Single-Chip SiGe Transceiver Chipset for E-band Backhaul Applications from 71 to 76 GHz

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1 Introduction

The smartphone revolution has led to a growing demand in mobile data traffic which subsequently has resulted in increased throughput per user. The high mobile data requirements has led to the deployment of advanced 4G services like Long Term Evolution (LTE) by the mobile network operators and this is expected to grow further in the coming years. LTE and LTE Advanced will provide users with higher data rates which will increase data traffic drastically. The increasing data rate puts an enormous burden on the network operator's backhaul networks. The bulk of today's basestation infrastructure is not ready to support the required high data throughput using the existing microwave backhaul techniques. The connection between the basestations is usually planned for lower data rates up to 100 MBit/s which has to be increased significantly to meet the demands for LTE systems. Though optical fiber based backhaul networks can handle a huge data throughput, they are faced with the challenge of easy and cost-effective deployment. The concept of small cells make the deployment of fiber optic based solution even complex and expensive and sometimes even not feasible. This is where the wireless backhaul technology comes into place. A new solution using millimeter wave backhaul opens upto 10 GHz bandwidth in the E-band (71-76 and 81-86 GHz) and 7 GHz bandwidth in the V-band (57–64 GHz). The high bandwidth and channel spacing offered at these frequencies enables data rates higher than 1 Gbps for video and data service even with simple modulation schemes.

Infineon has developed a complete family of packaged RF Transceivers for mobile backhaul applications – supporting both the V-band and E-band frequencies with its BGT60, BGT70 and BGT80 ICs. The modular approach followed by Infineon provides same package dimensions and RF footprint for all the three chipsets which enable customers to quickly setup a radio system at any of the above allowed frequency bands. The highly integrated ICs help to eliminate discrete components, thereby simplifying the customer's system design and time-to-market. This also helps to reduce the total cost of the mmWave backhaul solutions.

The ICs are designed in Infineon´s advanced SiGe:C (Silicon Germanium) technology with device transit frequency of 200 GHz, that enable integration of several mmWave building blocks such as Power Amplifier (PA), Low Noise Amplifier (LNA), Up- and Down-Convertor, Programmable Gain Amplifier (PGA), Voltage Controlled Oscillator (VCO) and more with high performance into a single chip. This technology is proven and fully qualified for other Infineon millimeter- and microwave chipsets already. Furthermore, Infineon is the leading company to house these single chipsets into a plastic Embedded Wafer Level Ball Grid Array (eWLB) package which can be processed in standard SMT flow.

In this application note, the performance of Infineon's fully integrated E-Band Transceiver BGT70 for 71 to 76 GHz on its evaluation board is described in detail.

All the measurements presented in this application note are done port-to-port on Infineon's EVB i.e. Board losses (~2dB) are not dembedded. The measurements are done at backside chip temperature of 45°C. This leads to an additional loss of 1dB. For the specifications of BGT70 transceiver IC, please refer the datasheet of BGT70.

2 About E-Band Backhaul Application

Solutions using millimeter wave backhaul in the E-band of 71-76 and 81-86 GHz open up 10 GHz bandwidth for a full-duplex wireless radio link. It allows gigabit data rates with the simplest modulation scheme which minimize linearity requirements of the transmitter power amplifier (PA). With more spectrally efficient modulations, data rates even higher than 10 Gbps can be achieved. Antennas at high frequencies become compact and can provide higher gain than their contemporaries at lower microwave frequencies which can improve the link condition.

The technical specifications for the E-band communication was specified by ETSI within the document **ETSI TS 102 524** "*Fixed Radio Systems; Point-to-Point equipment; Radio equipment and antennas for use in Point-to-Point Millimeter wave applications in the Fixed Services (mmwFS) frequency bands 71 GHz to 76 GHz and 81 GHz to 86 GHz*" in 2006. The approach for E-band backhaul is to allow site-by-site coordination through the so-called "pencil beam" concept of operation, in which strict requirements are placed on the antenna radiation pattern requiring at least 43 dBi antenna gain with a half-power beamwidth of about only 2 degree. To ensure a high data rate communication, 19 channels of bandwidth 250 MHz each and 125 MHz spacing at the band edge are defined within each of the 5 GHz bandwidth. Aggregation of any of the 19 channels is allowed. Minimum radio interface capacity (RIC) of 150 Mbps with the simplest two-state binary modulation and up to 19 Gbps with high level modulation scheme like 128-QAM is specified. Maximum equivalent isotropically radiated power (EIRP) is specified to 45 dBW which is equivalent to about +30 dBm output power at the antenna port.

