DEMO DISTANCE2GO

XENSIV™ 24 GHz radar demo board

Board version V1.1

About this document

Scope and purpose

This application note describes the key features of Infineon's DEMO DISTANCE2GO board equipped with the XENSIV™ 24 GHz BGT24MTR11 MMIC and the 32-bit Arm® Cortex®-M4 based XMC4200 microcontroller and helps the user to quickly get started with the demonstration board.

1. The application note describes the hardware configuration and specifications of the sensor module in detail.
2. It also provides a guide to configure the hardware and implement simple radar applications with the firmware/software developed.

Intended audience

This document serves as a primer for users who want to get started with hardware design for distance measurement and speed estimation using Frequency Modulated Continuous Wave (FMCW) and Doppler radar techniques at 24 GHz.

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1 Introduction

The DEMO DISTANCE2GO is a demonstration platform for Infineon's silicon-germanium (SiGe) based 24 GHz BGT24MTR11 radar chipset. The board is capable of measuring distance, speed and direction of movement (approaching or departing). These features of the board make it suitable for various applications such as motion detection, presence sensing, proximity sensing, etc.

The Distance2Go board consists of the following key components:

- BGT24MTR11 – highly integrated 24 GHz transceiver MMIC with one transmitter (TX) and one Receiver (RX)
- XMC4200 – 32-bit Arm® Cortex®-M4 based microcontroller for signal processing
- IRLHS2242 – 20 V single P-channel HEXFET power MOSFET for duty-cycle operation
- XMC4200 onboard debugger – licensed firmware for Serial Wire Debug (SWD) and UART to USB communication

The radar techniques used on the board are Continuous Wave (CW/Doppler) radar for velocity estimation and FMCW for distance measurements. In the CW/Doppler technique, the principle of the Doppler effect is used. The radar transmits a constant frequency signal continuously and receives the echo signal from the moving target. The change in phase between the transmitted and received signal is used to calculate the target's velocity.

In FMCW, the time delay between the transmitted and received chirp is used for measuring distance to the target(s). The transmitted and received signals are mixed and then quantized for further processing. An onboard low-noise fractional-N Phase Locked Loop (PLL) performs the frequency control and FMCW ramp generation. Multi-stage low-noise baseband amplification stages are used for enhanced target detection.

The module provides a complete radar system evaluation platform including demonstration software and a graphical user interface (GUI), which can be used to display and analyze acquired data in time and frequency domain. An onboard breakable debugger with a licensed firmware from SEGGER enables easy debugging over USB. Infineon's powerful, free-of-charge toolchain DAVE™ can be used for programming the XMC4200 microcontroller. The board also features integrated micro-strip patch antennas on the PCB with design data, thereby eliminating antenna design complexity at the user end.

This application note describes the key features and hardware configuration of the Distance2Go module in detail.

1.1 Key features

The primary features of the Distance2Go board are:

- Measuring distance of multiple targets in a user-configurable range (1 to 50 m)
- Detecting motion, presence, speed and direction of movement (approaching or retreating) for human targets
- Small form factor: 5 x 3.6 cm
- Operational in different weather conditions such as rain, fog, etc.
- Can be hidden in the end application as it detects through non-metallic materials
- Dual analog amplifier stages for the RX channel
- Micro-strip patch antennas with 12 dBi gain and 20 x 42 degrees Field of View (FoV)
- Onboard PMOS switch for duty-cycle operation and lower power consumption

Note: The platform serves as a demonstrator platform with the software to perform simple motion sensing and ranging. The test data in this document show typical performance of Infineon-produced platforms. However, board performance may vary depending on the PCB manufacturer and specific design rules they may impose and components they may use.

2 System specifications

Table 1 gives the specifications of the Distance2Go module.

Table 1 Distance2Go module performance specifications

Parameter	Unit	Min.	Typ.	Max.	Comments
System performance					
Minimum speed	km/h		0.35		Based on the formula: Min speed (m/s) = λ /(2 × $N_{FFT,D}$ × PRT) in D2G_Doppler_FMCW firmware λ = wavelength (m) $N_{FFT,D}$ = DOPPLER_FFT_SIZE PRT= Pulse Repetition Time
Maximum speed	km/h		5.6		Based on the formula: Max speed (m/s) = λ /(4 x PRT) in D2G_Doppler_FMCW firmware λ = wavelength (m) PRT= Pulse Repetition Time
Minimum distance	cm		50		Radar Cross-Section (RCS) = 1 m^2 and 10 m^2
Maximum distance	m		15 26		RCS = 1 m^2 RCS = 10 m^2
Range accuracy (for values beyond 50 cm)	cm		±30 ±20		RCS = 1 m^2 RCS = 10 m^2
Power supply					
Supply voltage	V		5	5.5	
Supply current	mA		400		All blocks on (no duty-cycle)
Transmitter characteristics					
Transmitter frequency	GHz	24.0		24.25	
Effective Isotropic Radiated Power (EIRP)	dBm		+21		**Conditions:** BGT P_{OUT} : +11 dBm Loss (TX_{OUT} to ant. input = 2 dB) Simulated ant. gain = +12 dBi
System phase noise with PLL	dBc/Hz		-89		At 100 kHz offset, VCOARSE = VFINE. Measured in CW mode
External oscillator frequency	MHz		40		
Receiver characteristics					
Receiver frequency	GHz	24.0		24.25	

Table 1 Distance2Go module performance specifications

Parameter	Unit	Min.	Typ.	Max.	Comments
System performance					
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Minimum distance	cm		50		Radar Cross-Section (RCS) = 1 m^2 and 10 m^2
Maximum distance	m		15 26		RCS = 1 m^2 RCS = 10 m^2
Range accuracy (for values beyond 50 cm)	cm		±30 ±20		RCS = 1 m^2 RCS = 10 m^2
IF conversion gain – low gain (stage 1)	dB		34		Default setting of the sensor module when delivered
-3 dB bandwidth – low gain (stage 1)	kHz		2 to 200		Default setting of the sensor module when delivered
IF conversion gain – high gain (stage 1 + stage 2)	dB		64		Can be selected by reconfiguring the ADC pins in DAVE™ project
-3 dB bandwidth – high gain (stage 1 + stage 2)	kHz		14 to 120		Can be selected by reconfiguring the ADC pins in DAVE™ project
Antenna characteristics (simulated)					
Antenna type			2 x 4		
Horizontal – 3 dB beamwidth	Degrees		42		
Elevation – 3 dB beamwidth	Degrees		20		
Horizontal sidelobe level suppression	dB		-13		
Vertical sidelobe level suppression	dB		-13		

Note: The above specifications are indicative values based on typical datasheet parameters of BGT24MTR11 and simulation of several other parameters (antenna characteristics and baseband section) and can vary from module to module. The numbers above are not guaranteed indicators for module performance for all operating conditions.

3 Hardware description

3.1 Overview

The Distance2Go module contains a radar main board and a breakable debugger board, as shown in Figure 1. The radar main board contains four important sections:

- RF part – consists of the Infineon 24 GHz radar MMIC – BGT24MTR11 and includes micro-strip patch antennas for the TX and RX sections;
- Analog amplifier part – provides the interface between the RF and digital parts of the board;
- Frequency control part – contains a low-noise fractional-N PLL;
- Digital part – consists of XMC4200, 32-bit Arm® Cortex®-M4 microcontroller from Infineon to sample and process the analog data from the radar front end and to configure the BGT24MTR11 and PLL via an SPI.

The board demonstrates the features of the BGT24MTR11 RF front-end chip and gives the user a complete "plug and play" radar solution. It makes it possible to quickly gather sampled radar data that can be used to develop radar signal processing algorithms on a PC or implement target detection algorithms directly on the microcontroller using DAVE™.

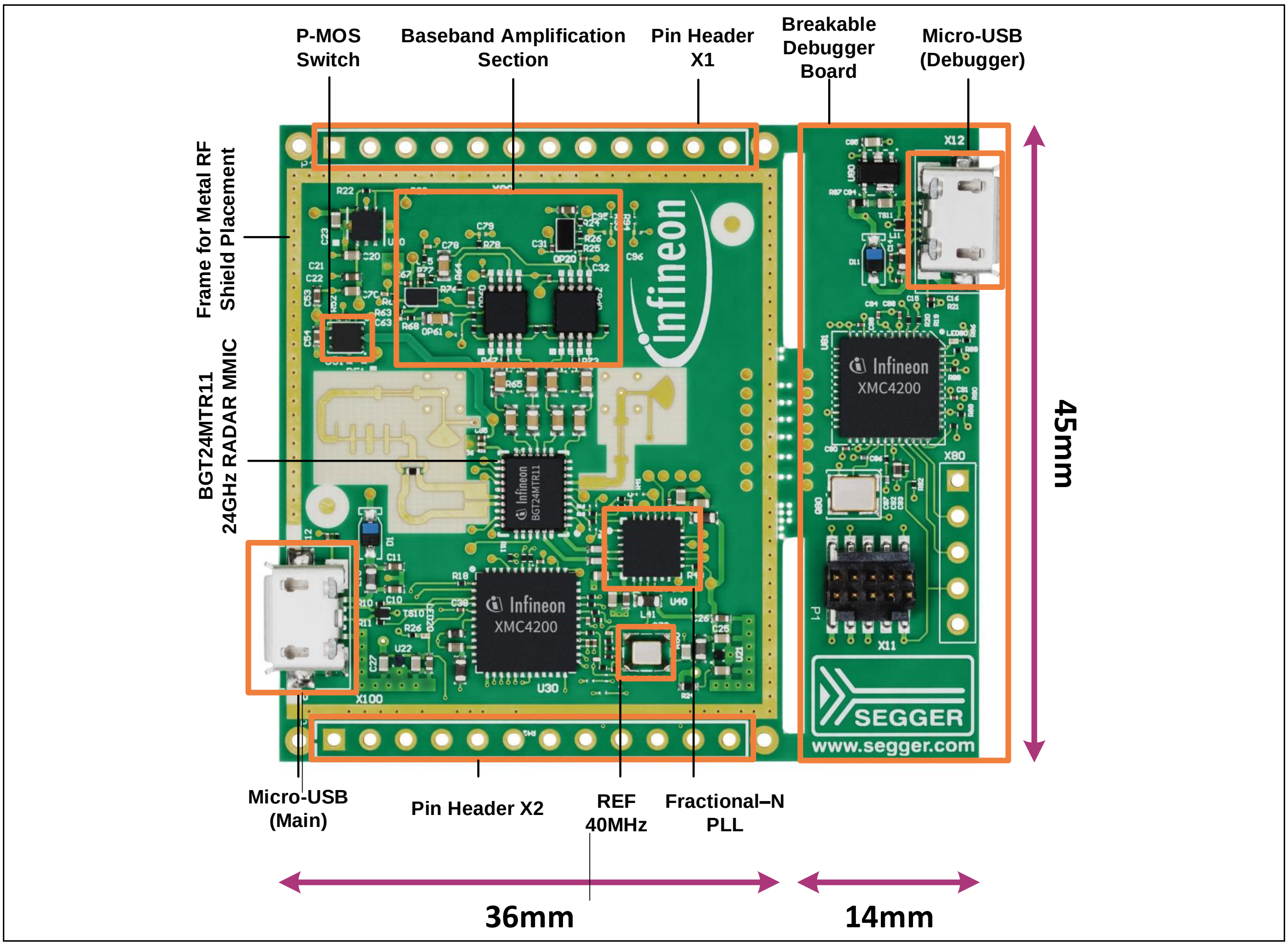


Figure 1 Distance2Go board with main components and dimensions

3.2 Hardware features

The Distance2Go demo board has the following features:

- BGT24MTR11 24 GHz RF front-end chip with 1 TX and 1 RX with the following specifications:
    - Low Noise Figure (NF_{SSB}): 12 dB
    - High conversion gain: 26 dB
    - High 1 dB input compression point: -12 dBm
    - Switchable prescaler with 1.5 GHz and 23 kHz output
    - On-chip power and temperature sensors
- XMC4200 Cortex-M4 microcontroller for sampling and signal processing of the analog signals with the following features:
    - 80 MHz CPU frequency, 256 kB Flash and 40 kB RAM size
    - Two Capture/Compare Units (CCU4) for use as general-purpose timers
    - Two 12-bit ADCs, eight channels each, with input out-of-range comparators and a 12-bit DAC with two channels
    - USB 2.0 device, with integrated PHY, Controller Area Network interface (MultiCAN), Full-CAN/Basic-CAN with two nodes, 64 message objects (MOs), data rate up to 1 MBit/s
    - Four Universal Serial Interface Channels (USICs), providing four serial channels, usable as UART, double-SPI, quad-SPI, I^2C, I^2S and LIN interfaces
- Onboard breakable debugger with UART communication
- Onboard low-noise fractional-N PLL with chirp generation
- Dual analog amplifier stage for each RX channel with user-configurable gain settings
- Power supply:
    - Via micro-USB connector
    - Via external power supply (5 V maximum)

3.3 Block diagram

Figure 2 shows the block diagram of the demo board. The board is split into a RF unit and a breakable debugger unit for programming. The RF unit consists of the highly integrated 24 GHz transceiver MMIC BGT24MTR11 with 1 TX and 1 RX. The MMIC features an integrated Voltage Controlled Oscillator (VCO), Power Amplifier (PA), integrated temperature and power sensors, prescalers and IQ receivers.

The board also has integrated micro-strip patch antennas, and a Wilkinson combiner is used to combine the differential transmitter output power from the radar MMIC before feeding it to the antennas. Each receiver channel is connected to a dual analog amplifier stage at its IF outputs. A 32-bit Arm® Cortex®-M4 XMC4200 microcontroller is used to sample and process the analog down-converted signals from the baseband amplifiers using the integrated 12-bit ADC and control the radar chip via the SPI. The output power of the radar chip and the gain of its receive section can be controlled via the SPI settings. There are also SPI commands to read out the different sensor outputs.

A low-noise fractional-N PLL IC is used to perform the frequency control and ramp generation. The output of the /16 integrated prescaler on the radar MMIC is connected to the PLL RF input pins, and the output voltage from the PLL charge pump is connected via a loop filter to the tuning ports of the BGT24MTR11, thereby forming a closed-loop system. This procedure is used to lock the transmitted signal of the module to an output frequency inside the ISM band. The /65536 integrated prescaler produces a low-frequency output signal (23 kHz), which is connected to a CCU4 of the XMC4200 for monitoring purposes.

