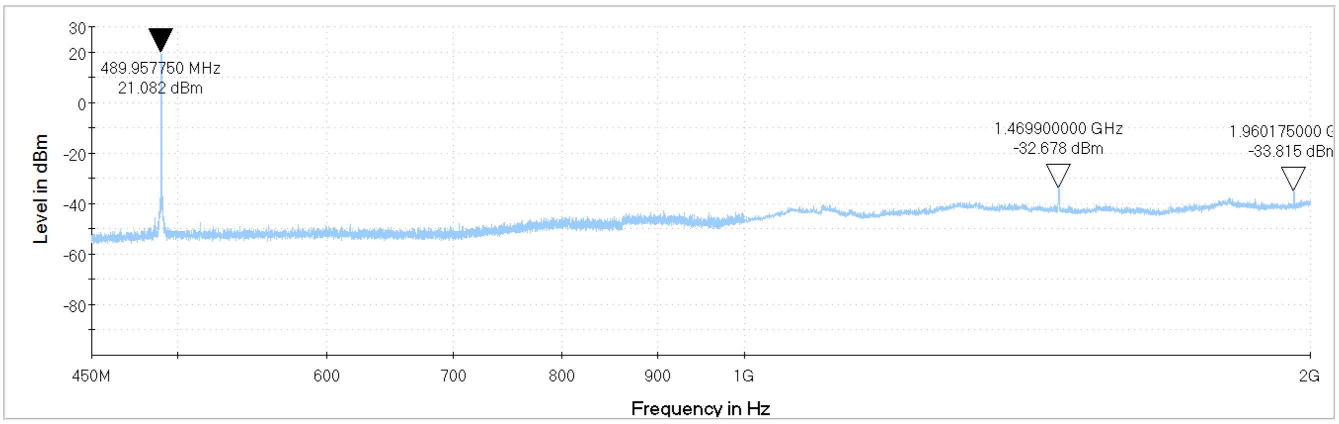

Figure 5. Tx Spectrum Plot at 21 dBm Peak EIRP and Whip Antenna

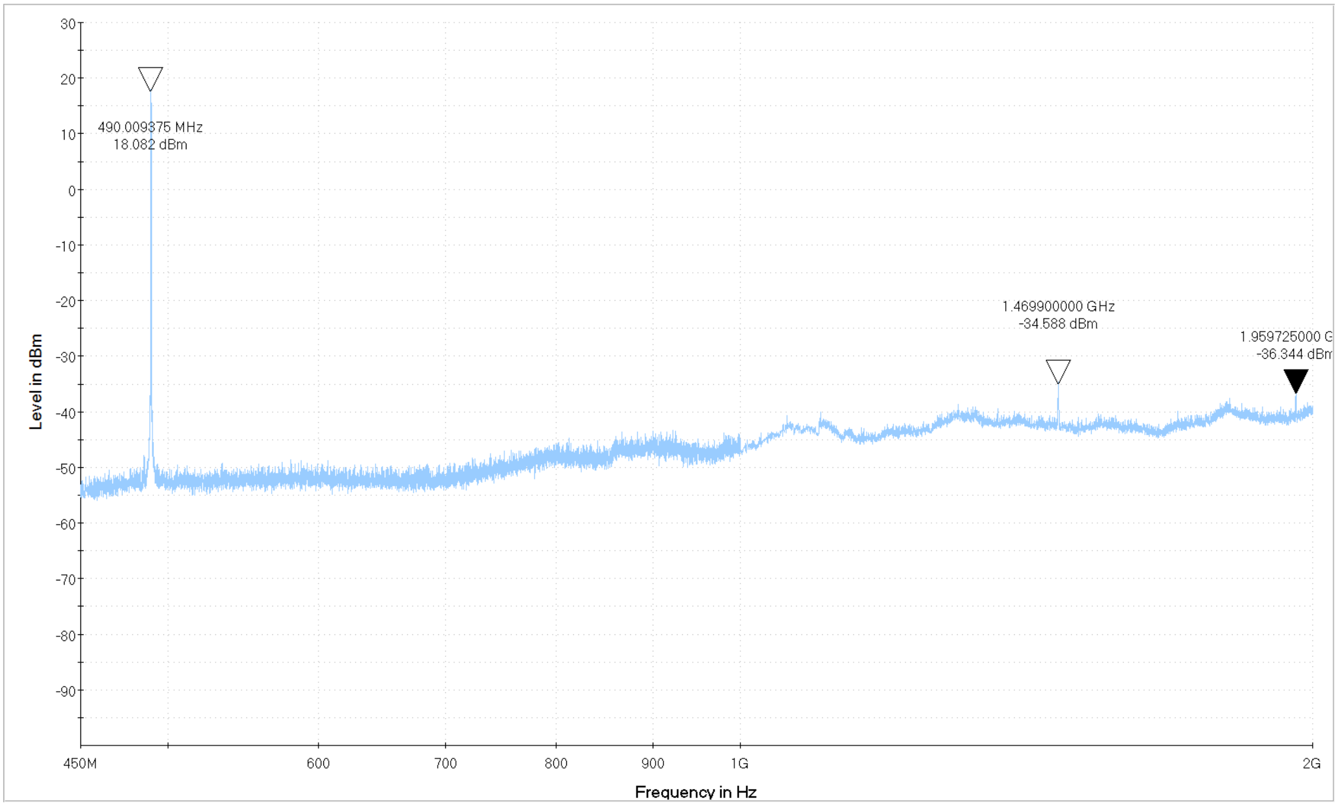

Figure 6. Tx Spectrum Plot at 18 dBm Peak EIRP and On-Board Integrated PCB Antenna

3.2 *Tx Output Power and Harmonics*

The output power was measured at 470 MHz, 490 MHz and 510 MHz. For each frequency, the harmonics were measured up to the tenth harmonic. The output power level varied 0.1 dB for the whole frequency band (see Table 1). All conducted harmonics are below -30 dBm. If the power is increased furthermore, then the 4fc is the harmonic with the least margin.

Table 1. Conducted Output Power and Harmonics, V_{USB}

fc	2fc	3fc	4fc	5fc	6fc	7fc	8fc	9fc	10fc	
470	940	1410	1880	2350	2820	3290	3760	4230	4700	MHz
20.8	-41	-45	-33	-43	-55	-48	-48	-55	-55	dBm
490	980	1470	1960	2450	2940	3430	3920	4410	4900	MHz
20.9	-55	-42	-35	-45	-55	-55	-55	-55	-55	dBm
510	1020	1530	2040	2550	3060	3570	4080	4590	5100	MHz
20.9	-48	-40	-34	-42	-55	-42	-55	-55	-55	dBm

3.3 Tx Output Power Dynamic Range