A large channel bandwidth with a higher modulation scheme demands higher carrier-to-noise ratio (CNR), which imposes stringent requirements on the high frequency transmitter and receiver design. For example, a typical receiver with 12 dB noise figure at the antenna port in an E-band radio system using 500 MHz channel bandwidth and 16-QAM modulation would need about the same minimum receiver signal power level as a system using 1250 MHz BW and FSK to ensure the bit error rate (BER) of 1E-6. This also limits the maximum distance of an E-band radio link to 2 to 3 km.

The radio link can be either in full-duplex (FDD) or half-duplex (TDD) system configuration. In FDD E-Band systems, one of the two frequencies sub-bands 71 – 76 GHz or 81 - 86 GHz is used for transmission and the other for reception. In a TDD system, the same frequency band is used for transmit or receive mode.

3 Infineon E-Band BGT70 RF Front-End Transceiver Chipset

3.1 Key Features

- BGT70 covers the E-Band frequency range from 71 to 76 GHz
- Fabricated with Infineon’s advanced Silicon-Germanium (SiGe) technology
- Housed in Infineon’s **E**mbedded **W**afer **L**evel **B**all-Grid Array (eWLB) **P**ackage
- BGT70 can be programmed via SPI interface to work either in transmit (TX) or/and receive (RX) mode
- Zero IF – differential I/Q interface – direct conversion architecture
- Differential RF transmit output signaling
- Differential RF receive input signaling
- Differential intermediate frequency I/Q signaling
- Peak detector at VGA input at transmit path
- Peak detector at PA output at transmit path
- Built-in temperature sensor
- SPI interface
- ESD protected device
- BITE (**B**uilt-**I**n-**T**est **E**quipment) for self-test and calibration in production at Infineon to verify RF performance
- Can support TDD or FDD systems

Applications:

- E-Band from 71 to 76 GHz FDD or TDD systems for telecommunication applications

Product Name	Package	Marking
BGT70	PG-WFWLB-119-1	BGT70TR11

3.2 Description of BGT70

Currently, different mmWave system implementations based on III/V-compound semiconductor, silicon bipolar or silicon CMOS technologies have been reported. The advancements in SiGe based technologies in the last years have resulted in their increased use for applications in the mmWave regime with their successful deployment in several existing commercial mmWave applications. Infineon has a long history of research & development with SiGe based technologies and the BGT70 transceiver IC is designed with one of Infineons in-house advanced SiGe bipolar process.

The single-chip transceiver chipset BGT70 is manufactured with Infineon's 200 GHz-f_T SiGe-technology and applicable for telecommunication applications in the microwave and mmWave range. Infineon's 200 GHz Silicon Germanium (SiGe) technology is proven and qualified for Millimeter (e.g. 77 GHz automotive radar) and Microwave chipsets (e.g. 24 GHz automotive/industrial radar). BGT70 uses fully-differential direct conversion architecture for the transmitter and receiver. A Fully-differential (balanced) architecture helps to mitigate the effects of common-mode interference and RF grounding issues, which become extremely critical at higher operating frequencies. Also a differential architecture offers the advantage of reduced even-order harmonics.

The direct conversion architecture simplifies the frequency up/down-conversion process and can reduce bulky and expensive off-chip filtering components. Through the direct conversion architecture of the transceiver, the interface between RF and baseband is simplified significantly compared to currently available discrete millimeter wave solutions. Furthermore, the offering of the single chip solution in a eWLB plastic package makes a major difference to the market. With the packaged chipset, customers can save cost and reduce the time-to-market significantly.

The outstanding RF performance of SiGe technology – such as deliverable saturated output power of up to 14.5 dBm, a low receiver noise figure of 8 dB and excellent VCO phase noise performance better than -83 dBc/Hz at 100kHz offset – allow designers to implement systems with high modulation schemes up to QAM64 with a sample rate of more than 1 Giga Samples per second (GS/s) or simple systems with QPSK with large bandwidth through channel aggregation. ESD (Electrostatic Discharge) performance of more than 1 kV increases robustness. The low power consumption of less than 2 W for this backhaul transceiver family also allows network operators to reduce related fixed expenses.

In general, Infineon's single-chip E-Band transceiver offers customers the following advantages:

- lower production cost
- broadband high data rate telecommunication which enable Gbps radio link
- compact single chip integration leading to much smaller form factor
- excellent device performance
- individual VCO centering taking into account process and temperature variation
- robust design & insensitive to interference through direct conversion architecture and fully differential topology
- standard plastic package allows industrial assembly and cleaning tool can be used
- integrated ESD protection, also for the RF ports

- low power consumption
- product family approach with the same foot print i.e. same PCB layout possible for E-Band radios
- Integrated Built-in-Test-Equipment (BITE) allows “known-good-die” delivery to customers

Figure 1 shows the functional block diagram of Infineon’s BGT70 E-band transceiver IC. The BGT70 transceiver chipset provides a highly integrated solution featuring several RF building blocks namely, a Voltage Controlled Oscillator (VCO), a frequency divider (/16), an I/Q modulator, a Programmable Variable Gain Amplifier (VGA), a Power Amplifier (PA), a Low Noise Amplifier (LNA), an I/Q demodulator, and integrated envelope and power detectors with temperature sensors all controlled by an industry standard SPI interface on a single chip housed in a compact, plastic eWLB package (6 mm x 6 mm). The whole IC is up to 1kV ESD protected according to Human-Body-Model (HBM). Following is a short description of each building block.