The module is powered over the micro-USB plug, and several low-noise voltage regulators are used to provide a regulated power supply to the different building blocks .The BGT24MTR11 MMIC is supplied over a PMOS, which enables operation of the sensor in a duty-cycle mode. The breakable onboard debugger comes preloaded with licensed firmware for debugging and communicating with the main radar MCU via the UART pins. Pin headers on the PCB enable the sensor module to be interfaced with an external processor.

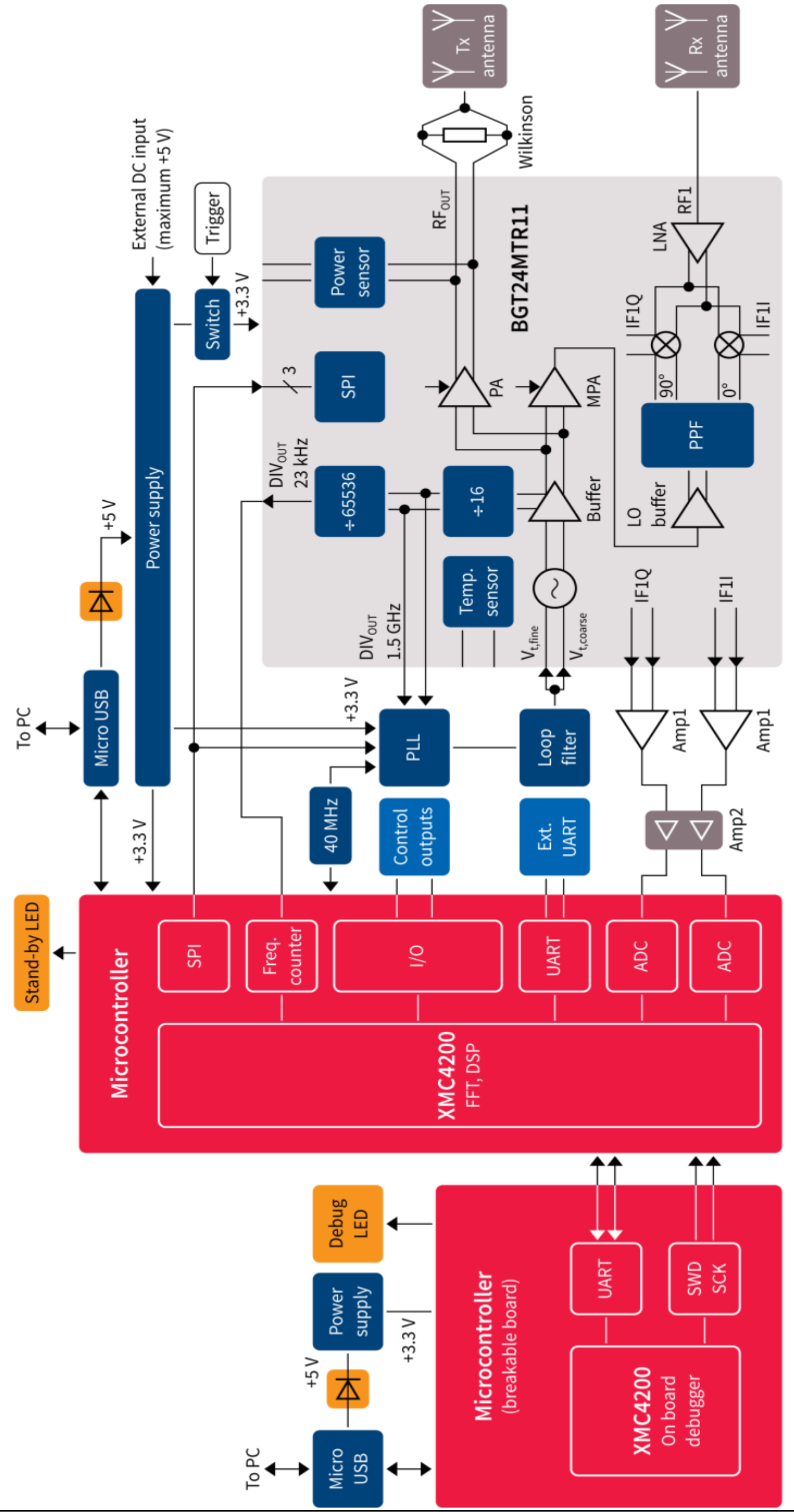

Tx antenna
Rx antenna
Wilkinson
RF_{OUT}
BGT24MTR11
Power sensor
SPI
3
PA
MPA
LNA
RF1
IF1Q
IF1I
90°
0°
PPF
LO buffer
Buffer
÷65536
÷16
DIV_{OUT} 23 kHz
DIV_{OUT} 1.5 GHz
Temp. sensor
$V_{t,fine}$
$V_{t,coarse}$
External DC input (maximum +5 V)
Trigger
Switch
+3.3 V
Power supply
+5 V
To PC
Micro USB
+3.3 V
PLL
Loop filter
40 MHz
Control outputs
Ext. UART
Amp1
Amp1
Amp2
Stand-by LED
Microcontroller
SPI
Freq. counter
I/O
UART
ADC
ADC
XMC4200
FFT, DSP
Debug LED
Power supply
+5 V
+3.3 V
To PC
Micro USB
Microcontroller (breakable board)
UART
SWD SCK
XMC4200
On board debugger

Figure 2 Block diagram – Distance2Go demo board

3.4 Power supply

Figure 3 shows the power supply concept used on the module. The board is powered via micro-USB connector when used with a PC. The power supply can also be provided via an external DC input pin (5 V maximum). The USB plugs on the main board as well as the breakable debugger board can be used to supply the module.

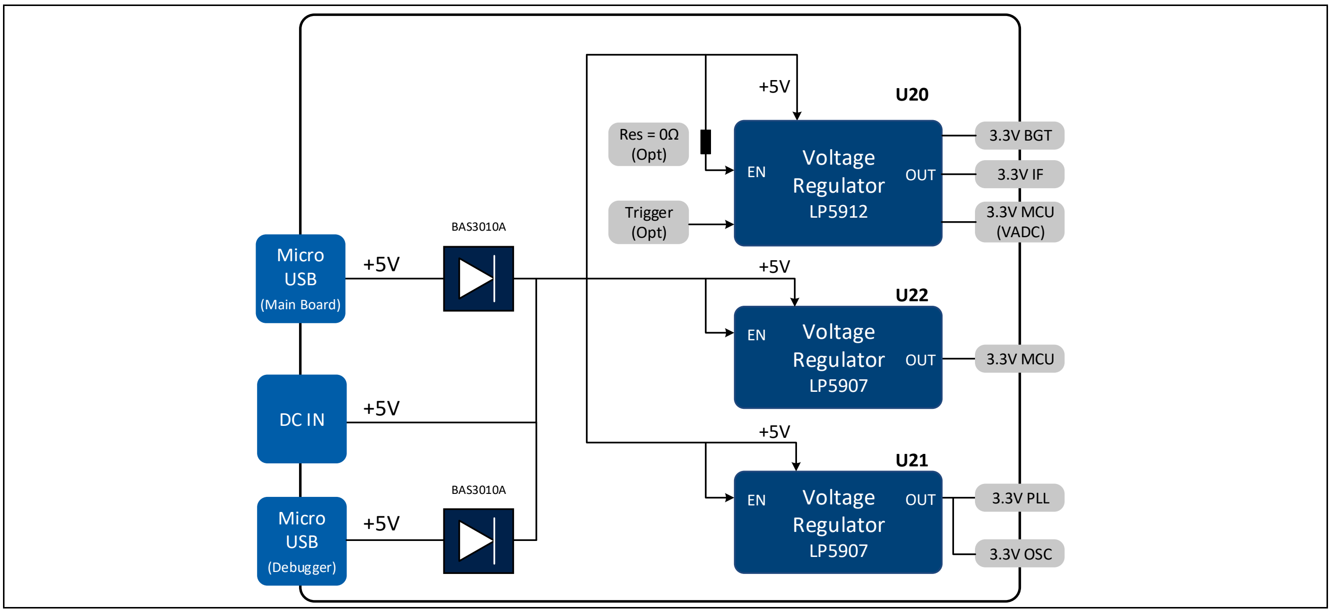


Figure 3 Block diagram – power supply concept

The power supply via the USB or external input is provided to three different voltage regulators. The 24 GHz transceiver MMIC is powered by a low-noise voltage regulator U20. U20 has an enable pin, which is connected to the input voltage pin via a 0 Ω resistor R22, as shown in Figure 4. The module also provides an option to trigger the enable pin via the P1.4 of the MCU. In this case, the resistor R22 must be removed and a 0 Ω resistor must be soldered in place of R23. Regulator U20 is also used to supply the analog domain of the XMC4200 MCU and the baseband IF amplifiers. A second low-noise voltage regulator U22 is used to supply the digital MCU of the board. A third low-noise regulator U21 is used to power up the PLL and the 40 MHz reference oscillator. The enable pins of U21 and U22 are hardwired to their input voltage pins on the PCB and are not available to the user.

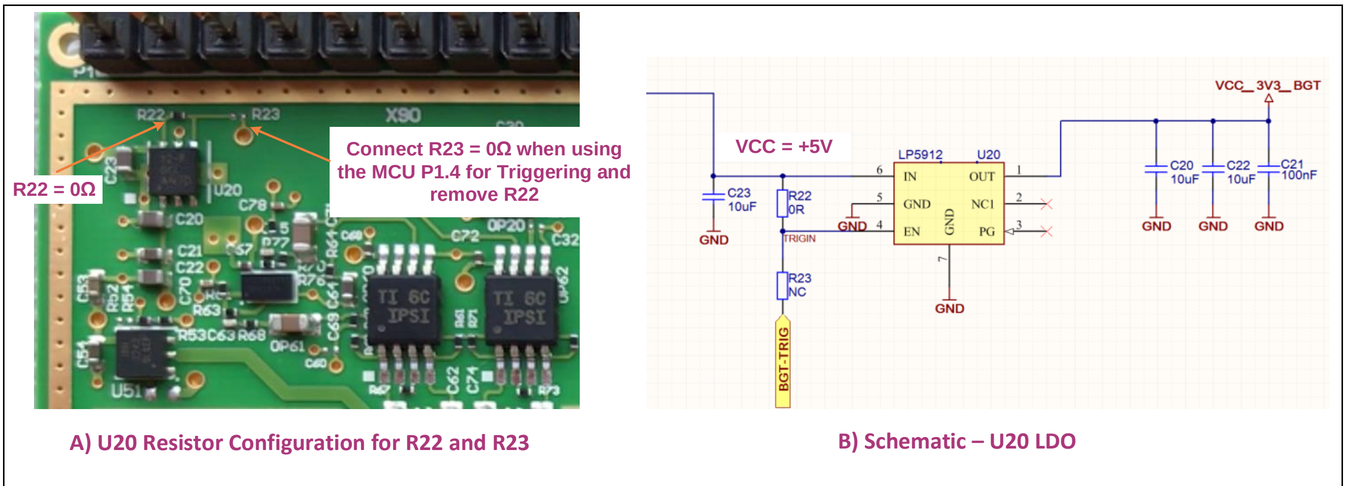


Figure 4 Configuration of U20 regulator for low-power operation

3.5 RF front end

Figure 5 shows the top view of the RF front end. The RF front end can be shielded with a cover and absorber material to get the best RF performance. The following paragraph describes the various sections of the RF front end in detail.

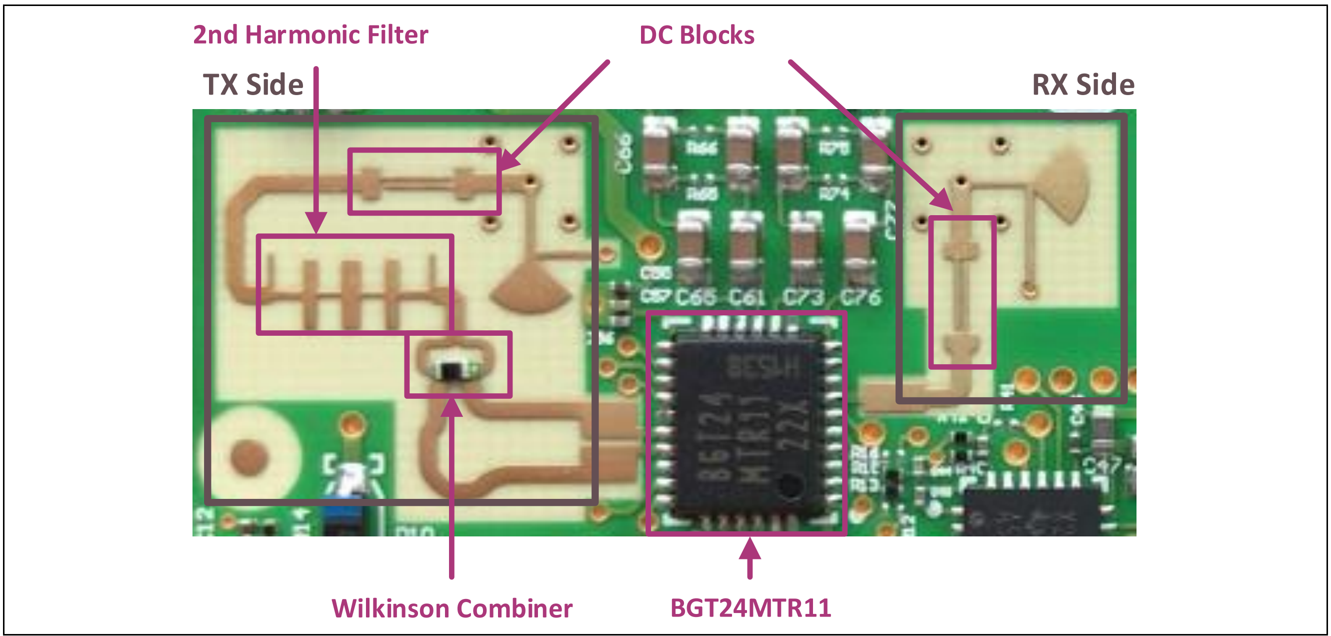


Figure 5 RF front end overview (top)

3.5.1 Board stack-up

It is necessary to use a defined board layer stack-up for proper functioning of the RF part. All the micro-strip RF parts must be calculated according to the stack-up used. The cross-sectional view of the PCB is shown in Figure 6. The module uses a six-layer stack-up with a symmetrical RO-4350B core. The matching structures for the transmitter and receiver part are designed based on this stack-up.