Output power was measured at 490 MHz. In the CMD_PROP_RADIO_DIV_SETUP, the IB bit fields were varied in the TxPower register from minimum to maximum (see Table 2). The other bit fields in the TxPower register were set to GC: 0x03, boost: 0x00 and tempCoeff: 0x00.

Table 2. Tx Output Power Dynamic Range, V_{USB}

0x00	0x01	0x02	0x03	0x04	0x05	0x06	0x07	0x08	0x09	IB
3.2	8.6	11.6	13.6	14.9	16.0	16.8	17.5	17.9	18.4	dBm
0x0A	0x0B	0x0C	0x0D	0x0E	0x0F	0x10	0x11	0x12	0x13	IB
18.8	19.2	19.4	19.7	19.8	20.0	20.1	20.2	20.3	20.4	dBm
0x14	0x15	0x16	0x17	0x18	0x19	...	0x1F	0x2F	0x3F	IB
20.5	20.6	20.6	20.7	20.7	20.8	...	20.9	21.1	21.2	dBm

The output power dynamic window is 18 dB: 21.2 dBm (0x3F) to 3.2 dBm (0x00).

3.4 Tx Output Power and Current Consumption

Output power was measured at 490 MHz. In the CMD_PROP_RADIO_DIV_SETUP, the IB bit fields were varied in the TxPower register from minimum to maximum. The other bit fields in the TxPower register were set to GC: 0x03, boost: 0x00 and tempCoeff: 0x00. 3.3 V power to the EM was supplied by an external voltage source.