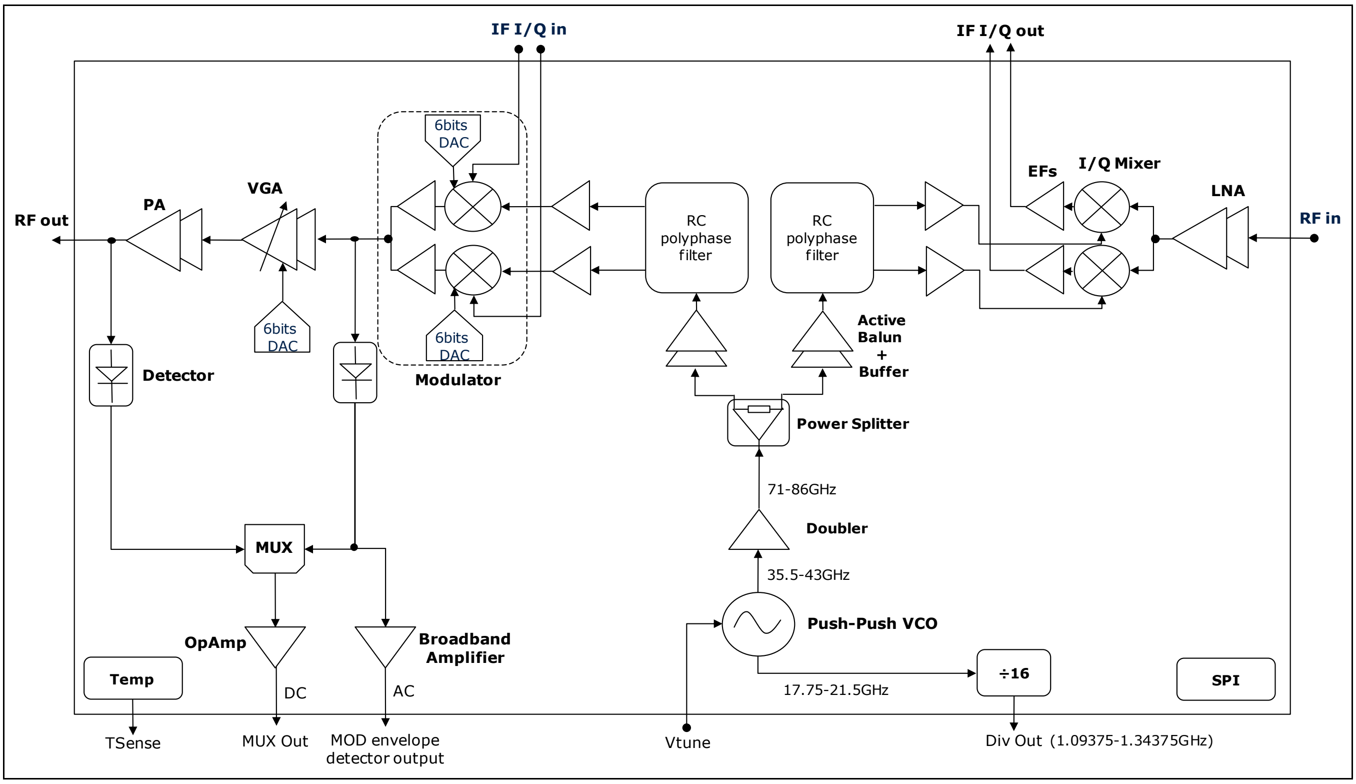


Figure 1 Block Diagram of BGT70 Transceiver Chipset

Transmitter

The transmitter section (TX) of BGT70 has fully differential architecture and includes I/Q modulators with buffer amplifiers, a programmable variable-gain amplifier (VGA), step-gain buffer amplifier, power amplifier (PA), envelop tracking detector (PPD MOD) and a power detector (PPD PA). The output of the power amplifier is 100Ω differential. The transmitter achieves an output 1dB compression point of 12 dBm and a saturated output power of 14.6 dBm.

