EFR32MG24 QFN40 0 dBm Minimum BOM Gas Sensor Design Reference Manual

Silicon Labs provides customers with a hardware design example for Electrochemical Sensing applications in a 27 x 20 mm size with EFR32MG24, an external DC-DC Boost converter and a sensor IC. The external circuitry of EFR32MG24 is comprised of 8 passive components in total, while still complying with the ETSI and FCC RF harmonic spurious regulations. This document describes the hardware design and provides pre-compliance RF test data. Additionally, design files including schematic and layout CAD designs, BOM, PDF, ASCII files and Gerbers, are available under Silicon Labs website at the Silicon Labs hardware design examples Github page.

The hardware design utilizes an EFR32MG24 chip in a QFN40 package.

It is pre-compliance tested and appears to be fully compliant with ETSI and FCC regulatory standards.

KEY POINTS

- Brief description of EFR32MG24 QFN40 gas sensor reference design
- RF test data provided, including antenna impedance, gain and efficiency, conducted and radiated power and harmonics, RX sensitivity and power consumption.

The hardware design includes the following circuit components:

- EFR32MG24A010F1536IM40-B
- Built-in PCB Inverted-F Antenna (IFA)
- 10-pin mini-simplicity debug connector
- CR1216 coin cell battery and battery holder accessories
- Electrochemical gas sensor IC (Texas Instruments LMP91000)
- DC-DC boost converter for a 3 – 3.3 V supply voltage (ANALOG DEVICES MAX17223)
- External passive components

1. Introduction

The EFR32MG24 QFN40-based electrochemical sensing design is virtually provided for customers, since design files, including schematic and layout CAD design files, BOM, PDF, ASCII files and Gerbers, are available at the Silicon Labs hardware design examples Github page but there is no orderable part number for the board itself.

Due to the efficiency focused nature of the various electrochemical sensing applications (<5-6 mA total current consumption goal for extended battery life) the 0 dBm PA is recommended for use. Additionally, with a small CR1216 lithium coin cell battery, the 10 dBm PA, at any power level, draws more current than the coin cell might be able to output without a significant voltage drop, even for short-burst applications. Therefore, the module is labeled for 0 dBm output power level. However, the design is pre-tested by Silicon Labs and is compliant with FCC and ETSI regulatory standards at TX output power levels as high as +8 dBm, while being powered by a Silicon Labs Wireless Starter Kit (WSTK). If high power is the aim, it is recommended to use a bigger coin cell (e.g. CR2032) and slightly increase the dimensions of the PCB (while keeping the antenna area untouched).

The module utilizes 4 electrical layers and an on-board printed antenna. The entire module dimension is 27x20 mm. The module includes a so-called 10-pin mini-simplicity header for programming and debugging purposes (see connection details in AN958). This connector can be omitted from designs where the size of the PCB is even more restricted, and simple test points could be added instead for the UART TX, UART RX, and the 3-wire SWD programming interface.
The on-board printed antenna is tuned with the coin cell battery inserted, with no plastic enclosure or a human body (like an arm) in the proximity.
The on-board printed antenna is tuned by its geometry to have maximum RF performance. Due to the minimum BOM attribute of the design, the placeholders for the PCB antenna tuning are not populated.