The efficiency is always at the maximum for the highest output power level (see Table 3). If 21 dBm is not required, then the biasing resistor (R21) can be reduced from 12k to a lower value (for example: 10k or 8.2k). This is ideal for optimizing the efficiency for a lower output power. The bias tuning is dependent of the supply voltage. All measurements are based upon 3.3 V supply.

Ideally, the radio and R21 biasing should be powered with 3.6 V for the lowest current consumption. 3.3 V was chosen due to it is a more common voltage level and this is also used on the SmartRF06EB. When the design [3] (schematic shown in Figure 3) was powered with 3.6 V_{PSU}, the output power increased a further 1.4 dB compared to the values shown in Table 3. However, the efficiency did not improve: 22.1 dBm (38.6%) and 22.8 dBm (42.5%). If the power supply is changed from 3.3 V, then the (R21) biasing needs to be adjusted for optimal efficiency.

Table 3. Tx Output Power, Current Consumption and Efficiency, 3.3 V_{PSU}

0x00	0x01	0x02	0x03	0x04	0x06	0x09	0x0B	IB
4.5	9.9	12.8	14.7	15.8	17.5	18.6	19.4	dBm
40.4	43.1	46.7	51	54.6	62.1	69.7	75.6	mA
2.1	6.9	12.4	17.5	21.1	27.4	31.5	34.9	%
0x0C	0x0D	0x0E	0x10	0x19	0x1F	0x2F	0x3F	IB
19.6	20.1	20.2	20.4	21.0	21.1	21.3	21.4	dBm
77.5	82.2	83.9	86.7	94.1	96.1	98.6	99.4	mA
35.7	37.7	37.8	38.3	40.5	40.6	41.5	42.1	%

23 dBm to 33 dBm output power can also be achieved if the power supply to the MOSFET [4] is increased from 3.6 V to 9 V (see Figure 7). The 0402 discrete package size used in Figure 3 will have to increase in size due to the extra power.

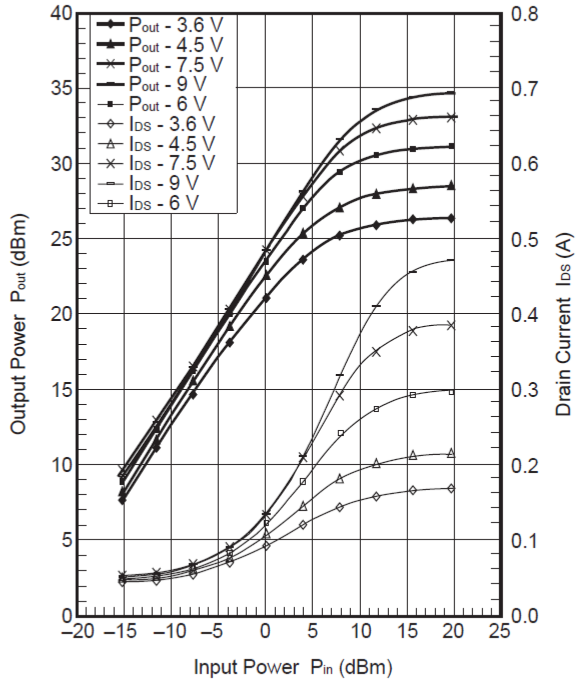

Figure 7. Increasing Power Supply to the MOSFET

3.5 Rx Current Consumption

The static Rx current consumption was measured at 6.5 mA at 3.3 V_{PSU}.

3.6 Sensitivity

For the differential reference design [3] with external biasing, the sensitivity is approximately -110 dBm for a data rate of 50 kbps. This reference design shown in Figure 3 uses single ended configuration of Rx and Tx to avoid the need for two SPDT switches. With single ended configuration only one SPDT is required. The sensitivity is reduced by 2 dB with single ended configuration compared to differential configuration.

External biasing of the LNA is possible then the RxTx pin must be connected to RF_P via an inductor (270 nH). An advantage with external biasing is the sensitivity is improved by approximately 1 dB. Internal biasing was initially chosen for this configuration to keep the total cost as low as possible.

Therefore, the sensitivity delta between single ended configuration with internal biasing and differential configuration with external biasing is 2.5 dB. The SPDT switch has an insertion loss of approximately 0.5 dB. To keep the external BOM costs as low as possible, LQG inductors are used instead of wire-wound (WW) inductors which also causes an additional 0.5 dB of loss.