The IF I/Q input of the transmitter is designed for AC-coupled interface and requires external capacitors. The IF inputs are 100Ω differentially matched. The modulator outputs are connected to a programmable variable gain amplifier (VGA) followed by a step-gain buffer amplifier, prior to power amplification by the PA. The gain of the VGA is controlled by a 6-bit Digital to Analog Converter (DAC) providing a dynamic range of 17.7 dB. The step-gain buffer amplifier placed between the VGA and PA can be switched on and off with a gain step of about 5 dB. Therefore the dynamic range of the VGA, and thus of the transmitter can be increased to about 24 dB if required.

The balance between the modulators I and Q paths is very important to achieve an optimum image and LO rejection at the transmitter output. To control/modify the balance between the modulators' I and Q paths, another 6-bit DAC control circuit is utilized in the modulator biasing circuit to modify the bias condition of each path thereby enabling digital control of the I/Q balance via the integrated SPI interface. Chapter 10.1.1 describes the usage of Infineon SPI software for LO signal rejection at the TX output. Image rejection can also be improved by adjusting the phase and amplitude difference of the IF input signals. Figure 13, shows a BGT70 measurement set up with a Direct Digital Synthesizer (DDS). The DDS is used to generate I/Q input signals for the BGT70 transmitter. It allows varying the phase and amplitude of the input I and Q signals. An image and LO rejection around 50 dB is achieved.

A mode-conversion and a matching circuit is required on the evaluation board to connect the differential outputs of the power amplifier to a commonly used "pencil-beam"-like mmWave antenna array, with single-ended waveguide feed.

Voltage-Controlled-Oscillator

BGT70 includes a high performance internal Voltage-Controlled-Oscillator (VCO) to generate the desired Local Oscillator (LO) signals. The VCO is based on a push-push type architecture with fundamental frequencies around 18 GHz. A push-push type VCO is one whose core oscillates at half of the desired output frequency. It provides a fundamental as well as a second harmonic output. The second harmonic output around 36 GHz is fed into a frequency doubler to generate the E-band LO signals for transmit and receive sections of the IC. The frequency of the VCO can be varied with a single DC voltage (Vtune) within a range of 0 V to 5.5 V covering the entire frequency range from 71 to 76 GHz. The tuning sensitivity (Kvco) of the VCO is in the range of 3.3 to 0.8 GHz/V. At 73 GHz the VCO has a phase noise of -84 dBc/Hz at 100 kHz offset and -105 dBc/Hz at 1 MHz offset. A passive power splitter splits the E-Band output from the frequency doubler for transmit and receive sections of the IC and a passive polyphase filter is used to generate the quadrature signals for the up and down-conversion mixers.

To lock the VCO, an external PLL circuit with a precise quartz-oscillator can be used. A frequency divider is integrated in the chipset. The VCOs fundamental frequency signal (~ 18 GHz) is divided by 16 (or in other words the output frequency of the TX is divided by 64) before it is fed to the PLL circuit for comparison with the reference signal. The frequency divider output is designed for 100Ω differential load with an output power level of about -9 dBm.

An important feature of BGT70 is that each device gets its own individually tuned VCO guarded through 100% test and centering of the VCO frequency so that the whole E-Band frequency range of 71 to 76 GHz can be used over the operating temperature range.

Receiver

BGT70 consists of a quadrature (IQ) Receiver (RX) with 100 Ω differential inputs. Before down-conversion, the received signal is amplified by a Low Noise Ampliter (LNA) which is then split by a passive power divider for the quadrature (I/Q) down-conversion mixers. The mixers are followed by an emitter-follower buffer amplifier with low ohmic outputs. The emitter-follower buffer prevents loading of the mixers by an external load. The receiver gain is 19.5 dB at 73 GHz. The input 1dB compression point is -13.5 dBm. The overall double-side-band (DSB) noise figure of the receive path is 8.3 dB. The receiver with its differential I and Q outputs is designed to have its best performance with differential load impedance higher than 400 Ω. The receiver IF output ports are designed for AC coupling with external capacitors. The bandwidth of the RX IF outputs is more than 500MHz with a lower cutoff frequency less than or equal to 3 kHz, depending on the value of the external AC coupling capacitors used.

DC Supply, Temperature Sensor and Power Detectors

Three individual DC supplies are designed for the transceiver; Vcc, Vcc VCO and Vcc temp (temperature sensor). By ensuring proper filtering, one common supply of 3.3 V can be used for the whole chip. The complete evaluation board draws a current of 640 mA from the DC supply. The transmitter or the receiver can be separately turned on and off. 561 mA current is drawn by the chipset if only the transmitter is turned on, while the receiver takes 428 mA. **These current consumption values include the current consumed by additional circuitry on the evaluation board like PLL and microcontroller as well.**

A temperature sensor and two Peak-Peak Detectors (PPD) are integrated in the BGT70 chipset.