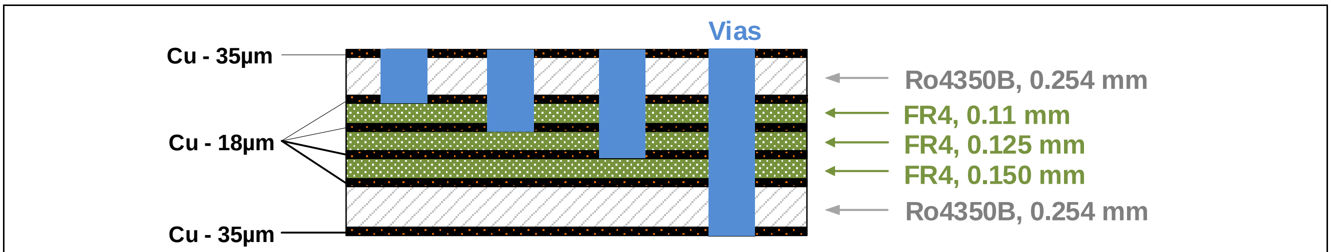


Figure 6 PCB cross-section

The most important part for the RF micro-strip components is the top and bottom RO-4350B, 0.254 mm-thick core. On the top layer (layer 1) are the micro-strip structures, and layer 2 is the RF ground for the micro-strip components used on the top layer. Layer 3 and layer 4 are used for routing various signals. On the bottom layer (layer 6) are the micro-strip patch antennas and layer 5 is the RF ground for the micro-strip patch antennas. The substrate thickness for the other layers has been chosen considering the blind-via diameters used on the PCB, and this can vary depending on the PCB manufacturing technology (aspect ratio). From simulations it was observed that such minor variation of the thickness of these FR4 substrates has a very low impact on the RF performance.

3.5.2 BGT24MTR11 – 24 GHz transceiver MMIC

The heart of the sensor module is the highly integrated BGT24MTR11 24 GHz transceiver MMIC. Figure 7 shows the detailed block diagram of the MMIC.

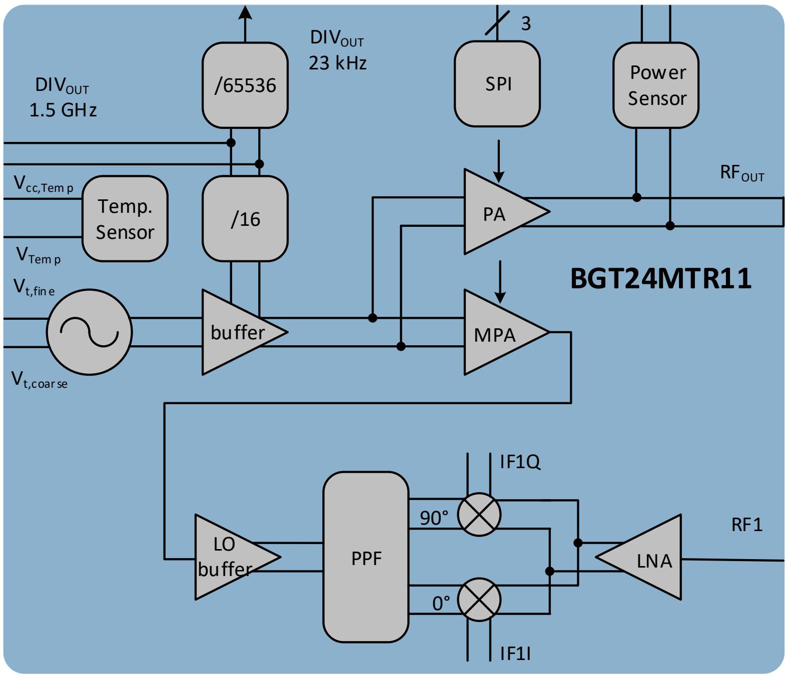


Figure 7 Block diagram – BGT24MTR11

The MMIC features a very high level of integration, which includes a VCO with prescaler outputs for frequency control, transmitter chain including amplifiers for both TX and LO outputs, as well as the complete receiver section including Low-Noise Amplifier (LNA) and mixer. The VCO is a free-running, fundamental oscillator. It can be controlled by two tuning inputs – one for coarse pre-adjustment, and one for fine-tuning.

There are two prescalers available in the VCO section of the chip. The first prescaler has an output frequency of 1.5 GHz and can be used to feed an RF PLL for frequency control. The second prescaler has a 23 kHz square-wave output that may be used by a microcontroller-based software loop. The TX section consists of a power amplifier with a differential output. Its typical output power is +11 dBm and can be reduced in eight steps down to 2 dBm. A part of the TX signal is used as the LO signal for the on-chip mixer.

The receiver section has a single-sideband NF of 12 dB and a voltage conversion gain of 26 dB. The gain of the LNA can be reduced by a typical gain-step of 5 dB. The built-in quadrature down-conversion mixer translates the RF signal directly to zero-IF.

Additionally, the chip features power sensors both on TX outputs and LO outputs, as well as a temperature sensor that supports the implementation of a software-based loop to control the VCO. The settings of the different internal building blocks can be controlled via an SPI.

3.5.3 Module transmitter section

The transmitter output of BGT24MTR11 is differential. The differential outputs are first connected over matching structures followed by a Wilkinson power combiner. The matching structures compensate for the bondwire inductance and other parasitic effects due to the VQFN package. Figure 8 shows the schematic of the transmitter section and the dimensions of the matching structures used at the TX outputs.

The Wilkinson power combiner combines the differential signals into single-ended ones. Following the power combiner a second harmonic micro-strip filter is used. The harmonic filter provides an attenuation greater than 20 dB for frequencies around 48 GHz and shows a simulated loss of approximately 0.5 dB. The filter path then goes over a DC block and a feed-through via to the other side of the PCB to the antennas. The simulated loss for the entire RF section connecting the TX output from the MMIC to the antennas on the other side of the board including the vias is approximately 2 dB. There are DC shorts before the feed-through vias for enhanced ESD protection.

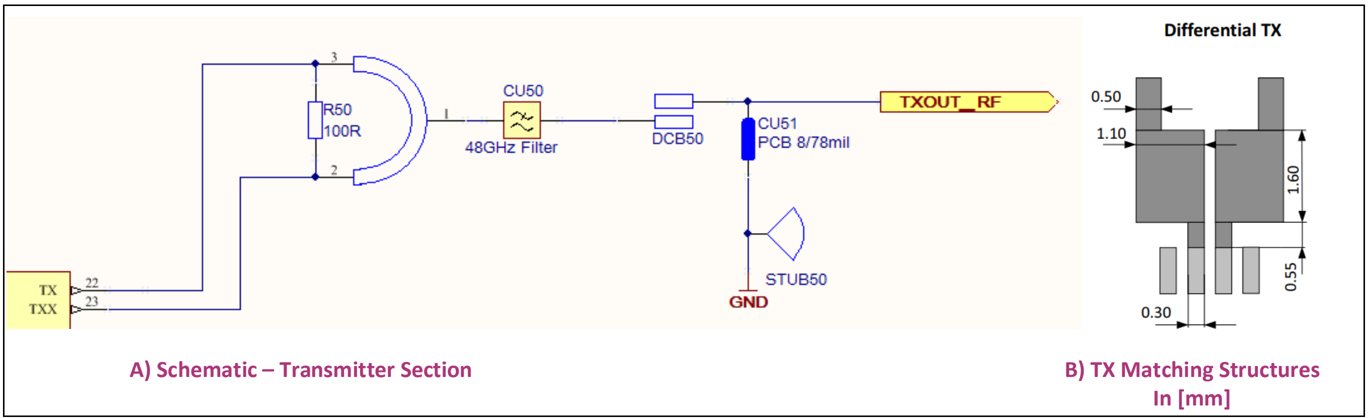


Figure 8 Transmitter section schematic and matching structure dimensions

3.5.4 Module receiver section

The receiver input of the BGT24MTR11 is single-ended. The RX input is connected over a matching structure, a DC block, and a feed-through via to the antennas on the other side of the board. Figure 9 shows the schematic of the receiver section and the dimensions of the matching structures used at the RX input. The simulated loss for the entire RF section connecting the RX input at the MMIC to the antennas on the other side of the board including the vias was approximately 1 dB. There are DC shorts before the feed-through vias for enhanced ESD protection.

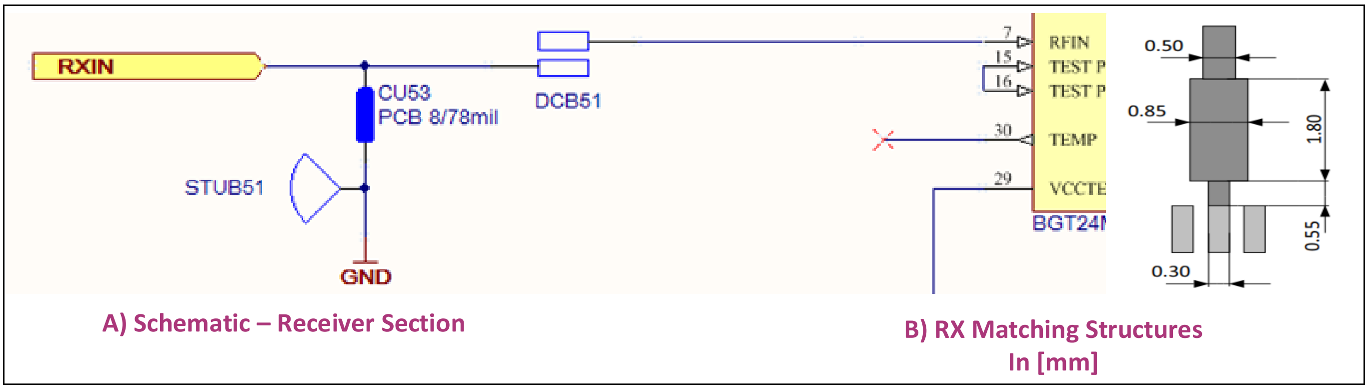


Figure 9 Receiver section schematic and matching structure dimensions

3.5.5 Antennas

Distance2Go features 2 x 4 micro-strip patch antennas for both transmit and receive sections. The antennas have a simulated gain of approximately 12 dBi and an opening angle of 20 x 42 degrees. The simulation includes via losses. Figure 10 shows the simulated 2D and 3D radiation pattern.