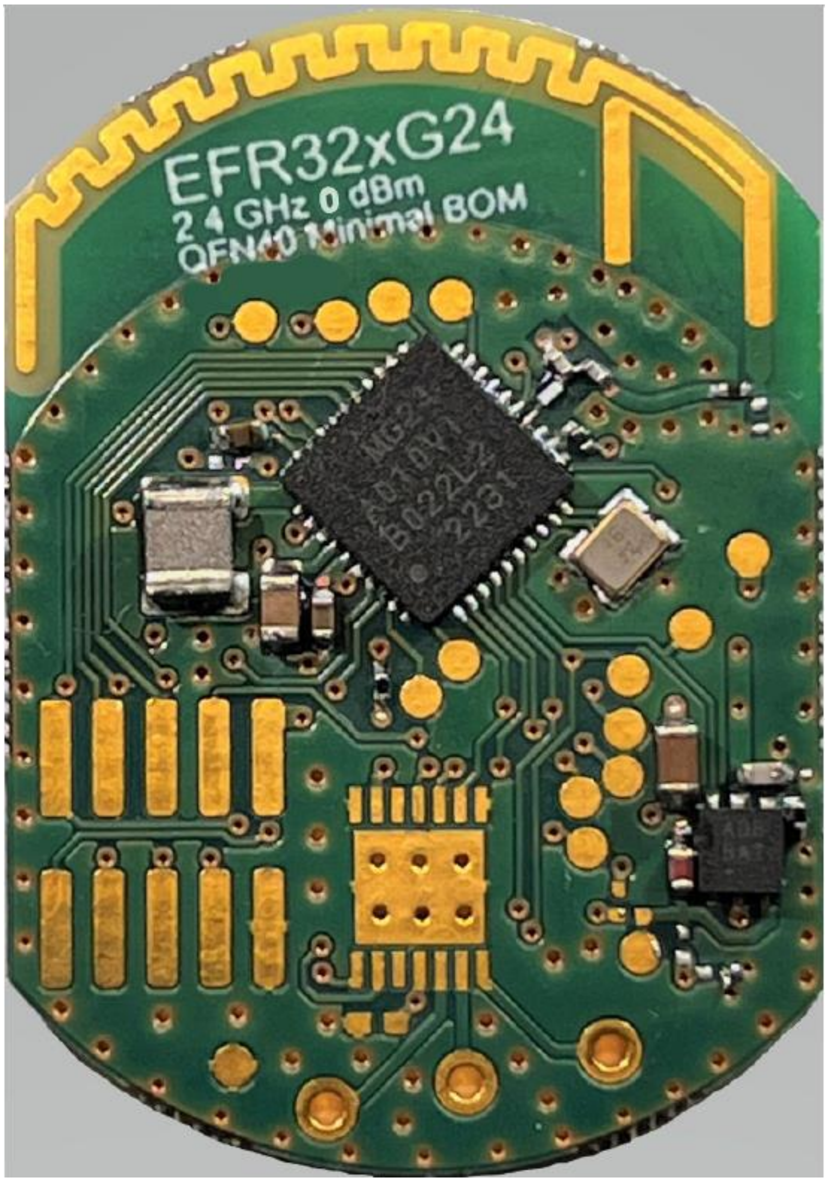

Figure 1.1 EFR32MG24 Minimum BOM sensor design

Note:

- The length of the printed antenna on the manufactured PCB of the photograph above is shortened during the tuning process (see Chapter 2.).