The temperature sensor indicates the backside temperature of the chip. The output voltage of the temperature sensor is calibrated with on-wafer measurement over temperature. It can be read out at the Tsense port. The Tsense port is a high impedance port. Its output voltage is equivalent to the backside temperature of the bare die in the package. Infineon specifies the performance of the device with a backside temperature range of -40°C to +85°C.

An envelope tracking detector PPD MOD is designed after the I/Q modulator and the VGA. Through its fast response and broad bandwidth up to ~300 MHz, it is able to deliver the real-time envelop of the signal. This information is useful for the system design to track the signal and feedback to modem for closed-loop signal control.

Another power detector PPD PA is placed after the power amplifier. It delivers DC voltage proportional to the output power of the transmitter.

Control Interface

There is an industrial standard SPI interface built-in in BGT70. Through the SPI interface, the various functional blocks in the device can be separately turned on and off. The settings for VGA gain level, buffer amplifier on/off or I/Q balance for the TX path can also be executed through the SPI interface. Please refer to Chapter 10 for detailed information. The register map of the chip can be found in the datasheet.

4 Typical Measurement Results

In Chapter 4, typical measurement results of the E-Band 71 to 76 GHz transceiver BGT70, are summarized. Please note that these measurements are performed **on the Infineon evaluation board at room temperature**.

Table 1 Measurement Results - DC Parameters

Parameter	Symbol	Unit	Value	Condition
Voltage Supply	Vcc	V	3.300	
Current Consumption				
- IC powered on, TX off, RX off	ICoff	mA	323	
- TX on, RX off	ICTX	mA	561	@ max power
- TX off, RX on	ICRX	mA	428	
- TX on, RX on	ICTRX	mA	640	@ max power

The current values are of complete EVB. For BGT70 current consumption only please refer Datasheet.

Table 2 IF Port Features and Sensor Characteristics

Parameter	Symbol	Unit	Value	Condition
Output Power Vs PA Peak Detector Readout Relation * PPD_PA selected via MUXout * This provides the output power level at the landing pad	Pout PPD_PA (MUX out)	dBm V	$Pout = t_1 * \ln(\frac{PPD\_PA - y_0}{A_1})$ $y_0 = 0.92899$ $A_1 = 0.14084$ $t_1 = 6.04829$	
Temperature Sensor Sensitivity	Tsense	mV/K	5	
Load Impedance for Tsense Output	$Rsens_{load}$	MΩ	1	single-ended
IF Input Interface at TX				
Signaling				differential
IF Load Impedance	IFload	Ω	100	differential
IF Bandwidth	IFBW	MHz	500	
IF Lower Cutoff Frequency	IFlow	kHz	3	external Capacitance > 1µF required
IF Higher Cutoff Frequency	IFhigh	MHz	500	
IF Coupling on Board			AC	value to be specified
I/Q Amplitude Imbalance	IQAI	dB	0.5	
I/Q Phase Imbalance	IQPI	deg	8	
IF Output Interface at RX				
Signaling				differential
IF Load Impedance	IFload	Ω	400	Differential, minimum value
IF Bandwidth	IFBW	MHz	500	
IF Lower Cutoff Frequency	IFlow	kHz	3	external Capacitance > 1µF required
IF Higher Cutoff Frequency	IFhigh	MHz	500	
IF Coupling on Board			AC	value to be specified
I/Q Amplitude Imbalance	IQAI	dB	1	
I/Q Phase Imbalance	IQPI	deg	7	

Table 3 Measurement Results - Transmitter

Parameter	Symbol	Unit	Value			Condition
Frequency	Freq	GHz	71	73	76	
TX Output						
Output Signaling				differential		
TX-Port Load Impedance	TX_{load}	Ω		100		differential
TX Chain Gain	G_{TX}	dB	24.4	29.4	31.6	From one IF port to Waveguide port
Output Referred P-1dB	$OP\text{-}1dB_{TX}$	dBm	8.8	12	12	differential 100 Ω load
Saturated Power	P_{sat}	dBm	11.6	14.6	14.6	differential 100 Ω load
Output Referred IP3	$OIP3_{TX}$	dBm	16.9	17.7	15.7	differential 100 Ω load
PA Control Dynamic Range	P_ctrl_d	dB		17.7		
LO feed-through Suppression	LO_s	dBc		-57		before LO calibration
PA Control Step	P_ctrl_s	dB		1		6 bits
Image Rejection	IMR	dB		30		w/o feedback loop