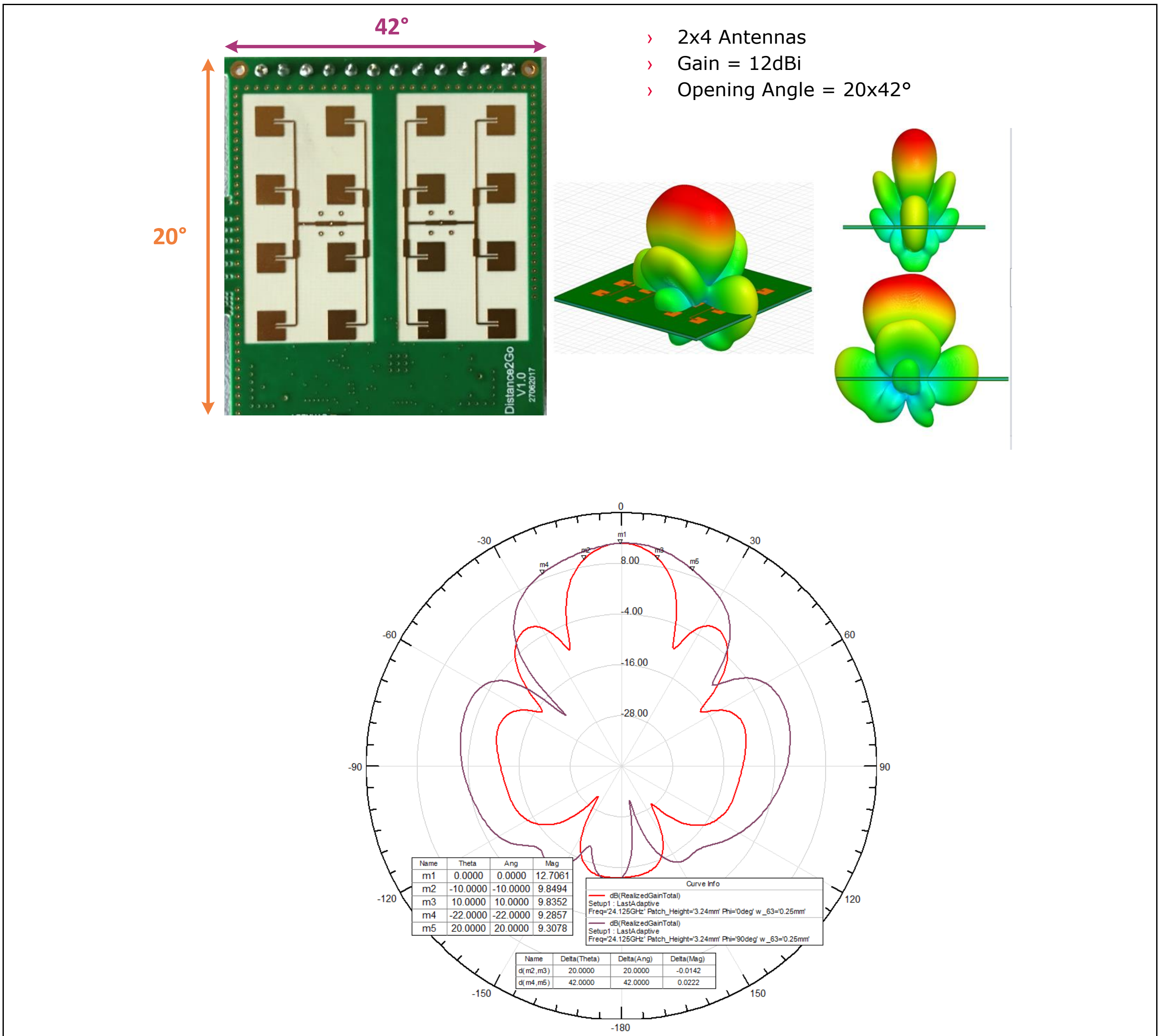
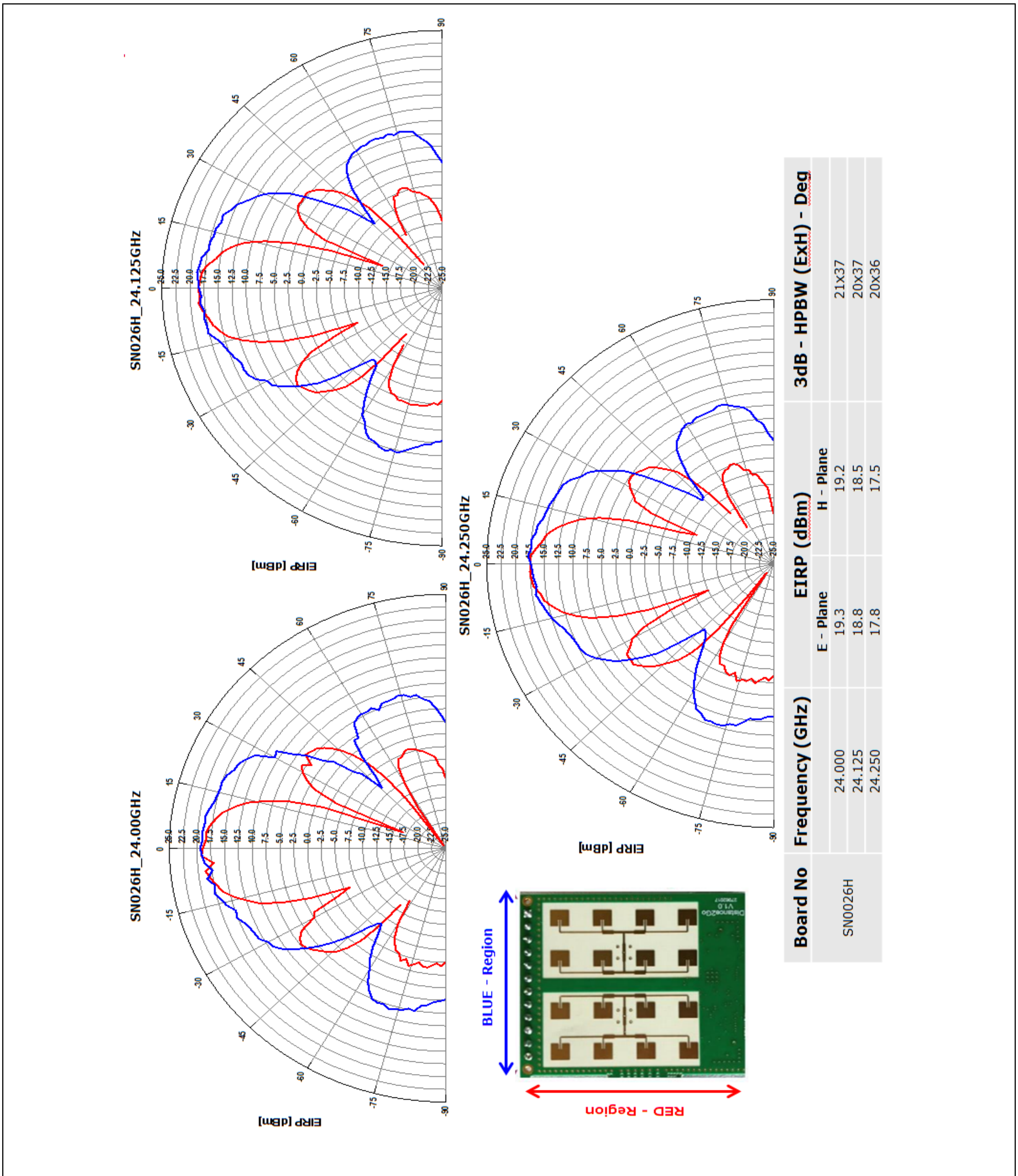


Figure 10 2D and 3D radiation pattern for micro-strip patch antennas (simulated)

Based on PCB material tolerances, the antenna performance can vary significantly from one production lot to another. Samples within the same production lot can also show significant variation in EIRP. This will in turn affect the EIRP of the sensor module. The EIRP variation of the modules also depends on the minimum, typical and maximum output power specifications of the BGT24MTR11 transmitter.

It must be noted that the values of 20 x 42 degrees are for 3 dB Half Power Beamwidth (HPBW). This implies that the gain of the antenna beyond these angles is 3 dB lower than the maximum gain at 0 degrees. In practical cases, a target with large RCS can still be detected for this reduced gain. In addition, weaker targets (i.e., low RCS) near the radar can also be detected outside the opening angles. Therefore a careful judgement has to be made regarding the radar detection zone by taking into account both the distance of the target from radar and also the target RCS.

The sensor was measured in an anechoic chamber to determine the EIRP and opening angle. Figure 10 shows the measured radiation characteristics within the ISM band. The sensor was operated in a continuous-wave mode for these measurements. Duty-cycle was turned off, which resulted in a PCB temperature close to 80°C. The higher operating temperature reduces the output power of the BGT24MTR11 MMIC by approximately 1 dB.



Board No	Frequency (GHz)	EIRP (dBm) E - Plane	EIRP (dBm) H - Plane	3dB - HPBW (ExH) - Deg
SN0026H	24.000	19.3	19.2	21x37
	24.125	18.8	18.5	20x37
	24.250	17.8	17.5	20x36

Figure 11 Measured radiation characteristics

3.6 Prescaler output and PLL section

BGT24MTR11 has two prescaler outputs: Q1/Q1n and Q2. Q1/Q1n represents the VCO output divided by a factor of 2^4 and is differential. Q2 represents the VCO output divided by a factor of 2^{20}. The Q1/Q1n output is connected to the RF input terminal of a low-noise fractional-N PLL with integrated ramp/chirp generation functionality. The prescaler output from the MMIC is DC-coupled. This is connected to the PLL via capacitors C51 and C52. The VCO can be controlled by DC inputs on two different pins: VCOARSE (Pin 5) and VFINE (Pin 4) of the BGT24MTR11. The VCOARSE and VFINE pins are tied together and connected to the PLL's charge pump output voltage via a loop filter circuit. The loop filter has been optimized for a wide bandwidth and low phase noise operation. A 40 MHz reference oscillator is used as the clock source for the PLL. Table 2 lists the loop filter components with their values.

Table 2 PLL loop filter components and values

Component	Value
C42	3.3 nF
C43	220 pF
C44	100 pF
R40	2.7 kΩ
R42	330 Ω

With the above values and appropriate PLL register and charge pump current settings, a phase noise better than -88 dBc/Hz is achieved for offset frequencies between 10 kHz and 1 MHz. For phase noise measurements the module was set into continuous-wave mode (Doppler) operation. The loop filter provides a wide bandwidth (greater than 250 kHz). The current firmware version provided with the module is tested with sawtooth ramps from 500 µs to 3 ms. In principle, use of other ramp types (e.g., triangular) and other ramp durations should also be possible. However, this is not tested using the provided firmware and may require reconsidering other system timing settings (e.g., duty-cycle, waiting times, etc.). The module can be configured for both Doppler and FMCW operation by choosing the appropriate PLL settings.

For the optimized PLL settings, refer to the DAVE™ project delivered with the "Radar Distance2Go" tool. To reduce the power consumption of the module, the PLL can be enabled/disabled via the Chip Enable (CE) pin or SPI. Apart from the SPI pins, Table 3 lists the other PLL pins accessible on the module via the MCU for various configuration settings.

Table 3 PLL pin description

Pin number – PLL	Description	Functionality	MCU pin connection
Pin 12	MOD	Multiplexed input/output pins for ramp triggers, FSK/PSK modulation, FastLock and diagnostics	P1.1
Pin 13	CE	Chip enable	P0.6
Pin 17	MUXOUT	Multiplexed input/output pins for ramp triggers, FSK/PSK modulation, FastLock and diagnostics	P2.1
Pin 20	TRIG 1	Multiplexed input/output pins for ramp triggers, FSK/PSK modulation, FastLock and diagnostics	P1.2
Pin 21	TRIG 2	Multiplexed input/output pins for ramp triggers, FSK/PSK modulation, FastLock and diagnostics	P1.3

The Q2 prescaler output from the BGT24MTR11 has 23 kHz frequency, and this signal is fed into the CCU4 of the XMC4200 MCU. This can be used to keep the VCO inside the ISM band by controlling the tuning voltage pins via the MCU's DAC. This procedure would eliminate the need for hardware PLL but requires complex ramp generating techniques and signal processing algorithms for proper target detection. The Distance2Go PCB is designed to implement this functionality if desired. However, Infineon currently does not provide any firmware, supporting such software-based ramp generation for distance measurement. When using the Q2 output, it is particularly important to keep the Q1/Q1n output terminated to obtain a proper Q2 signal at the microcontroller timer input. It is recommended to keep the Q2 divider off during signal processing to prevent unwanted spurs.

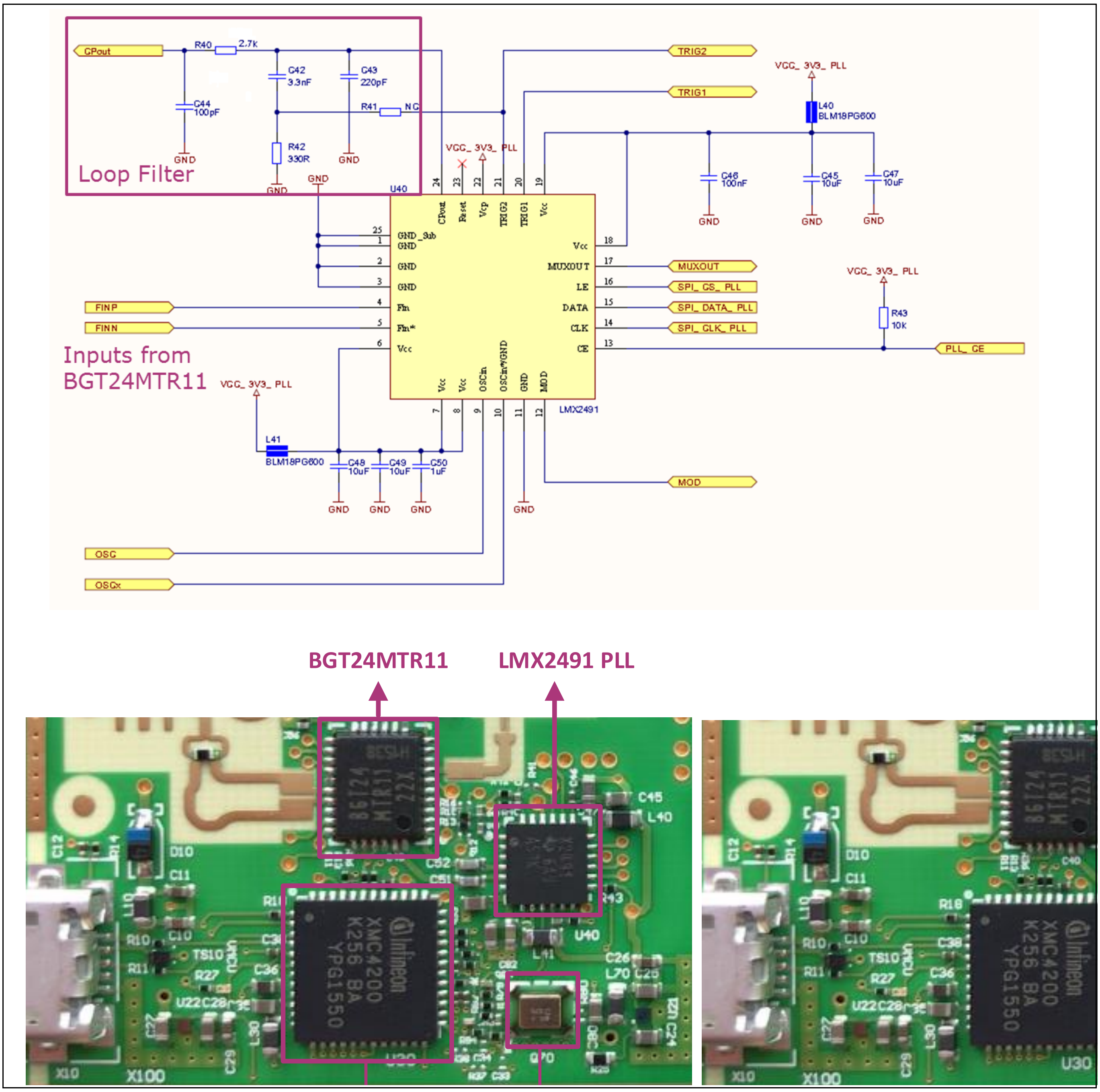


Figure 12 PLL section overview with loop filter components

3.7 Analog baseband section

The BGT24MTR11 provides both in-phase and quadrature-phase Intermediate Frequency (IF) signals from its receiver. The in-phase and quadrature-phase signals are differential in nature, thus making available four different IF output signals (IFIP, IFIN, IFQP and IFQN). Depending on the target in front of the radar antennas, the analog output signal from the BGT24MTR11 chipset can be very low in amplitude (µV to mV range). To process these low amplitude signals it is necessary to amplify the IF signals that comes out of the RF front end with analog amplifiers.

Each IF path comprises two stages of low-noise amplification. The first stage consists of two low-noise instrumentation amplifiers (OP60 and OP62), which also perform the differential to single-ended conversion of each pair of the IF signals. The second amplification stage consists of a single dual-channel op-amp (OP61) and provides a further 30 dB of amplification. An additional op-amp (OP20) is used to generate the reference voltage of 1.65 V for the baseband section. Figure 13 shows the location of the baseband components on the PCB and Figure 14 shows the detailed schematic of the baseband amplifier section.