2. Schematic Design

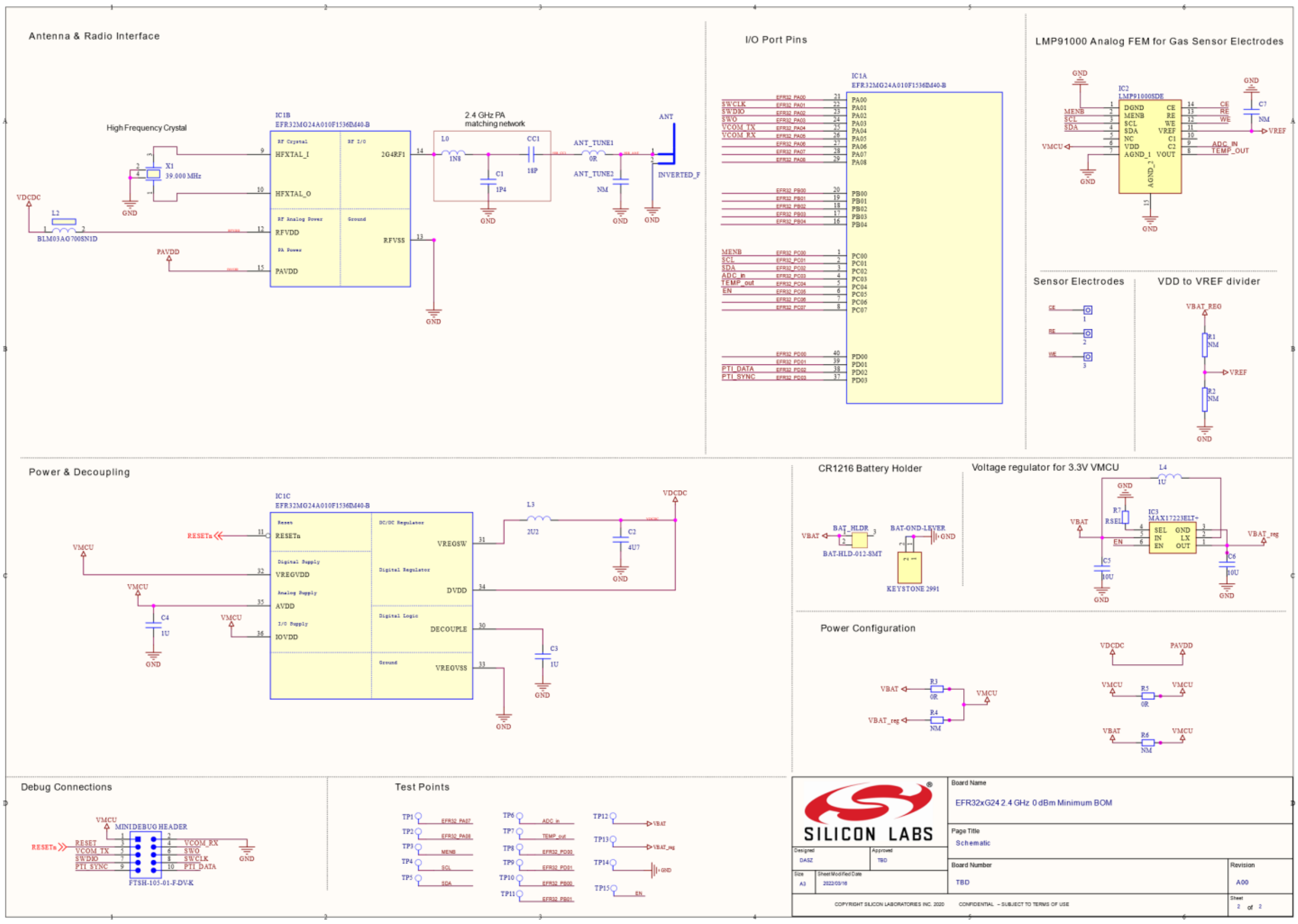

Figure 2.1 Complete schematic

To further reduce component count, the external LFXO crystal is omitted from design with the internal LFRCO functioning instead as the low frequency clock source. The on-chip 1.8 V DCDC converter output supplies both RFVDD and PAVDD pins to limit the current consumption profile to maximize battery life. The RF front-end consists of only three passive matching components: an LC low pass filter that also functions as the impedance matching circuit, and the necessary DC-block capacitor. The matching network transforms the PA output impedance to 50 Ohm, therefore no external antenna matching components are necessary as the antenna is designed to 50 Ohm impedance and 2.45 GHz resonance.

Table 2.1 EFR32MG24 passive component values

Matching network			EFR32 DC-DC output external components		DECOUPLE filtering	AVDD filtering	RVDD filtering
L0	C1	CC1	L3	C2	C3	C4	L2
1.8 nH	1.4 pF	18 pF	2.2 uH	4.7 uF	1 uF	1 uF	BLM03AG700SN1D ferrite

The external circuitry of the chemical gas sensor and external DC-DC boost converter follow the guidelines recommended in their respective datasheets.

A brief description of the 3-electrode LMP91000 gas sensor is the following:

The Reference Electrode’s (RE) voltage is compared internally to an adjustable reference voltage. The internal comparator circuitry injects current to the so called Control Electrode (CE) according to the comparator output. The current flowing through the Working Electrode (WE) is proportionate to the measured substance. This current is read by an internal transimpedance amplifier which outputs an amplified analog voltage value, which is then lead to the ADC input of the EFR32MG24. The gas sensor can also read the temperature values of the environment to prevent overheating. The communication with the EFR32 is through an I2C interface.

The need for the external DC-DC converter is due the gas sensor’s minimum required 2.7 V supply voltage. The voltage of the coin cell decreases over its lifespan and the 3 to 3.3 V output of external DC-DC boost converter provides a stable high voltage regardless of battery age.

The power configuration of the EFR32 and the gas sensor can be configured as:

- Both the EFR32 and the gas sensor are supplied directly from battery.
- Both the EFR32 and the gas sensor are supplied from the output of the external DC-DC boost converter.
- The EFR32 is supplied directly from battery and the gas sensor is supplied from the output of the external DC-DC boost converter.

3. PCB layout and antenna design

Snapshots from the layout design are shown in the Figure 3.1 and Figure 3.2 below.
The PCB design follows the generic RF layout recommendations as much as possible on this space-constrained design. All components are located on the Top layer, except for the coin cell battery which is placed on the Bottom layer. The passive components used are from the same family as for the BRD4186C 10 dBm EFR32xG24 reference radio board.

The first inner layer ensures a low-impedance return path for the RF part by having continuous and unbroken ground plane on it. The layout design guidelines of AN928.2: EFR32 Series 2 Layout Design Guide were followed.

The antenna is tuned to resonate at 2.45 GHz by carefully choosing its width, length and meander gap distances. Similar considerations were made when choosing the proper parallel GND feedback leg geometry which has a role especially in the bandwidth of the antenna. Another function of the GND feedback leg is to tune the resonance impedance to 50 Ohm. This was investigated using the S11 plot, as the deeper the resonance minimum is, the closer the input impedance of the antenna is to 50 Ohm at that frequency.