Table 4 Measurement Results – LO Generation

Voltage Control Sensitivity	Kvco	GHz/V	2.4	1.6	0.9	@TX output
Phase Noise						
@100kHz Offset	$PN_{ssb100k}$	dBc/Hz	-83	-84	-85	SSB
@1MHz Offset	PN_{ssb1M}	dBc/Hz	-104	-105	-106	SSB
@10MHz Offset	PN_{ssb10M}	dBc/Hz	-125	-125	-125	SSB
Divider Output Power	$PDIV_{out}$	dBm		-9		differential 100 Ω load
VCO Tuning Voltage	V_{tune}	V	0		5.5	single tuning port

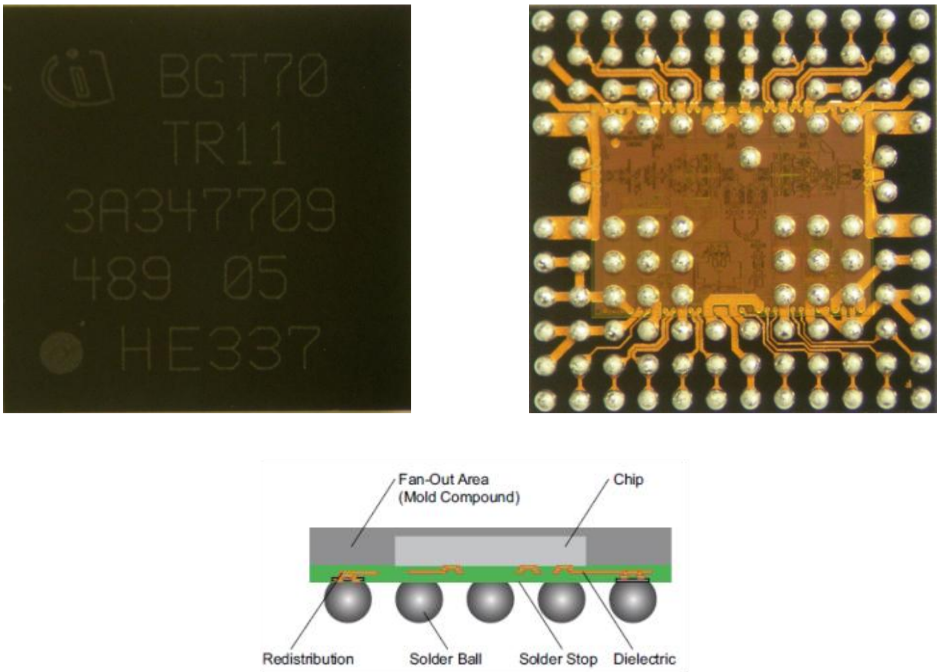
Table 5 Measurement Results - Receiver

Parameter	Symbol	Unit	Value			Condition
Frequency	Freq	GHz	71	73	76	
RX Chain						
Input Signaling						differential
Conversion Gain	CG_{diff}	dB	16.3	19.5	19.3	differential in **400Ω** load at IF Ports
Double-Side-Band Noise Figure	NFdsb	dB	9.9	8.3	9.1	
Input Referred P-1dB	$IP\text{-}1dB_{RX}$	dBm	-12.5	-13.5	-12	
Input Referred IP3	$IIP3_{RX}$	dBm	-5.3	-5.1	-6.3	
LO Residual Power at the RX Input	LO_{res}	dBm		-59		
RF-Port Load Impedance	RF_{load}	Ω		100		differential

5 Package

5.1 BGT70 in PG-WFWLB-119-1 Package

The BGT70 chipset is in eWLB type package PG-WFWLB-119-1 with bump balls of 300µm diameter and 150µm height as shown in **Figure 2**. The physical dimension of 6.0 x 6.0 mm² with a bump pitch of 500 µm is shown in **Figure 3**. The maximum height of the package is 0.8 mm with 0.1 mm planarity variation. The maximum variation of bump coplanarity is 80 µm. On top of the package, Pin 1 is marked by a laser marking. The product name and its production date code are also described there.



Package Dimension: 6.0 mm x 6.0 mm x 0.8 mm

Figure 2 Top View (left), Bottom View (right) and Side View of BGT70 in eWLB Package

For mmWave applications, eWLB offers excellent electrical and thermal characteristics. With a well-engineered design, it offers a comparable loss like a bonding wire package version but has large bandwidth which is required for broadband mmW applications. Furthermore, its outstanding thermal resistance of 15 K/W ensures its proper working even under critical environment. The BGA-like package form enables customers to use industrial standard reflow process to solder it.