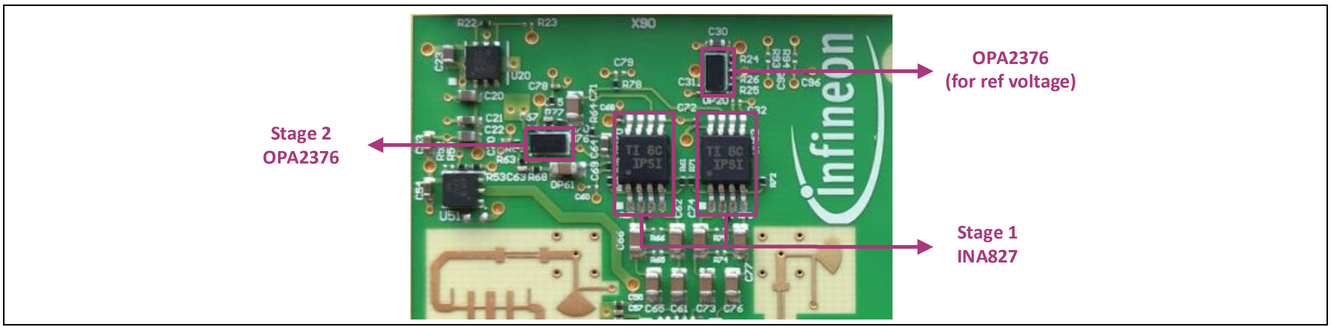


Figure 13 Baseband amplifier chain on PCB

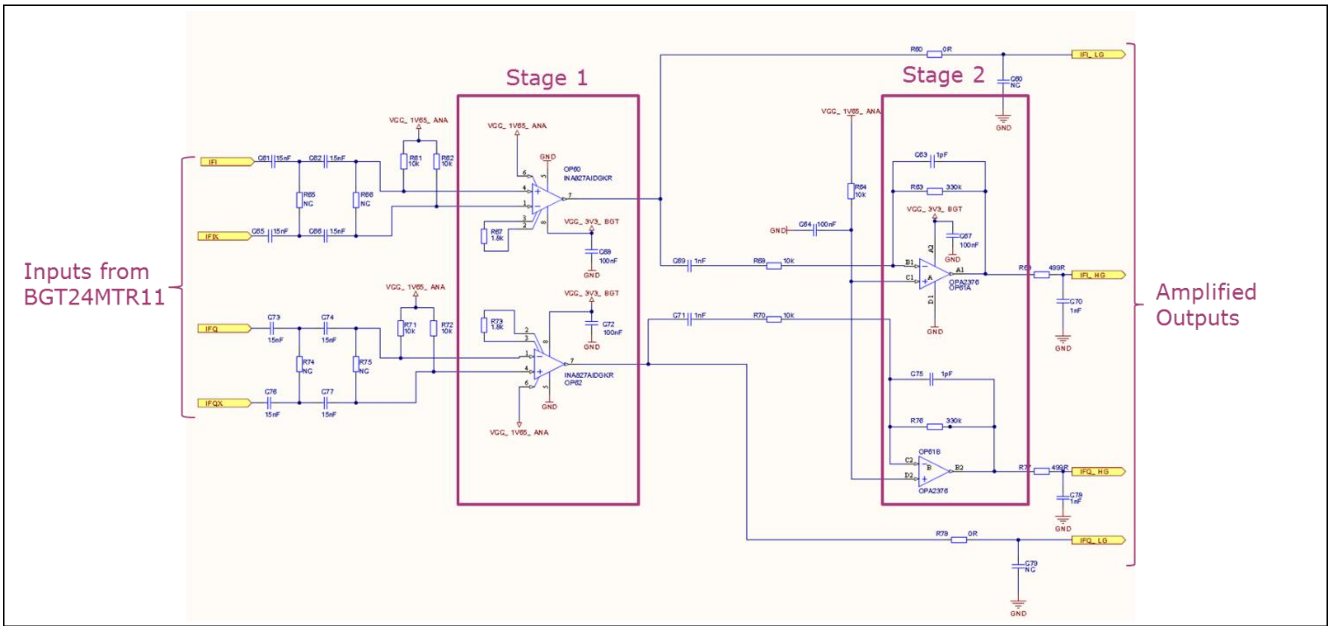


Figure 14 Baseband amplifier schematic

The Distance2Go module allows the user to select either the low gain (first stage only) or high gain (first stage + second stage) mode depending on the target RCS and the distance to be detected by simply configuring the MCU pin settings in the software. No hardware changes are needed for this process. Table 4 lists the MCU pins associated with each of the gain stages. Use the graphical pin select tool in the DAVE™ software to select the appropriate pins for signal processing.

Table 4 Baseband amplifiers to MCU pin connections

XMC4200 – QFN48 – port pin	Pin function
P14.0	IFI – low gain
P14.9	IFQ – low gain
P14.4	IFI – high gain
P14.3	IFQ – high gain

The gain and bandwidth of the IF stages are fixed and can be manually configured by the user by changing the resistor and capacitor values specified in Table 5.

Table 5 Baseband amplifier components and settings

IF stage	Designator	Gain	Bandwidth (-3dB)	Configurable components – I section	Configurable components – Q section
Stage 1 (low gain)	OP60, OP62	34 dB	2 kHz to 200 kHz	C61, C62, C65, C66, R61, R62 (for high-pass response) R67 (for gain and low-pass response)	C73, C74, C76, C77, R71, R72 (for high-pass response) R73 (for gain and low-pass response)
Stage 1 + stage 2 (high gain)	OP60, OP62 + OP61	64 dB	14 kHz to 120 kHz	All components as mentioned for stage 1 + C63, C69, R63, R68	All components as mentioned for stage 1 + C71, C75, R70, R76

3.7.1 Overview – low gain mode

The Distance2Go module in its delivery state is configured to use the low gain mode (stage 1).

Due to limited isolation between the TX and RX of the radar system, there is a feedthrough of the TX signal into the RX part. Due to this effect, there is always a dominant low-frequency component at the receiver output of the radar MMIC. The value of this low-frequency component depends on the value of the FMCW ramp settings. This low-frequency signal will be further amplified by the gain of the baseband section and may completely saturate the radar IF chain (ADCs and further amplifier stages). This effect is inherent to all FMCW radar systems and cannot be eliminated completely in the analog domain. However, by using appropriate filtering, the effect of this crosstalk can be minimized. This requires the implementation of filtering stages prior to the amplification of the IF signal by the baseband section. For this reason, the baseband section of the Distance2Go module is designed to have a bandpass characteristic. Stage 1 (low gain mode) is designed for a gain of 34 dB with a 3 dB bandwidth from 2 kHz to 200 kHz. The TX to RX crosstalk effect also limits the minimum distance that can be measured by the radar.

For targets with an RCS around 10 m^2, low gain mode enables measurement of distances up to 25 m. For targets with an RCS of 1 m^2 (corresponding to humans), detection is possible up to 12 m but also depends strongly on the measurement environment. To change the frequency response of the low gain stage, the components mentioned in Table 5 can be modified on the PCB. The low-pass response of this stage is fixed by the amplifier's internal bandwidth. The gain can be changed easily by configuring resistors R67 and R73. Figure 15 shows the frequency response of the low gain stage.

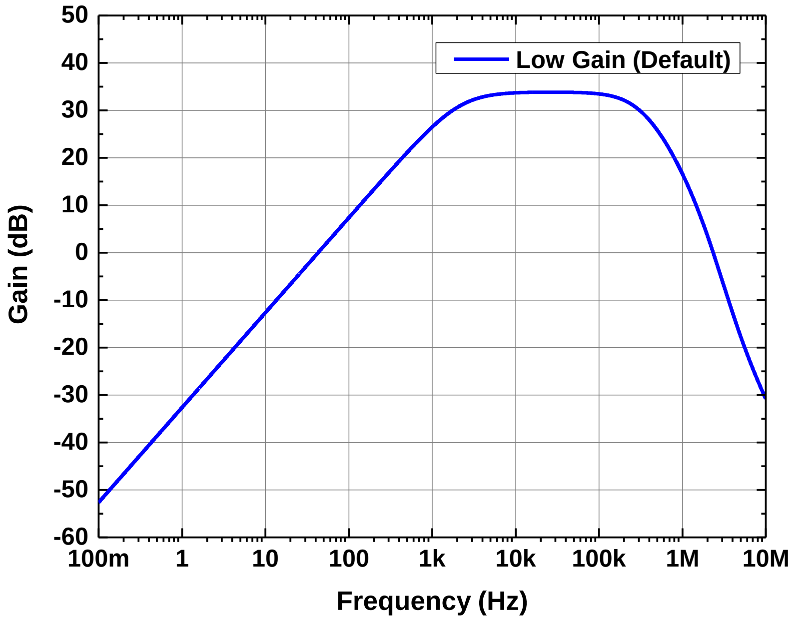
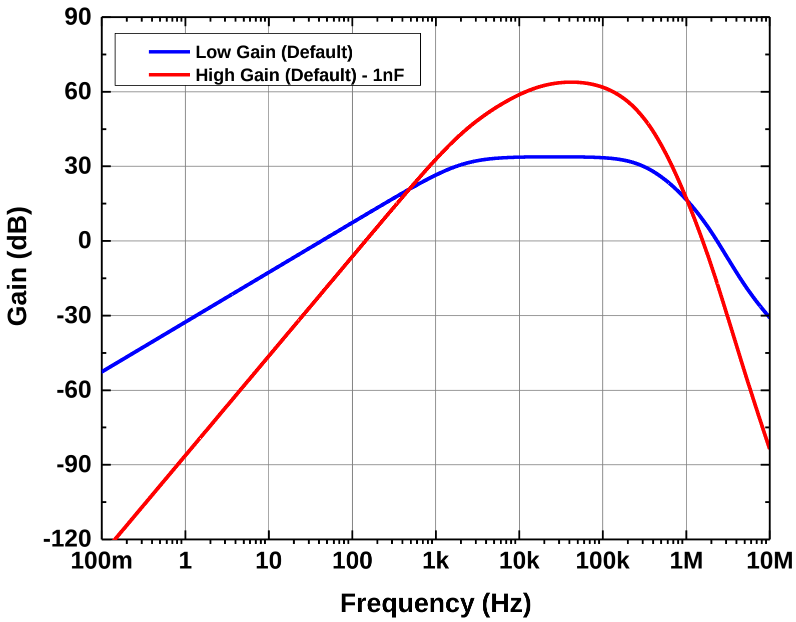


Figure 15 Baseband frequency response – low gain mode

3.7.2 Overview – high gain mode

The second amplification stage is optional and may be used depending on the application and the target RCS to be detected. The second IF amplifier is designed for an individual gain of 30 dB and in combination with the first IF stage provides a total IF gain of 64 dB with a 3 dB bandwidth from 14 kHz to 120 kHz, as shown in Figure 16.



(C69 = C71 = 1nF – Red Curve)

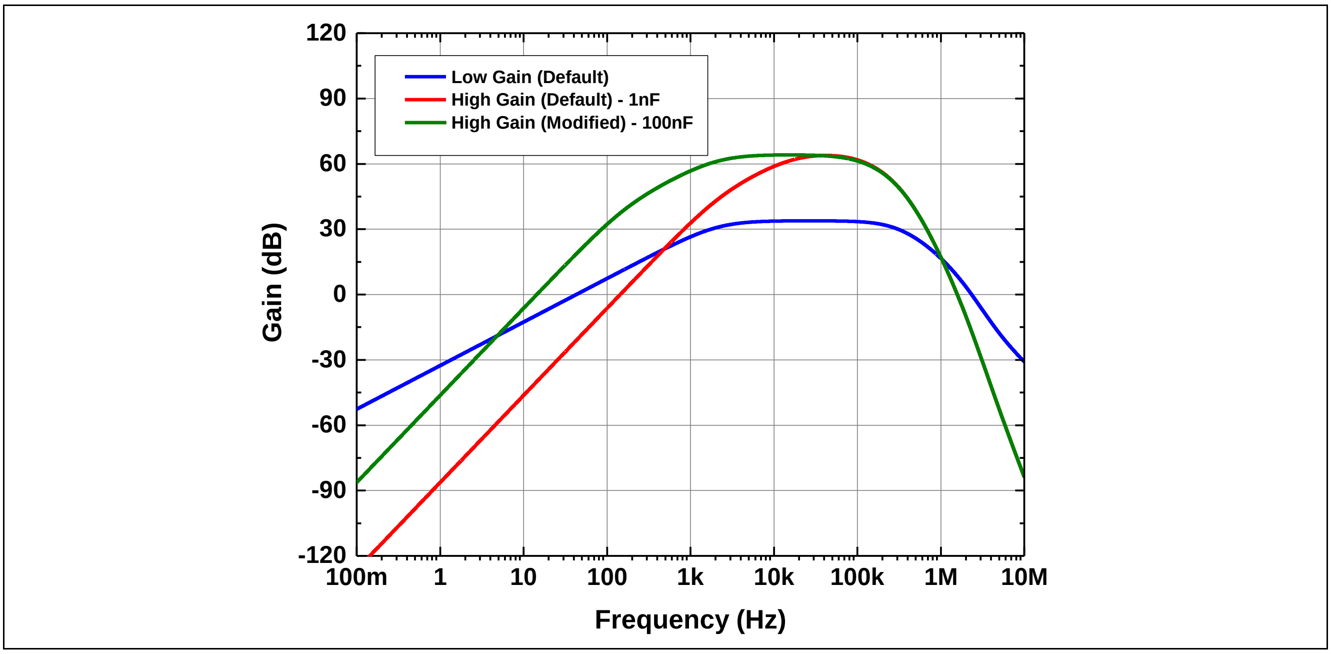
Figure 16 Baseband frequency response – high gain mode

For short-range measurements (less than 25 m) it is sufficient to use only a single IF amplification stage (low gain mode) thereby keeping the BOM cost low. For long-range measurements (greater than 25 m), and for targets with very low and varying RCS (e.g., human beings) the radar may not be able to provide precise detection depending on the environmental conditions. Also, the variation of several parameters (both RF and baseband) over different PCBs and silicon ICs makes the situation more complex. In such cases enabling the high gain mode on the module could improve the detection range. Especially when the IF frequencies are between 5 kHz and 100 kHz, the received signal strength could be improved sufficiently for detection by the radar.