A meandered antenna configuration appeared to provide better antenna efficiency and bandwidth properties compared to a general straight IFA design in this small form factor (additionally, the rounded shape of such gas sensors had to be taken into account when designing the antenna). The reason for this could be due to the definition of the Q factor (which is proportional to the reciprocal of the bandwidth), that is the ratio of the imaginary and real part of the antenna impedance. More antenna surface increases the real part of the impedance, therefore decreases Q factor or increases bandwidth. Meandering is usually not necessary for larger PCBs with larger antennas.

To maximize the length of the radiating element of the antenna (thus the bandwidth) in this confined dimension, the antenna feed leg is placed closer to the PCB which is relatively uncommon for IFA designs. Meandering also introduces a property that can be considered as a tradeoff: the radiating length of the antenna has to be longer than for a straight IFA with the same resonant frequency. This yields more bandwidth (due to the bigger antenna), but a larger occupied area. Fortunately, the design could comprise an antenna with the proper dimenions.

There is a also trade-off in choosing the size of the antenna copper clearance, as the bigger the clearance the better the antenna performance (bandwidth and efficiency), but also bigger the PCB is.

The manufactured PCB has the radiating part of the IFA antenna left longer then simulated in CST Studio in case the manufactured PCB has some unexpected detuning effects. Therefore, the tuning of the resonance frequency was done by cutting back the length of the antenna. As expected, the simulations proved to be an accurate estimation– as will be shown later – as the reduced 2.45 GHz resonant antenna length was exactly as long as calculated in CST studio.

Due to the nature of gas sensor applications (e.g. medical wearable devices), the antenna of the customer end product must be designed with the consideration of a human bodypart in the near field of the antenna, which detunes the resonance frequency downwards by a significant 100 to 300 MHz. In that scenario, a shorter antenna would be required, which could even further reduce the size but also decrease bandwidth and efficiency.

The design includes three holes in a line at the lower area of the PCB which are for the placement of the three gas sensor electrodes. The bottom side of the PCB over that area is not occupied, so a plastic case for the 3 gas sensors could be placed there.

The IFA antenna in the design files at Silicon Labs hardware design examples Github page is properly covered with solder mask, unlike on the photographed images of the manufactured units (see Figure 1.1), where the IFA is intentionally not covered with solder mask to allow for the possibility to modify it physically. Solder mask around the area of the antenna shifts the resonance frequency down by only a couple of MHz compared to the uncovered version. According to Figure 4.5, this shift would be well within the acceptable range.