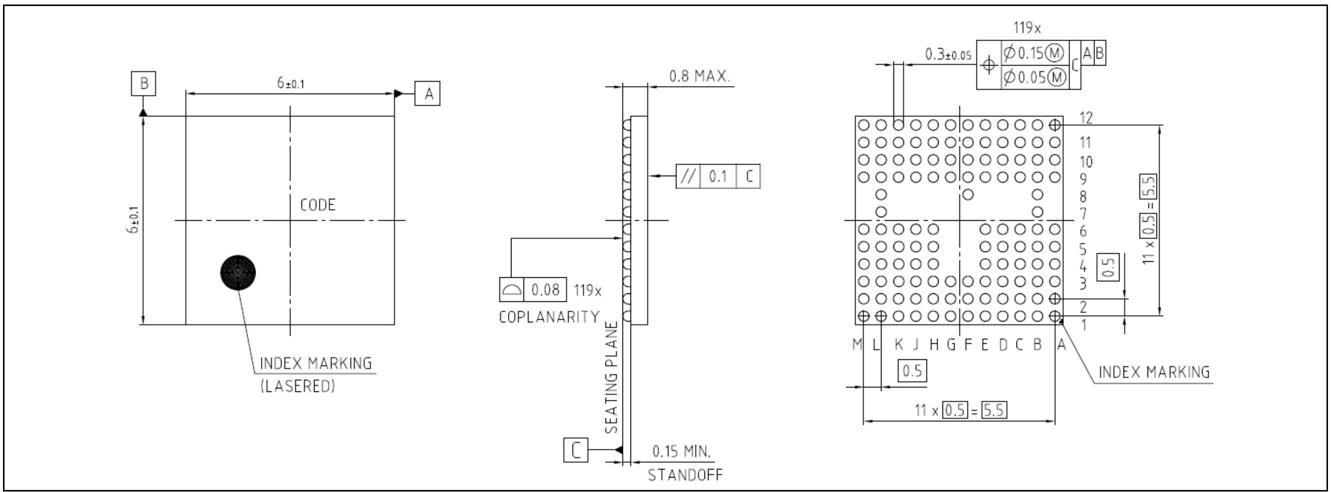


Figure 3 **Dimension of eWLB Package PG-WFWLB-119-1 for BGT70 (left: top view; center: side view; right: bottom view)**

5.2 Pin Definition and Function

Figure 4 shows the top view of BGT70 package eWLB PG-WFWLB-119-1 with the pin number assignment. The function of each pin is described in **Table 6** below.

The ground pins (in black color) are used not only for RF and DC but also as a heat sinker for the BGT70 chipset on the PCB.

It has to be noted that the four edge ground pins A1, A12, M1 and M12 are in fact not used in the transceiver IC but it is recommended to connect them to the RF ground for mechanical stability reason.