When enabling the high gain mode, it must be ensured that signals close to DC are not amplified significantly, leading to saturation of the ADCs. This may lead to several spurious signals at the IF output. To minimize the impact of the TX to RX leakage, the high gain mode operation offers a higher high-pass cut-off frequency than the first IF stage, as shown by the red curve in Figure 16. The operation of the high gain mode is very sensitive to the radar operating environment. If the environment surrounding the radar has many reflecting objects, all of them will be significantly amplified by the baseband section and may prevent the signal processing algorithm from separating the desired signal from the clutter.

The enabling of the high gain mode certainly benefits the detection of low RCS targets at longer distances. However, for certain targets like trees, grass (especially dry grass) and other vegetation, and very thin cables, which have even smaller RCS, detecting them successfully even at shorter distances becomes extremely challenging due to very weak reflected signals. For such applications just switching to high gain mode may not be beneficial anymore. Such applications may also require modification of the frequency response of the baseband amplifiers to achieve greater gain for lower frequencies.

For short distance measurements of targets with very low RCS it is recommended to provide more gain at lower frequencies by changing the high-pass corner frequency of the IF section. An easy way to achieve this on the Distance2Go platform is to enable high gain mode and modify only the C69 and C71 capacitors' values. This will reduce the high-pass filter cut-off frequency and thus provide higher baseband gain for low RCS targets at shorter distances from the radar. Figure 17 gives an example of such a case wherein the high-pass filter cut-off frequency is changed to 2 kHz from the default value of 14 kHz by changing the capacitor values of C69 and C71 from 1 nF to 100 nF (green curve). This also provides a much higher gain than the low gain mode for lower frequencies. However, doing this will also affect the TX to RX crosstalk component and will impact the minimum distance the radar can measure. In these cases, special signal processing techniques need to be applied in the digital domain to successfully detect and measure smaller distances to such targets.



(C69=C71=100nF – Green Curve)

Figure 17 Baseband frequency response – high gain mode improved

In general, the suggestions for using a second gain stage in the preceding sections are just helping the user to easily change the baseband section for different target scenarios, with minimal effort. For a final product design, great care must be taken to configure both the gain stages independently. There could be situations where the gain of the first stage is high enough to saturate the second stage completely due to the amplification of TX to RX crosstalk. Therefore for situations requiring the use of two stages of amplification, it is recommended to completely redesign the baseband section based on the application requirements, and if required modify all the components of the baseband section listed in Table 5.

3.7.3 IF section and FMCW ramp settings

The bandpass characteristics of the IF section are also determined from the FMCW ramp parameter settings. Different ramp settings result in different IF frequencies for targets at different distances. Table 6 gives an example of IF frequencies produced by stationary targets at particular distances corresponding to different sawtooth-type ramp parameters. These IF frequencies are also called as “beat frequencies”. The beat frequencies calculated in the table do not include the Doppler shift.

The $Beat\ Frequency\ (Fb)$ is calculated from the following formula:

$$Beat\ Frequency\ (Fb) = \frac{2 * \mathrm{R} * \Delta\mathrm{f}}{\mathrm{c} * T_r}$$

Where R = target distance in meter (m)

Δf = ramp bandwidth in Hertz (Hz)

T_r = ramp time in second (s)

c = speed of light in meter/second (m/s)

Table 6 IF frequency vs. FMCW ramp parameters vs. target distance

Ramp duration (µs)	Ramp bandwidth (MHz)	Beat frequency (kHz)			
		Target at 50 cm	Target at 10 m	Target at 30 m	Target at 50 m
1000	180	0.600	12	36	60
1000	220	0.733	14.7	44	73
1500	180	0.400	8	24	40
1500	220	0.489	9.8	29	49
2000	180	0.300	6	18	30
2000	220	0.367	7.3	22	36

3.7.4 Baseband amplifier settings for implementing Doppler radar

The Distance2Go module is optimized for FMCW radar. The firmware delivered with the module nevertheless also allows the user implementing Doppler radar to perform simple movement and direction of movement detection. However, due to the current high-pass filter cut-off frequency settings of both the gain stages, the Doppler effect produced by very small target movement will not be detected by the radar. Slow Doppler movements produced by targets far from the radar will not be detected either. The high-pass and low-pass filter settings that are currently optimized for the FMCW case significantly reduce the detection range of the radar for Doppler applications, especially for slow-moving targets. Therefore, for Doppler applications, it is recommended to modify the baseband amplifier filter section appropriately to enable the module to detect lower frequencies with sufficient amplification.

Once again, as mentioned in section 3.7.2, this can be easily achieved by modifying only the capacitor C69 and C71 values. Table 7 gives an overview of the Doppler frequencies generated by targets with different speeds. The baseband section should be configured accordingly to provide sufficient gain at these frequencies.

Table 7 Doppler shift frequencies for different speeds using 24 GHz radar

Speed (km/h)	1	1.5	2	2.5	3	4	5	6	8	10
Doppler shift (Hz)	44.4	66.7	88.9	111.1	133.3	177.8	222.2	266.7	355.6	444.4

3.8 Duty-cycle circuit for low-power operation (default mode)

The Distance2Go module offers the possibility to operate the BGT24MTR11 and PLL in a duty-cycle mode. This is done by enabling/disabling the PMOS (U51) over the pin P0.5 of the MCU, as shown in Figure 18. Toggling this pin allows switching on/off the power supply to the MMIC over the FET. The signal is low-active and has a pull-down resistor in place. The PLL is switched on/off using the CE pin. In its default state the module is already programmed for duty-cycle mode of operation.

It is strongly recommended to use the module in a duty-cycle mode to keep the overall power consumption and thermal dissipation low. The Distance2Go was designed to have a compact form factor. Keeping the BGT24MTR11 always turned on will heat up the module significantly and could result in undefined behavior. In such cases it is recommended to turn off all the unused building blocks inside the BGT24 via the SPI and for short distance measurements reduce the transmit output power to minimum. Also putting the microcontroller in a deep sleep mode when not in operation will help to minimize power consumption and thermal dissipation significantly. The current firmware does not include the settings to put the microcontroller in a power-optimized mode.

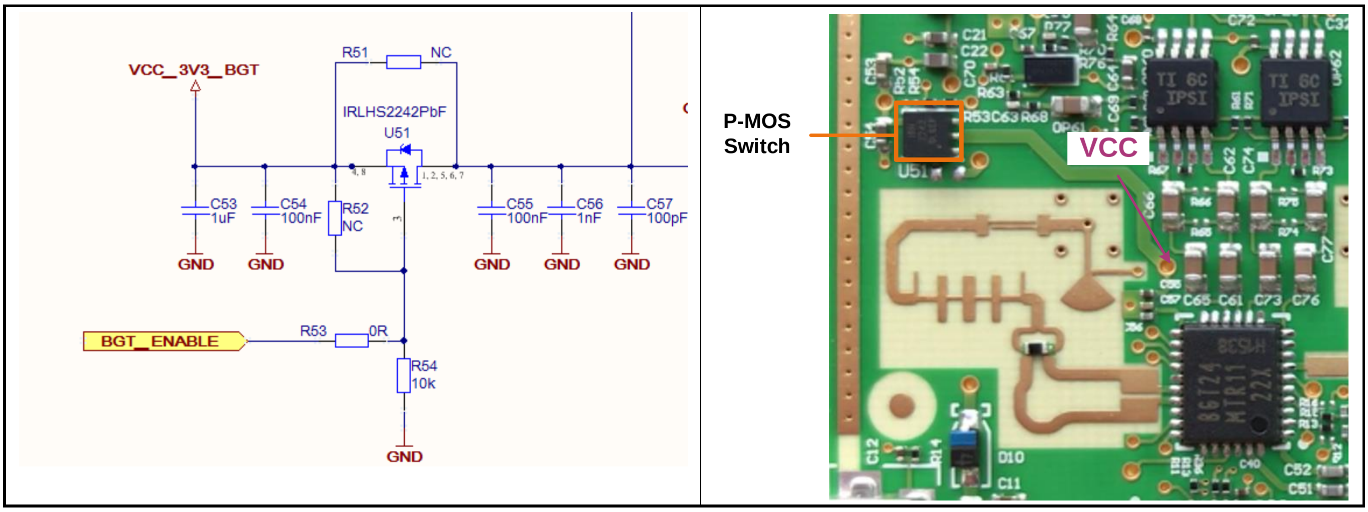


Figure 18 BGT24MTR11 duty-cycle concept

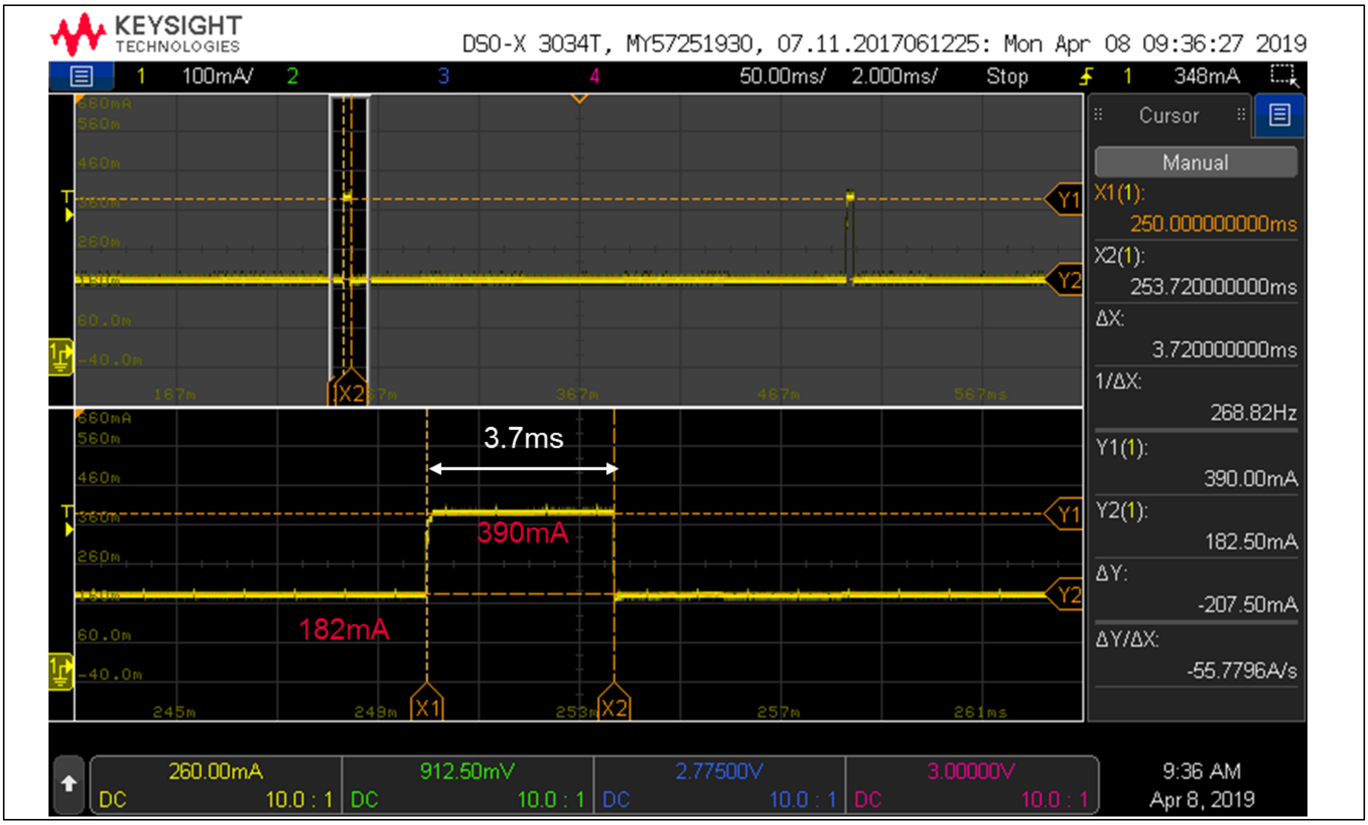


Figure 19 Duty-cycle vs. no duty-cycle current consumption

As shown in Figure 19, during duty-cycle on-time the demo board typically draws 390 mA, while during the duty-cycle off-time with deactivated BGT24MTR11 and PLL, only 182 mA. With the default configuration of 1.48 percent on-time the demo board has a typical average current consumption of 185 mA.

3.9 External pin header connectors

The Distance2Go module has the provision to connect two 12-pin headers on the edges of the board, as shown in Figure 20. Table 8 describes the pins.