50 kbps Sensitivity Level Summary:

- Differential configuration with external biasing: -110 dBm
- Single ended configuration with internal biasing: 2.5 dB loss
- Insertion Loss through switch: 0.5 dB
- Usage of LQG inductors instead of WW-inductors: 0.5 dB
- 50 kbps sensitivity on CC1310-7PA-4751 Ref Design: **-106.5 dBm**

If the data rate is reduced from 50 kbps and Long Range Mode utilized, then the following sensitivity levels can be achieved on the on CC1310-7PA-4751 Ref Design:

• 5 kbps sensitivity:	-116.5 dBm
• 2.5 kbps sensitivity:	-118.5 dBm
• 1.25 kbps sensitivity:	-119.5 dBm
• 0.625 kbps sensitivity	-120.5 dBm

3.7 Antenna Design

The PCB helical antenna shown in Figure 4 has been matched to 470 – 510 MHz with ANT 1: 4.7 pF and ANT2: 56 nH (see Figure 8). The antenna is matched for the complete band of 470 – 510 MHz (see Figure 9). The antenna was tested at 510 MHz in the anechoic chamber and the antenna efficiency is -4.1 dB (38.6 %). For the complete CTIA report summary, see Figure 10.

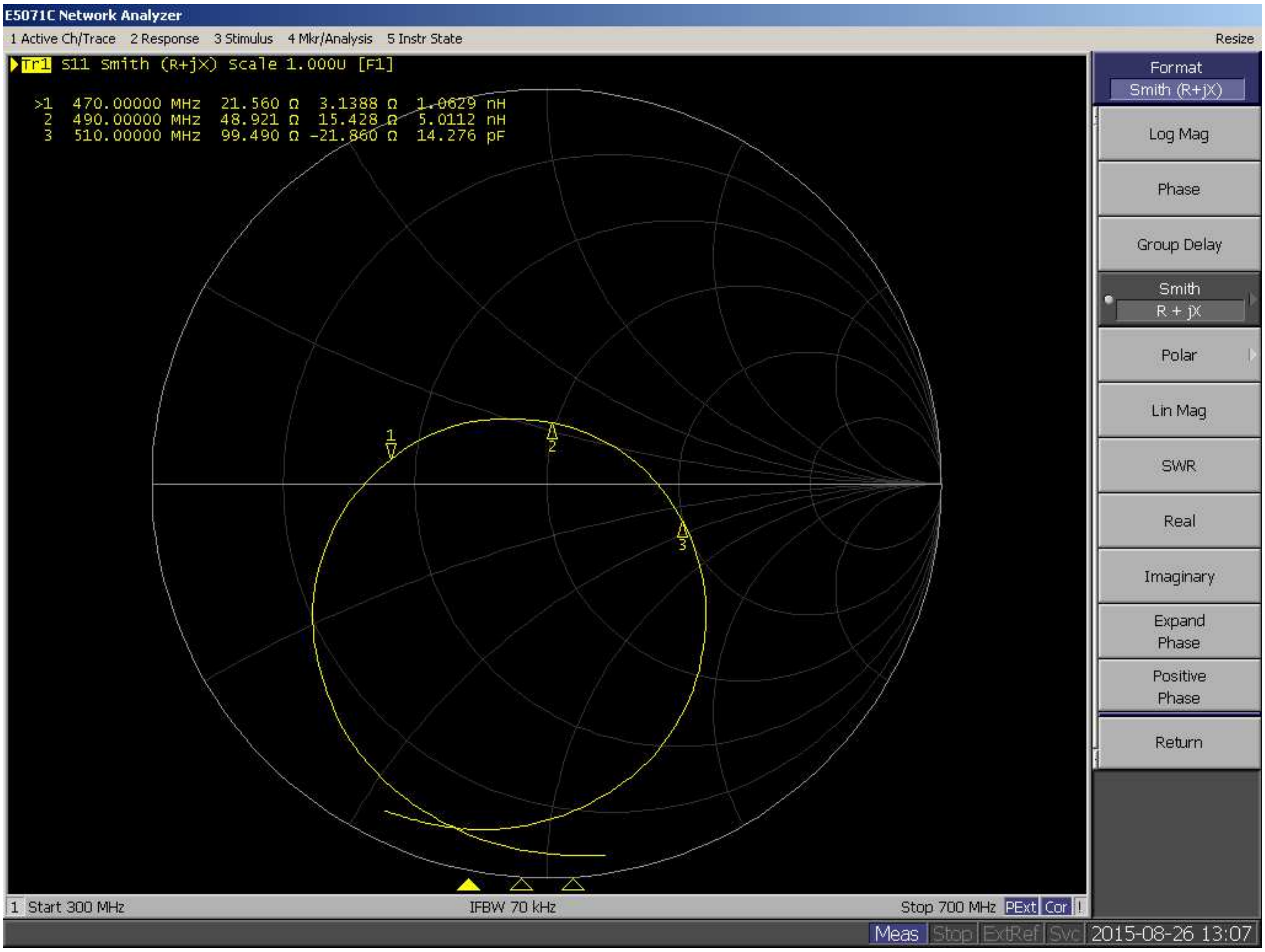

Figure 8. Matching of the Antenna With ANT1 and ANT2 Components

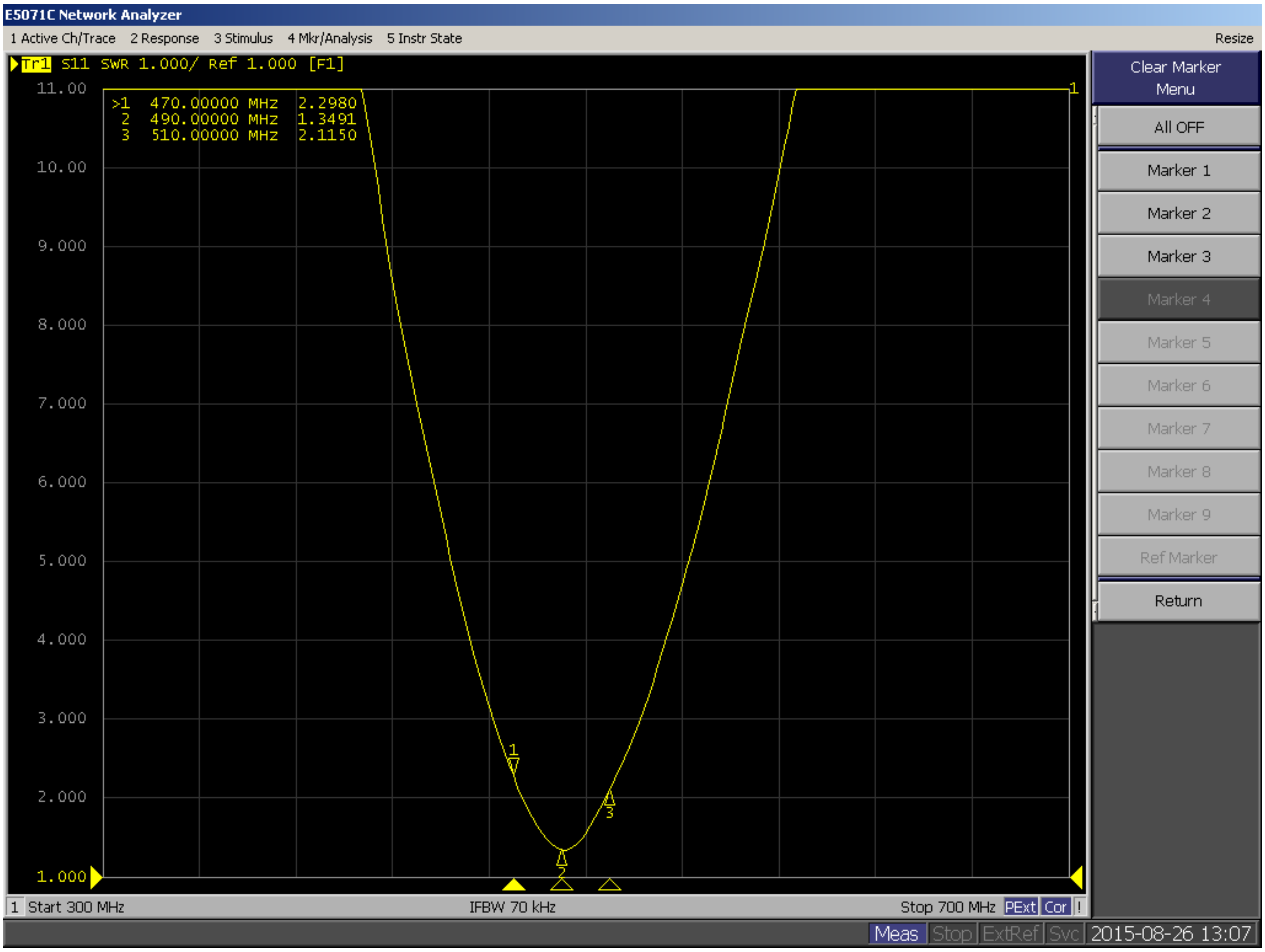

Figure 9. Antenna Bandwidth at VSWR: 2