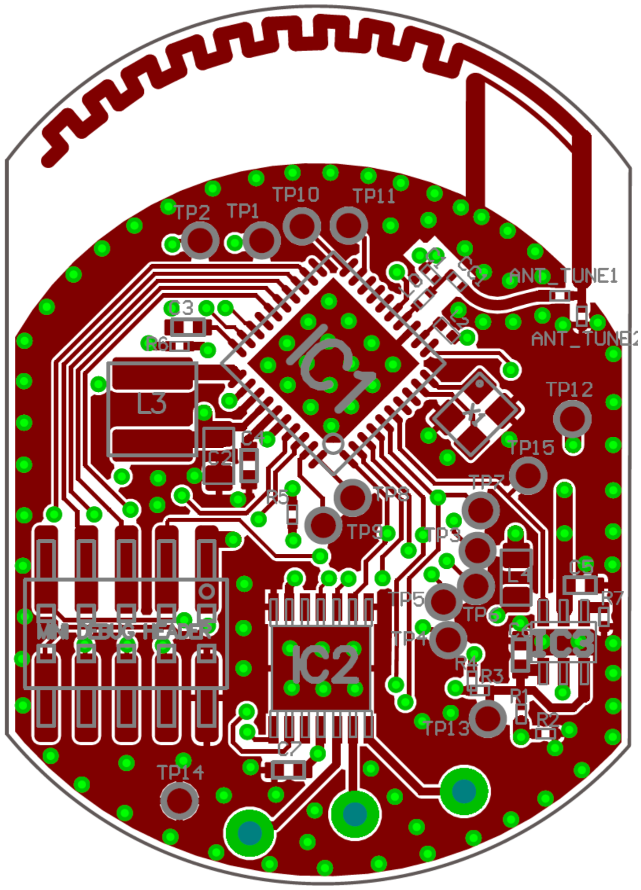

Figure 3.1 Top layer view

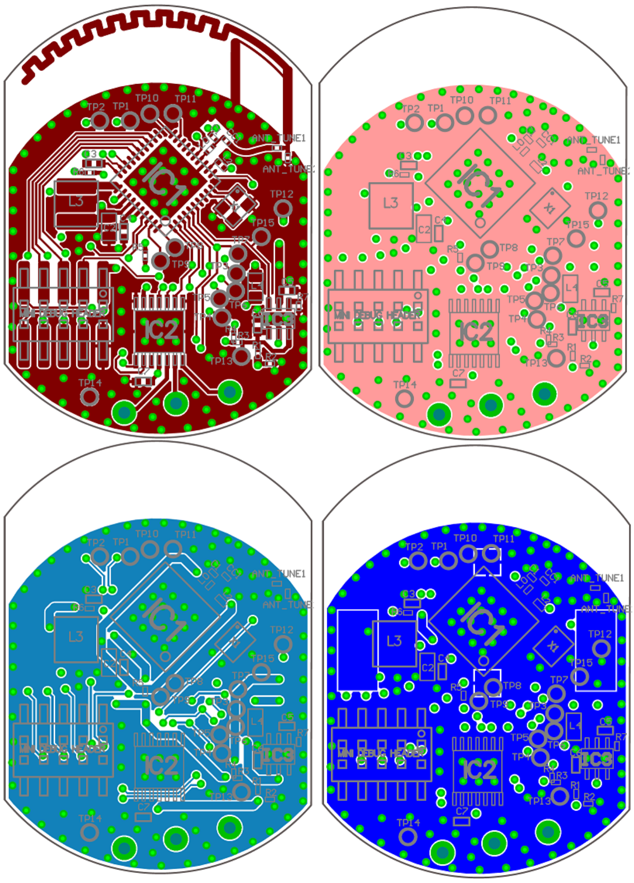

Figure 3.2 All 4 layers (Top, Inner 1, Inner 2 and Bottom)

<u>Notes</u>**:**

- The reduced length of the printed antenna on layout images above (from the design files) is the finalized tuned value.
- To prevent the VDD traces from being grounded out by the coin cell due to the presence of VDD vias and a short VDD signal running underneath it on the Bottom layer, the design incorporates a "lever" (Keystone 2991) for the coin cell that keeps it elevated and away from the Bottom layer.

4. Antenna simulation and measurements

The antenna design has been simulated in CST Studio 3D EM simulator tool. The simulated complete PCB structure is an import file from Altium Designer and is shown in the figure below. The excitation port is a 50 Ohm coaxial waveguide port at the input of the antenna.

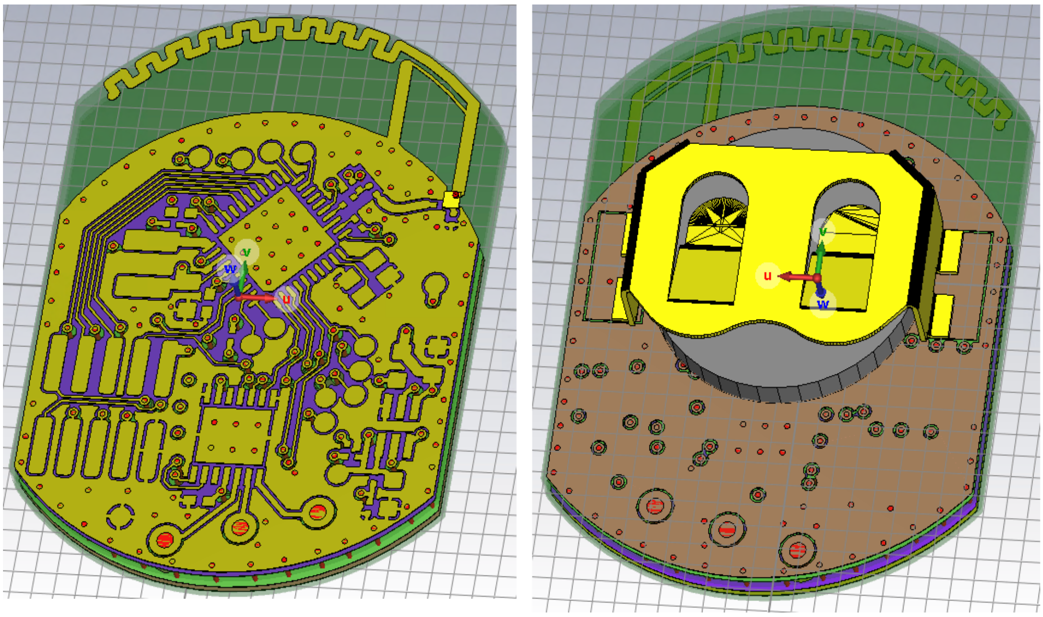

Figure 4.1 Simulation model in CST

The simulated antenna parameters are plotted in the following figures below.