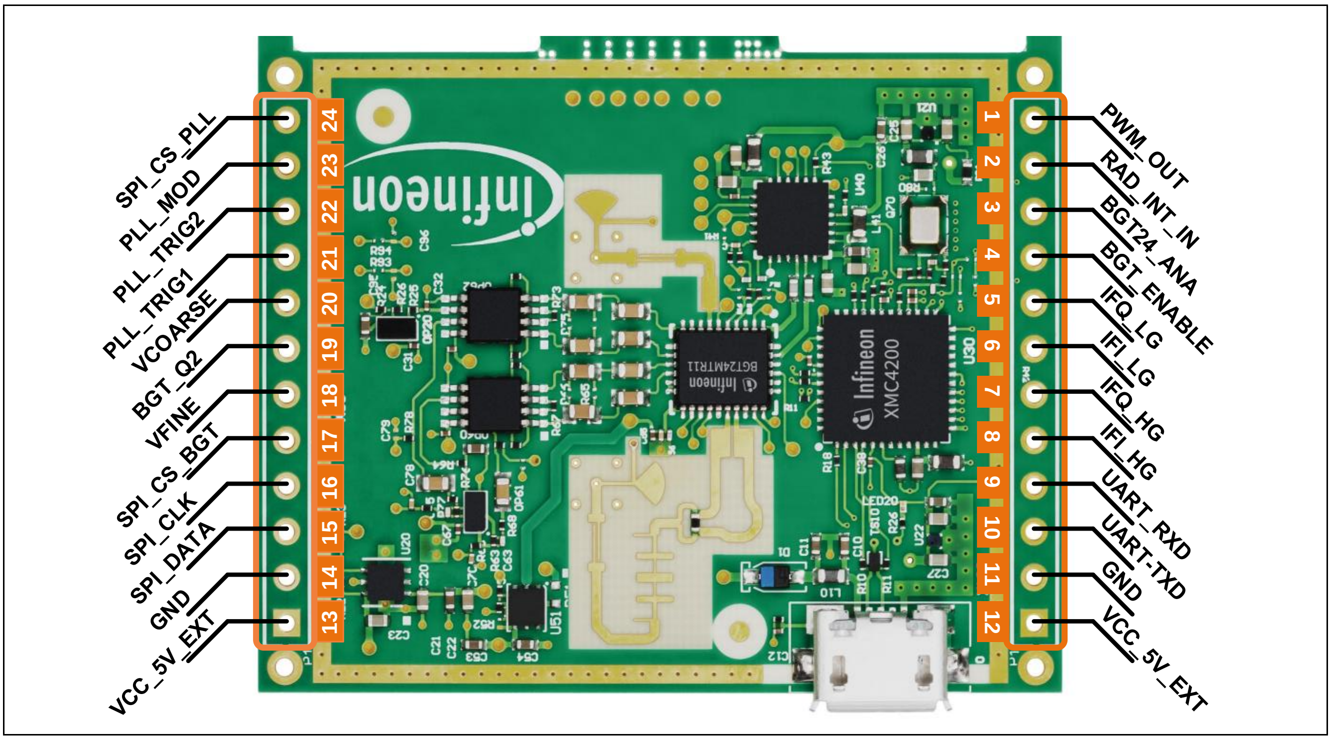


Figure 20 Distance2Go external header pin overview

Table 8 External headers – pin description

Pin number	Signal name	Pin description
1	PWM_OUT	External GPIO with CCU4 (user-configurable)
2	RAD_INT_IN	GPIO pin for interrupt signals (user-configurable)
3	BGT_24_ANA	Multiplexed output pins of BGT24MTR11 to read various sensor values
4	BGT_ENABLE	BGT24MTR11 duty-cycle pin to enable/disable the PMOS switch
5	IFQ_LG	BGT24MTR11 Q-channel – analog signal output – first gain stage
6	IFI_LG	BGT24MTR11 I-channel – analog signal output – first gain stage
7	IFQ_HG	BGT24MTR11 Q-channel – analog signal output – second gain stage
8	IFI_HG	BGT24MTR11 I-channel – analog signal output – second gain stage
9	UART-RXD	Receive pin for UART communication
10	UART-TXD	Transmit pin for UART communication
11	GND	Ground
12	VCC_5V_EXT	External +5.0 V input power supply pin (maximum = 5.5 V)
13	VCC_5V_EXT	External +5.0 V input power supply pin (maximum = 5.5 V)

Pin number	Signal name	Pin description
14	GND	Ground
15	SPI_DATA	SPI master out slave input/output
16	SPI_CLK	SPI clock input/output
17	SPI_CS_BGT	SPI chip select input/output – BGT24MTR11
18	VFINE	BGT24MTR11 – VCO fine-tuning input (0.5 to 3.3 V)
19	BGT_Q2	BGT24MTR11 Q2 prescaler output – 23 kHz
20	VCOARSE	VCO coarse tuning input (0.5 to 3.3 V)
21	PLL_TRIG1	Multiplexed input/output pins for ramp triggers, FSK/PSK modulation, FastLock and diagnostics
22	PLL_TRIG2	Multiplexed input/output pins for ramp triggers, FSK/PSK modulation, FastLock and diagnostics
23	PLL_MOD	Multiplexed input/output pins for ramp triggers, FSK/PSK modulation, FastLock and diagnostics
24	SPI_CS_PLL	SPI chip select input/output – LMX2491 PLL

The pin headers enhance the functionality of the module significantly. They enable probing the analog outputs of the sensor module and probing various other signals provided to the IC. In principle, the accessibility of several pins on the radar MMIC and the IF signals available via the external pin headers enables interfacing the module with an external signal processor. Apart from the onboard user LEDs, the external headers provide two additional user-configurable GPIO pins from the microcontroller with a number of features, and can be used to drive external shields such as the Infineon RGB LED lighting shield.

3.10 Microcontroller unit – XMC4200

The Distance2Go platform uses an XMC4200 32-bit Arm® Cortex®-M4 MCU to perform the radar signal processing. The XMC4200 takes care of communication with all the subsystems on the radar module, enables data acquisition, performs the complete radar signal processing (including sampling and FFT) and communicates the results via its UART or USB interface to an external device.

An XMC4200 in a 48-pin VQFN package is used, featuring an 80 MHz CPU frequency, 256 kB Flash and 40 kB RAM. Two 12-bit ADCs help to implement the radar signal sampling and acquire the various sensor data from the BGT24MTR11 MMIC. The MCU also has a USB 2.0 device interface, which enables communication with a PC directly. Figure 21 shows a system block diagram of the XMC4000 series MCUs.

Please refer to [2] for detailed information on the XMC4200 microcontroller.

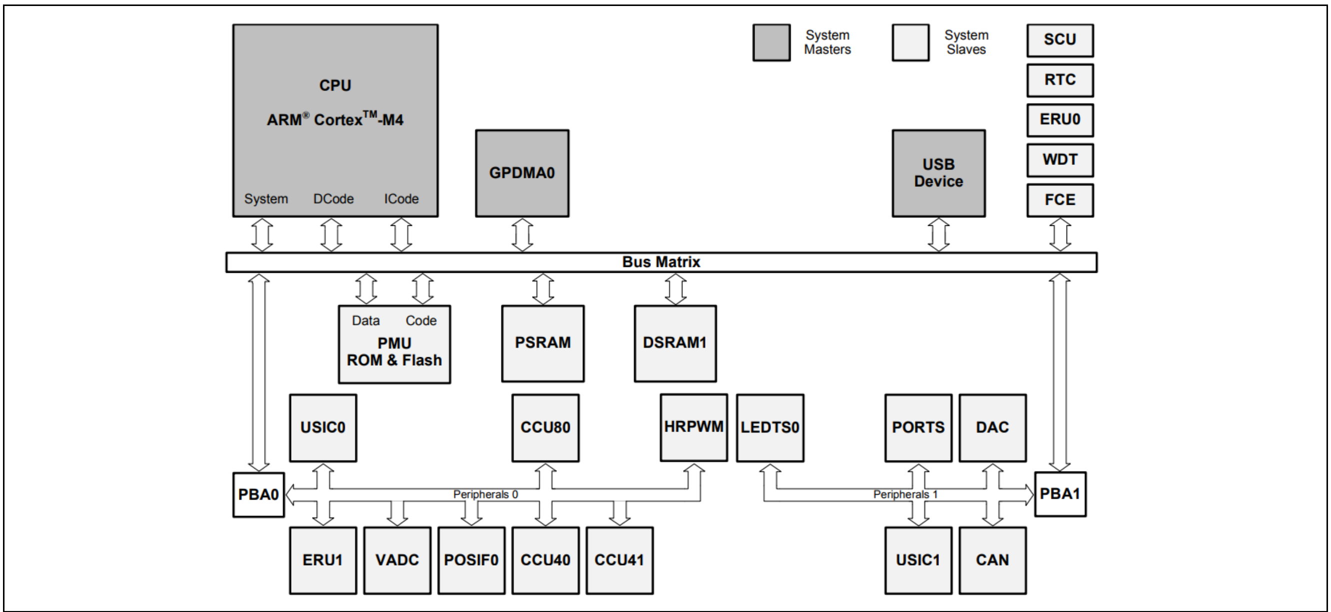


Figure 21 Block diagram – XMC4200

3.11 Onboard debugger and UART connection

The onboard breakable debugger supports two-pin SWD and UART communication. Both require the installation of SEGGER's J-Link driver, which is part of the DAVE™ installation.

During installation of the J-Link driver make sure to select the option "**Install USB Driver for J-Link-OB with CDC**", as shown in Figure 22.

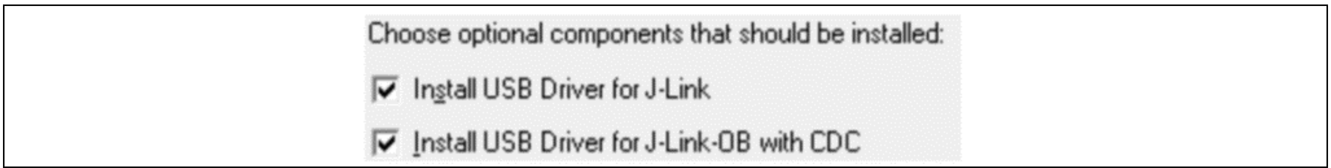


Figure 22 Recommended installation options for the J-Link driver

Table 9 shows the pin assignment of the XMC4200-VQFN48 MCU used for debugging and UART connection.

Table 9 XMC4200 pins used for debugging and UART communication

Port pin	Pin function
TMS (pin 33)	Data pin for debugging via SWD/SPD
TCK (pin 34)	Clock pin for debugging via SWD
0.1	Transmit pin for UART communication
0.0	Receive pin for UART communication

The debugger section supports communication between a PC/laptop and target XMC™ device via a UART-to-USB bridge). Therefore, the UART pins of the target XMC4200 on the radar main board are connected to the TX/RX pins of the debug connector. The TX pin of the debugger MCU is connected to the RX pin of the target XMC4200 MCU. The RX pin of the debugger is connected to the TX pin of the XMC™ target device.

The connectors X11 (Cortex-10 pin) and X80 (five-pin header) on the breakable debugger board were used for internal development and testing purposes and are not recommended for customer use.

The debugger section typically consumes 85 mA from a 3.3 V supply.

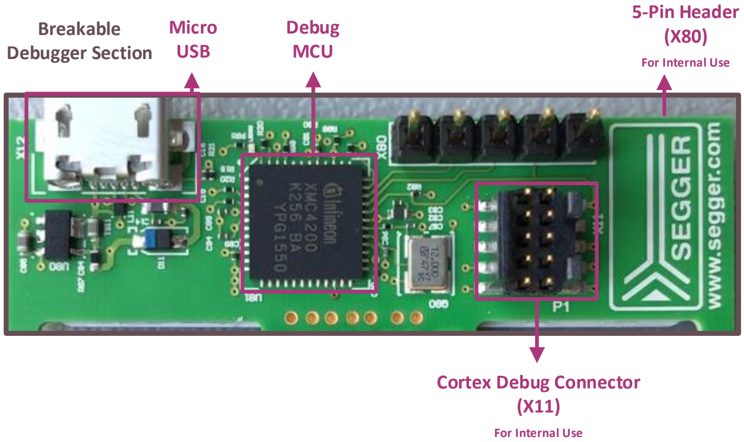


Figure 23 Breakable onboard debugger section

3.12 User LEDs

Some pins of the XMC4200 on the Distance2Go module are connected to external LEDs on the antenna side of the PCB for status indication. Table 10 lists the user LEDs pin assignment.

Table 10 User LEDs pin assignment

LED	MCU port pin
LED31 (red LED)	P2.0

4 Measurement results

A few Distance2Go demo boards were measured in an outdoor environment. This section gives an overview of the measurement set-up and presents a summary of the results for targets with two different radar cross-sections (1 m^2 and 10 m^2).

4.1 Measurement set-up

Figure 24 shows the measurement set-up.

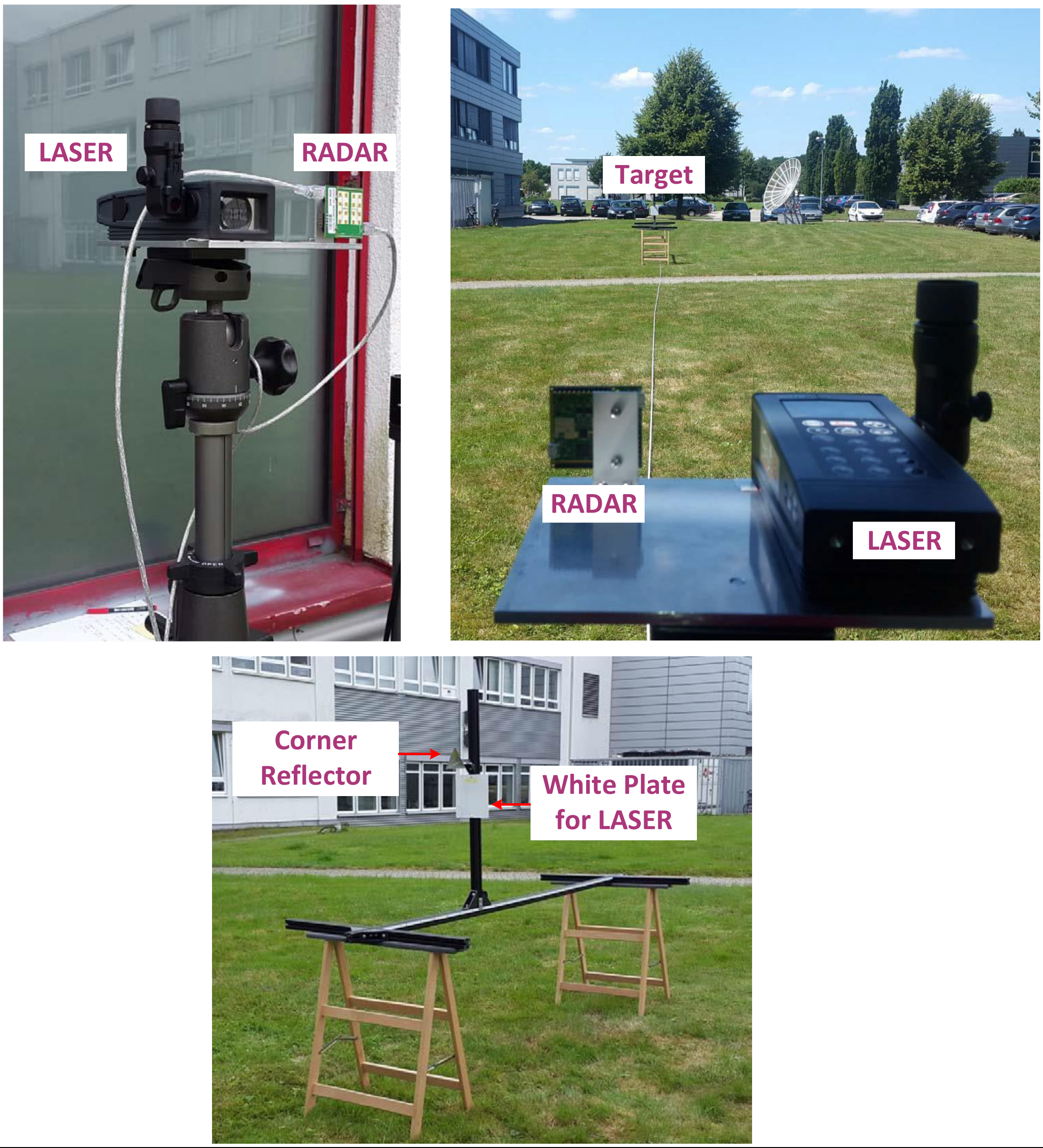


Figure 24 Distance2Go – Outdoor measurement set-up

The radar module was mounted on an aluminum plate together with a hand-held laser meter (DISTO pro4a from Leica Geosystems). The laser meter had a typical distance measurement accuracy of ±1.5 mm. The radar module and laser meter were both mounted on a tripod. The aluminum plate could be adjusted horizontally with a level. The radar height was typically set between 1.40 and 1.50 m, which is roughly the height of the shoulder of an adult person. The radar module was connected with two USB cables – one for DC and communication and a second for DC supply to ensure that enough DC power was available at the module. The radar and laser meter were aligned to a radar target placed on the opposite side on a mechanically adjustable rack, where a corner reflector with RCS = 1 m^2 was mounted. This target was roughly comparable to the RCS of an adult person. A measuring tape on the ground was used to get the radar target in the right position and distance, while all precise distance measurements were made with the laser meter. The measurements were also performed with a corner reflector with RCS = 10 m^2.