OTA Evaluation Results:

Total Radiated Power	-4,14 dBm
Peak EIRP	-1,04 dBm
Directivity	3,09 dBi
Efficiency	-4,14 dB
Efficiency	38,58 %
Peak Gain	-1,04 dBi
NHPRP 45°	-4,86 dBm
NHPRP 45° / TRP	-0,72 dB
NHPRP 45° / TRP	84,63 %
NHPRP 30°	-5,89 dBm
NHPRP 30° / TRP	-1,76 dB
NHPRP 30° / TRP	66,72 %
NHPRP 22.5°	-6,96 dBm
NHPRP 22.5° / TRP	-2,83 dB
NHPRP 22.5° / TRP	52,15 %
UHRP	-7,83 dBm
UHRP / TRP	-3,69 dB
UHRP / TRP	42,76 %
LHRP	-6,56 dBm
LHRP / TRP	-2,42 dB
LHRP / TRP	57,24 %
PGRP (0-120°)	-4,99 dBm
PGRP / TRP	-0,85 dB
PGRP / TRP	82,20 %
Front/Back Ratio	3,53
PhiBW	360,0 deg
PhiBW Up	360,0 deg
PhiBW Down	360,0 deg
ThetaBW	92,6 deg
ThetaBW Up	30,9 deg
ThetaBW Down	61,8 deg
Boresight Phi	285 deg
Boresight Theta	105 deg
Maximum Power	-1,04 dBm
Minimum Power	-25,38 dBm
Average Power	-5,16 dBm
Max/Min Ratio	24,34 dB
Max/Avg Ratio	4,12 dB
Min/Avg Ratio	-20,22 dB
Worst Single Value	-38,05 dBm
Worst Position	Azi = 15 deg; Elev = 165 deg; Pol = Ver
Best Single Value	-1,34 dBm
Best Position	Azi = 195 deg; Elev = 105 deg; Pol = Hor

Figure 10. PCB Helical Antenna Efficiency

4 Summary