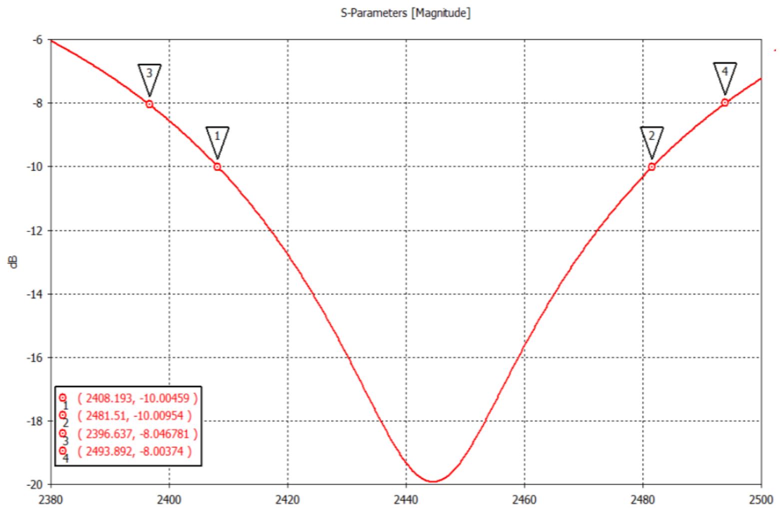

Figure 4.2 Simulated antenna S11

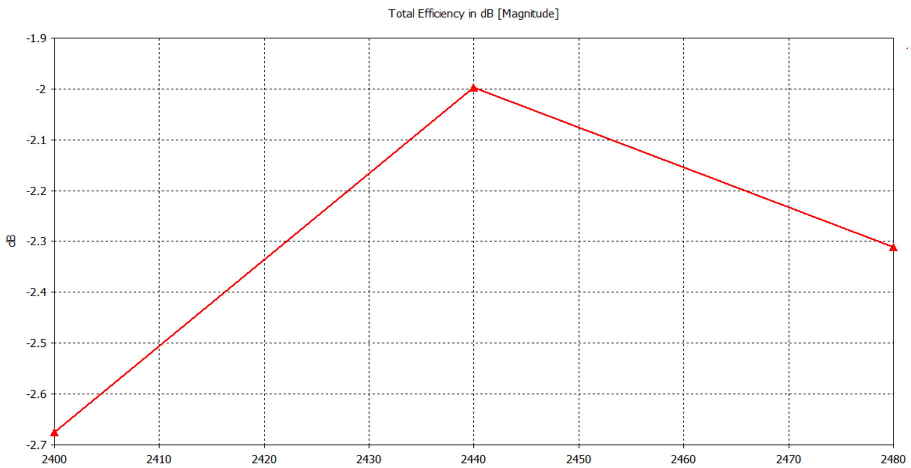

Figure 4.3 Simulated antenna efficiency

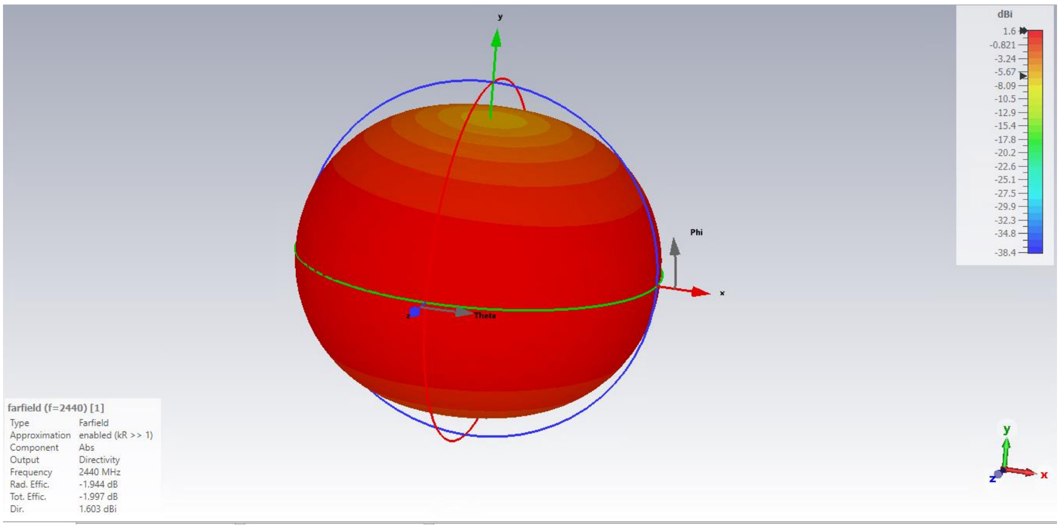

Figure 4.4 Simulated antenna far-field properties

The maximum gain can be calculated as:

Gain = maximum Total Efficiency (dB) + Directivity (dBi) = -1.997 + 1.603 = **-0.394 dBi**

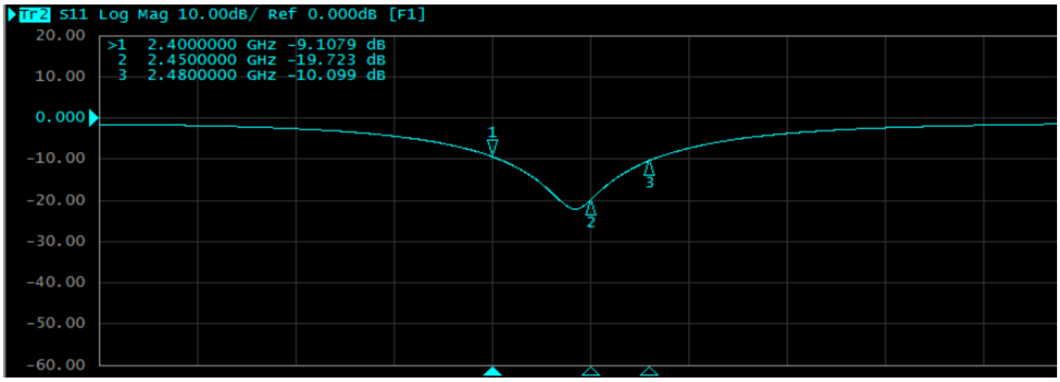

Figure 4.5 Measured S11 with the reduced antenna length for 2.45 GHz resonance

The measurement above was performed on a VNA with 50 Ohm port impedance, thus the antenna input impedance is close to 50 Ohm at 2.45 GHz.

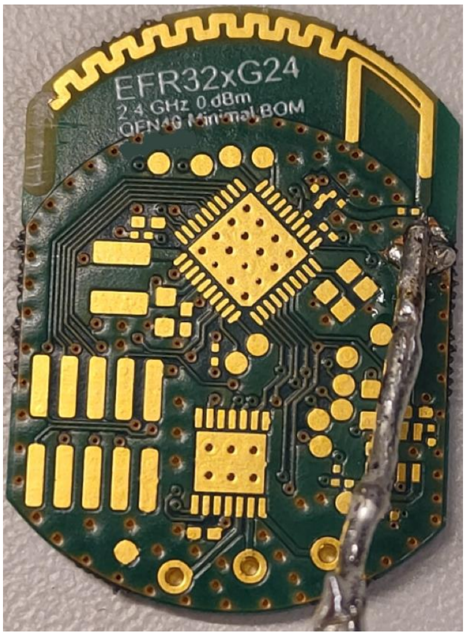

Figure 4.6 PCB with reduced antenna length for 2.45 GHz resonance

On Figure 4.6, a coaxial probe called pigtail is soldered onto the input of the IFA for the VNA measurement.
It is visible comparing Figure 4.1 to Figure 4.6 that the simulated ideal antenna length was an accurate predictor for the reduced length of the manufactured PCB. The same can be stated about the S11 parameters, comparing Figure 4.2 to Figure 4.5.

5. RF measurements

The module was powered from a Silicon Labs Wireless Starter Kit (WSTK) through the debug interface.
The power supply voltage conditions: VREGVDD = AVDD = IOVDD = 3.3 V, DVDD = RFVDD = PAVDD = 1.8 V

a. Conducted TX and RX measurements

The table below summarizes the conducted TX power and harmonic, and RX BER 0.1% measurements. The total TX current consumption was also measured directly at the coin cell connection.

Due to the lack of an SMA or U.FL connector in the design, a coaxial probe called pigtail was soldered onto the ouput of the co-planar transmission line that follows the matching network. The PCB antenna was electrically de-attached for these measurements by not populating the series antenna tuning placeholder at the antenna input.