4.2 Measurements

Measurements were performed in an outdoor environment using a Distance2Go board in its default configurations (listed in Table 11).

Table 11 Sensor settings for outdoor measurements

Parameter	Value
Transmitter output power	Set to maximum via SPI
Receiver LNA gain	Set to high via SPI
FMCW chirp type	Sawtooth
FMCW chirp bandwidth	220 MHz
FMCW chirp time	1.5 ms
Duty-cycle mode	Enabled
IF stage	Low gain mode (only first IF stage used)
Firmware version and type	Firmware 1 – standard FMCW – release Aug. 2017
Hardware version	Distance2Go_V1.0_27062017_SNR: 0006

All measurements were performed with the low gain mode of the baseband section. Based on the measurement environment an improvement in the maximum detection range of the radar may be possible by enabling high gain mode.

4.3 Range measurement accuracy

This section summarizes the range measurements results of the 24 GHz radar module for each target case and compares them with laser measurements.

Target with RCS = 1 m^2 – For targets with a radar cross-section of 1 m^2, the Distance2Go was able to detect them up to 16 m. Due to the fundamental limitations of FMCW radar as discussed in section 3.7.1, the minimum distance that could be measured by the module was around 50 cm. Between 50 cm and 7 m the measurement accuracy was better than ±20 cm. As the target moved beyond 7 m, the accuracy reduced to ±30 cm. Beyond 16 m it becomes extremely challenging to detect targets with such a low radar cross-section. Figure 25 shows the measurement results and the accuracy of the radar measurements in comparison to laser measurements.

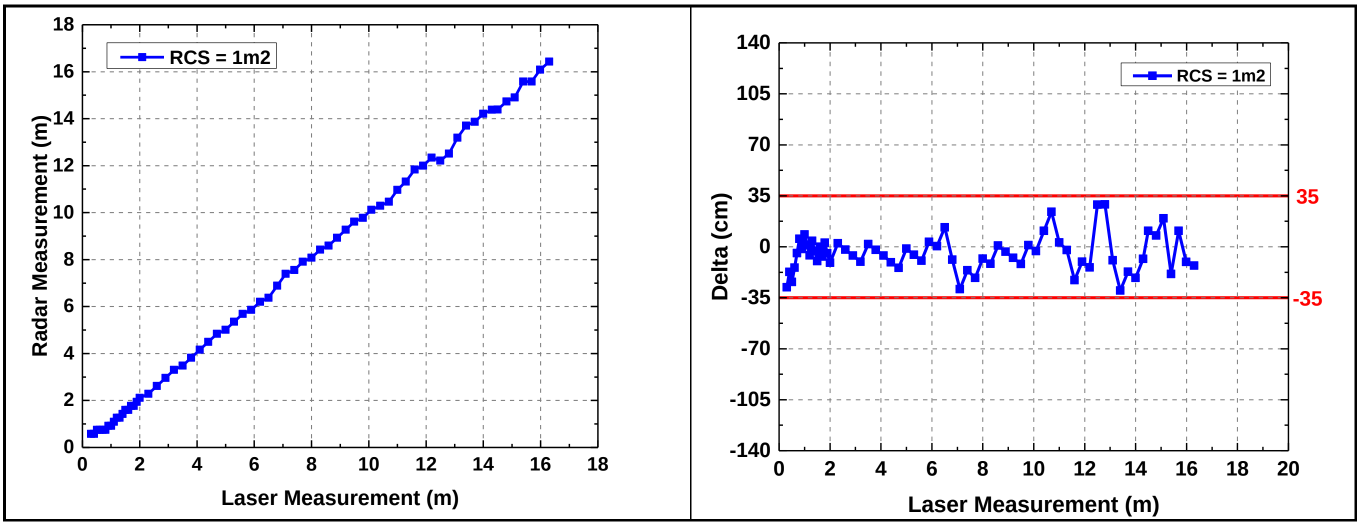


Figure 25 Distance measurements (radar vs. laser) – target with 1 m² RCS

Note: All the measurements were performed in an outdoor environment with minimal background clutter.

For indoor measurement cases, as with all FMCW radar, the maximum detection range of human targets will reduce significantly. It becomes very hard to quantify the maximum detection range in such indoor measurement cases reliably due to unknown levels of background clutter specific to each environment. Also the variation of several radar parameters like transmitter output power, receiver gain and antenna gain from PCB to PCB at these high microwave frequencies further complicates the scenario.

Target with RCS = 10 m² – Figure 26 shows the distance measurement results for a corner reflector target with RCS = 10 m². It can be observed that as the RCS increases, the measurement accuracy improves too. In this case, the module was able to detect the target up to 25 m with an overall accuracy of ±20 cm.

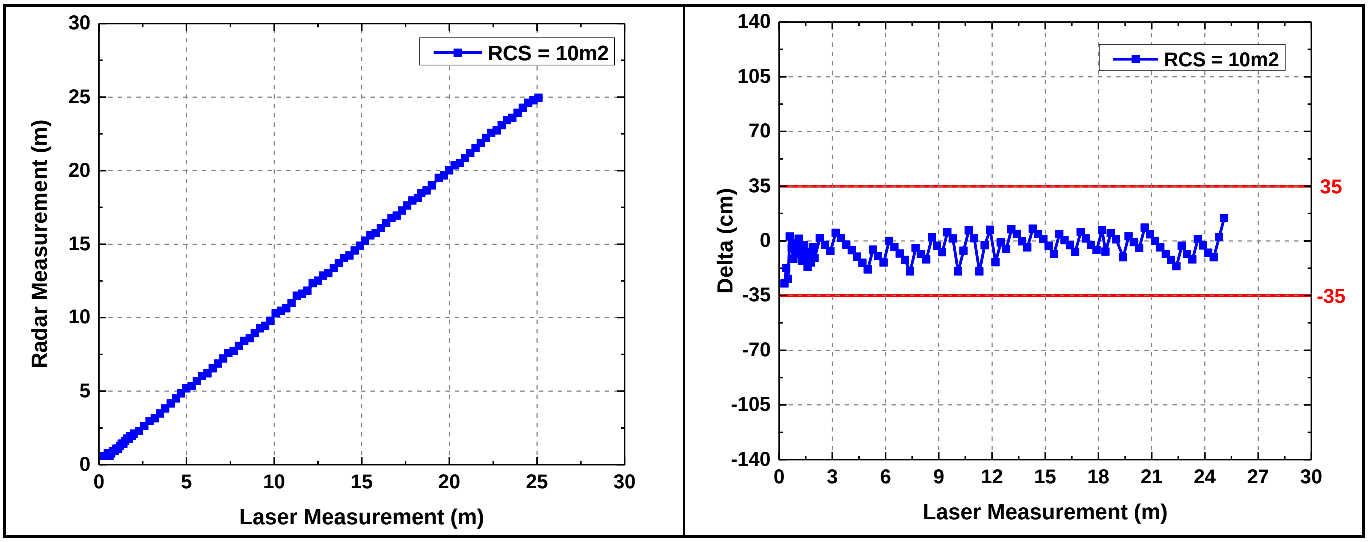


Figure 26 Distance measurements (radar vs. laser) – target with 10 m² RCS

4.4 Temperature chamber measurement

Temperature chamber measurements were performed for 25°C, 85°C and – 35°C. Figure 27, Figure 28 and Figure 29 show the results and verify that the Distance2Go demo board remains within the designated ISM band at these temperatures.

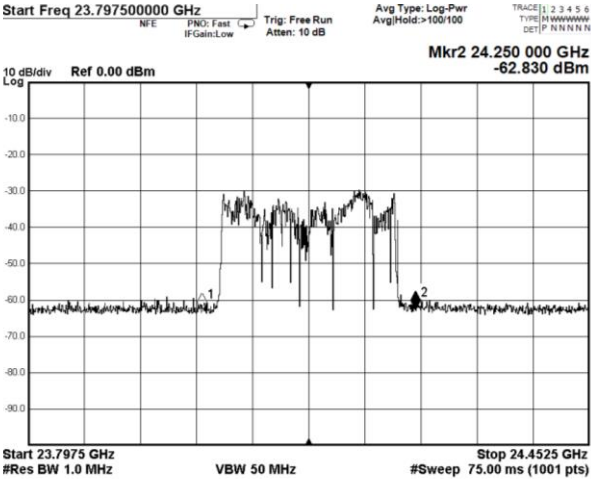


Figure 27 Temperature measurement at 25°C (markers at 24.000 GHz and 24.250 GHz)

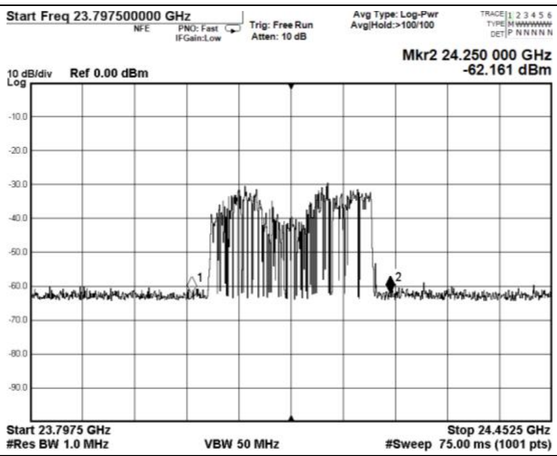


Figure 28 Temperature measurement at 85°C (markers at 24.000 GHz and 24.250 GHz)

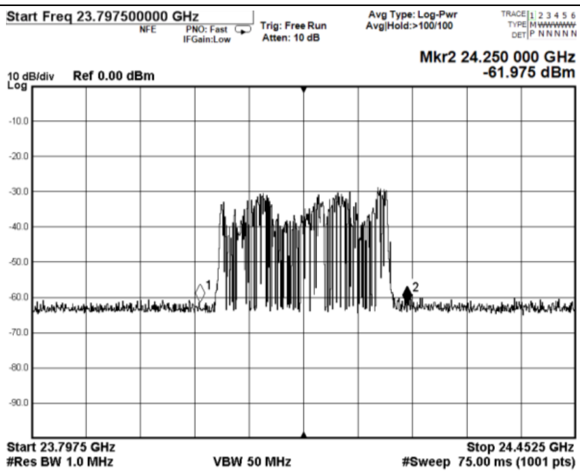


Figure 29 Temperature measurement at -35°C (markers at 24.000 GHz and 24.250 GHz)

5 Frequency band and regulations

5.1 24 GHz regulations

Infineon’s BGT24MTR11 radar sensor operates in the globally available 24 GHz bands. There is an industrial, scientific and medical (ISM) band from 24 to 24.25 GHz. However, each country may have different regulations in terms of occupied bandwidth, maximum allowed radiated power, conducted power, spurious emissions, etc. Therefore, it is highly recommended to check the local regulations before designing an end product.

5.2 Regulations in Europe

In Europe, the European Telecommunications Standards Institute (ETSI) defines the regulations. For more details on the ETSI standards, please refer to the document EN 300 440 V2.2.1. Please note that some countries do not follow harmonized European standards. Thus, it is recommended to check national regulations for operation within specific regions and monitor regulatory changes.

5.3 Regulations in the United States of America

In the USA, the Federal Communications Commission (FCC) defines the standards and regulation. The ISM band covers 24 to 24.25 GHz and one can operate field disturbance sensors anywhere within this band with allowed power limits for certain applications. For details, please refer to FCC section number 15.245 or 15.249.

6 Authors

Radar Application Engineering Team, Business Line "Radio Frequency and Sensors"

7 References

[1] Infineon BGT24MTR11 – 24 GHz Radar MMIC – datasheet

[2] Infineon XMC4200 32-bit Arm® Cortex®-M4 Microcontroller – datasheet

[3] Infineon Application Note – AN305 – User's guide to BGT24MTR11

[4] Infineon Application Note – AN341 – Using BGT24MTR11 in Low Power Applications

[5] 24 GHz industrial radar – FAQs

[6] ETSI regulations – EN 300 440 V2.2.1

[7] FCC regulations – 15.245, 15.249

Revision history

Document revision	Date	Description of changes
1.00	2017-08-31	Initial version
1.10	2017-11-03	p. 17: Radiation characteristics measurement results added p. 18: PLL loop filter components updated pp. 30–39: Schematics updated to reflect the new PCB version number with the loop filter component value change in the PLL section of the schematic p. 41: Resistor value R40 in the PLL loop filter section updated to 2.7k Section 3: Datasheet link added
1.20	2018-05-30	p. 25: PCB pin descriptions corrected p. 46: Links updated
1.30	2019-06-14	p. 30: Duty-cycle current measurements added p. 36: Temperature chamber measurement results added p. 40: Frequency regulations added Removed PCB production data section Moved Software and firmware description to 24 GHz Radar Tools and Development Environment User Manual
1.40	2019-09-16	p. 10: Added Minimum speed row to the System performance table
1.50	2020-05-05	p. 10: Correction on minimum and maximum speed values and formula
1.60	2023-02-14	Miscellaneous document cleanup updates

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