This application report is targeting the Chinese AMR market (470 MHz to 510 MHz) with CC1310 to achieve 17 dBm transmitted radiated output power with a small integrated PCB antenna. AMR products are compact and the antenna efficiency is typically low due to its physical size and the attenuation caused from the robust mechanical housing, which causes a reduction in the ERP. The output power can be increased to ensure a maximum ERP suited for each application. The CC1310-7PA-4751 reference design is a low cost, high efficiency discrete PA that can provide > 21 dBm conducted output power. Tx current consumption at 20 dBm is approx. 78 mA and for 21 dBm, approx. 94 mA. The design can easily be adapted to other frequencies such as 169 MHz, 433 MHz, 868/915/920 MHz. The efficiency can be optimized for various levels of maximum output power by changing the biasing and voltage supply.

5 References

1. *Achieving Optimum Radio Range* (SWRA479)
2. *CC1310 SimpleLink™ Ultra-Low Power Sub-1 GHz Wireless MCU Data Manual* (SWRS181)
3. CC1310EM-7PA-4751 Reference Design for China
4. Renesas (NE5550234) Data Sheet
5. Renesas (RQA0004PXDQS) Data Sheet
6. Skyworks (SKY13323-378LF) Data Sheet
7. Peregrine (PE4259) Data Sheet
8. *Antenna Selection Quick Guide* (SWRA351)
9. SmartRF Studio Download

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