Table 5.1 Conducted TX measurements with unmodulated CW signals [dBm]

<table>
<tr><th colspan="2">Power Settings</th><th>Frequency</th><th>fund</th><th>H2</th><th>H3</th><th>H4</th><th>H5</th><th>I_TX</th></tr>
<tr><td rowspan="5">10 dBm PA</td><td rowspan="3">35 raw</td><td>2402 MHz</td><td>7.6</td><td>-51</td><td>-41.5</td><td>< -60</td><td>-38.3</td><td>20.9 mA</td></tr>
<tr><td>2445 MHz</td><td>7.7</td><td>-50</td><td>-41</td><td>< -60</td><td>-38.1</td><td>21 mA</td></tr>
<tr><td>2480 MHz</td><td>7.6</td><td>-51</td><td>-41.5</td><td>< -60</td><td>- 38.3</td><td>20.9 mA</td></tr>
<tr><td>30 raw</td><td>2445 MHz</td><td>7</td><td>-51</td><td>-41.5</td><td>< -60</td><td>-38.5</td><td>18 mA</td></tr>
<tr><td>28 raw</td><td>2445 MHz</td><td>6.7</td><td>-48</td><td>-49</td><td>< -60</td><td>-38.8</td><td>16 mA</td></tr>
<tr><td>0 dBm PA</td><td>15 raw</td><td>2445 MHz</td><td>0.1</td><td>< -60</td><td>-51</td><td>< -60</td><td>-50</td><td>5.9 mA</td></tr>
</table>

The maximum allowed power level was determined by the most critical 5th harmonic. For the investigation, -38 dBm was taken as a minimum harmonic value that should not be exceeded, as considering a similar radiated value, there is still a couple of dB worst case modulated margin on the FCC -41.2 dBm limit (see Table 5.3).

For the RX measurement, an external RF signal generator was used to generate a 1Msps 500K 2GFSK PN9 modulated stream.

Table 5.2 Conducted RX measurements

Frequency	**BER 0.1%** (1M 500k 2GFSK)
2402 MHz	-97.6
2445 MHz	-97.6
2480 MHz	-97.6

<u>Conclusions from the conducted TX and RX measurements:</u>

- The conducted power (at higher powers) is about 1 dB less than the nominal value set.
- The current consumption is close to datasheet values.
- The BER 0.1% sensitivity corresponds to the datasheet reference -97.7 dBm value.

<u>Note:</u>

- Using the 10 dBm PA at an output power level of as low as 0 dBm still results in 12 mA power consumption.

b. Radiated TX measurements

The table below summarizes the radiated TX power and harmonic measurements. The radiated measurements were performed in an anechoic antenna chamber. The PCB was spun around all 3 symmetry planes (XY, XZ, YZ), while the receiver antenna was measuring the received power in a horizontal, then a vertical orientation.

The results can be seen in the table below (best case fundamental and worst case harmonics):

Table 5.3 Radiated TX measurements with unmodulated CW signals [dBm]

	Power settings	Frequency	fund	H2	H3	H4	H5
10 dBm PA	35 raw	2402 MHz	7.8	-48.5	-39.4	-57.2	-43.3
		2450 MHz	9.2	-56.7	-37.8	-58.3	-36.2
		2480 MHz	10.9	-48.8	-40.6	-57.1	-44
	30 raw	2450 MHz	7.9	-54.1	-41.3	-57	-39.8
	25 raw	2450 MHz	7.3	- 56	-43.2	-57	-39
0 dBm PA	**15 raw**	**2450 MHz**	**2.5**	**-59**	**-50**	**-57**	**-56**

The yellow values indicate that the -41.2 spurious limit of FCC was violated, however, the regulations concern modulated signals, and the measurements above were performance with an unmodulated CW signal. It is a common method to estimate the modulated values (worst case PHY) by subtracting 4.8 dB from the 3rd, and 6.3 dB from the 5th unmodulated CW harmonic values. This compensation results the following worst case harmonics:

- H3: -42.6 dBm (1.4 dB margin)
- H5 -42.5 dBm (1.3 dB margin)

<u>Conclusions from the radiated TX measurements:</u>

- A maximum 35 power setting proves to be the upper limit set by the 5th harmonic. This power level still allows 1.3 dB worst case modulated margin on the 5th harmonic.
- The 0 dBm PA at maximum power level complies with harmonic emission regulations with great margins.
- The maximum antenna gain seems to be around 2.5 dBi which showcases good antenna performance relative to the PCB size.

6. Final notes

- The EFR32MG24 Minimum BOM sensor design complies to FCC and ETSI harmonic regulations at 8 dBm output power or lower.
- Current consumption is close to datasheet reference values.
- RX sensitivity corresponds to the datasheet reference values.

For designs with a CR1216 lithium coin cell battery, the 0 dBm PA is recommended for use due to the higher current conspumption of the 10 dBm PA.

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