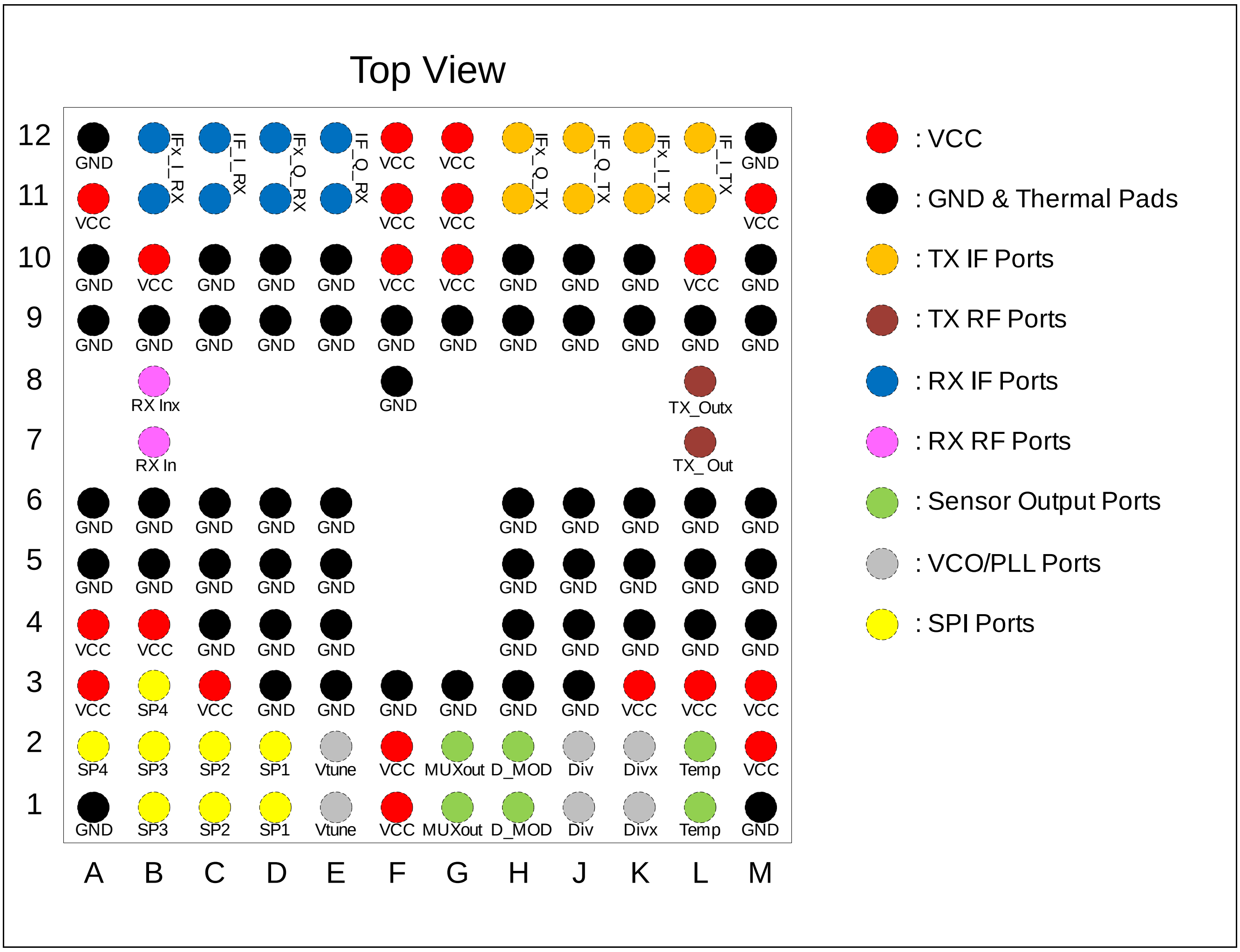


Figure 4 **Pin Number Assignment of BGT70 package eWLB PG-WFWLB-119-1 (Top View)**

Table 6 Pin Definition and Function

Pin No.	Name	Function
A3, A4, A11, B4, B10, C3, F10, F11, F12, G10, G11, G12, L10, M11	Vcc	DC supply for the transceiver chip – 3.3V
K3, L3, M2, M3	Vcc_Temp	Supply voltage for the temperature sensor – 3.3V
F1, F2	Vcc_VCO	Supply voltage for the VCO – 3.3V
E1, E2	Vtune	VCO tuning voltage
D1, D2	SP1	SPI Enable - chip select
C1, C2	SP2	SPI Dataout - SPI data sequence (device → control board)
B1, B2	SP3	SPI Data - SPI data sequence (control board → device)
A2, B3	SP4	SPI clock
G1, G2	MUXout	MUX output (PPD_PA or PPD_MOD DC level output)
H1, H2	D_MOD	Modulator detector output
L1, L2	Temp	Temperature sensor output – DC voltage
J1, J2	Div	Frequency divider output
K1, K2	DivX	Complementary frequency divider output
B7	RX_In	RF input of receiver
B8	RX_Inx	Complementary RF input of receiver
B11, B12	IFx_I_RX	Complementary inphase IF output of receiver
C11, C12	IF_I_RX	Inphase IF output of receiver
D11, D12	IFx_Q_RX	Complementary Quadrature IF output of receiver
E11, E12	IF_Q_RX	Quadrature IF output of receiver
L7	TX_Out	RF output of transmitter
L8	TX_OuTX	Complementary RF output of transmitter
L11, L12	IF_I_TX	Inphase IF input of transmitter
K11, K12	IFx_I_TX	Complementary inphase IF input of transmitter
J11, J12	IF_Q_TX	Quadrature IF input of transmitter
H11, H12	IFx_Q_TX	Complementary Quadrature IF input of transmitter
A5, A6, A9, A10, B5, B6, B9, C4, C5, C6, C9, C10, D3, D4, D5, D6, D9, D10, E3, E4, E5, E6, E9, E10, F3, F8, F9, G3, G9, H3, H4, H5, H6, H9, H10, J3, J4, J5, J6, J9, J10, K4, K5, K6, K9, K10, L4, L5, L6, L9, M4, M5, M6, M9, M10	GND	Ground and thermal pads
A1, A12, M1, M12	GND	A1, A12, M1, M12 are electrically not connected in chip but should be connected to ground for mechanical stability.

Note: all pins described in the same line need to be connected on the PCB.

6 About BGT70 Evaluation Board

6.1 Application Diagram and Schematic of the Evaluation Board

Figure 5 shows the top layer and component designators of evaluation board for BGT70. In addition to the BGT70 chip, the PLL circuit with a reference oscillator is also implemented on the evaluation board as shown in **Figure 6**. The application schematics for this Evaluation board are shown in **Figure 8** and **Figure 9**.

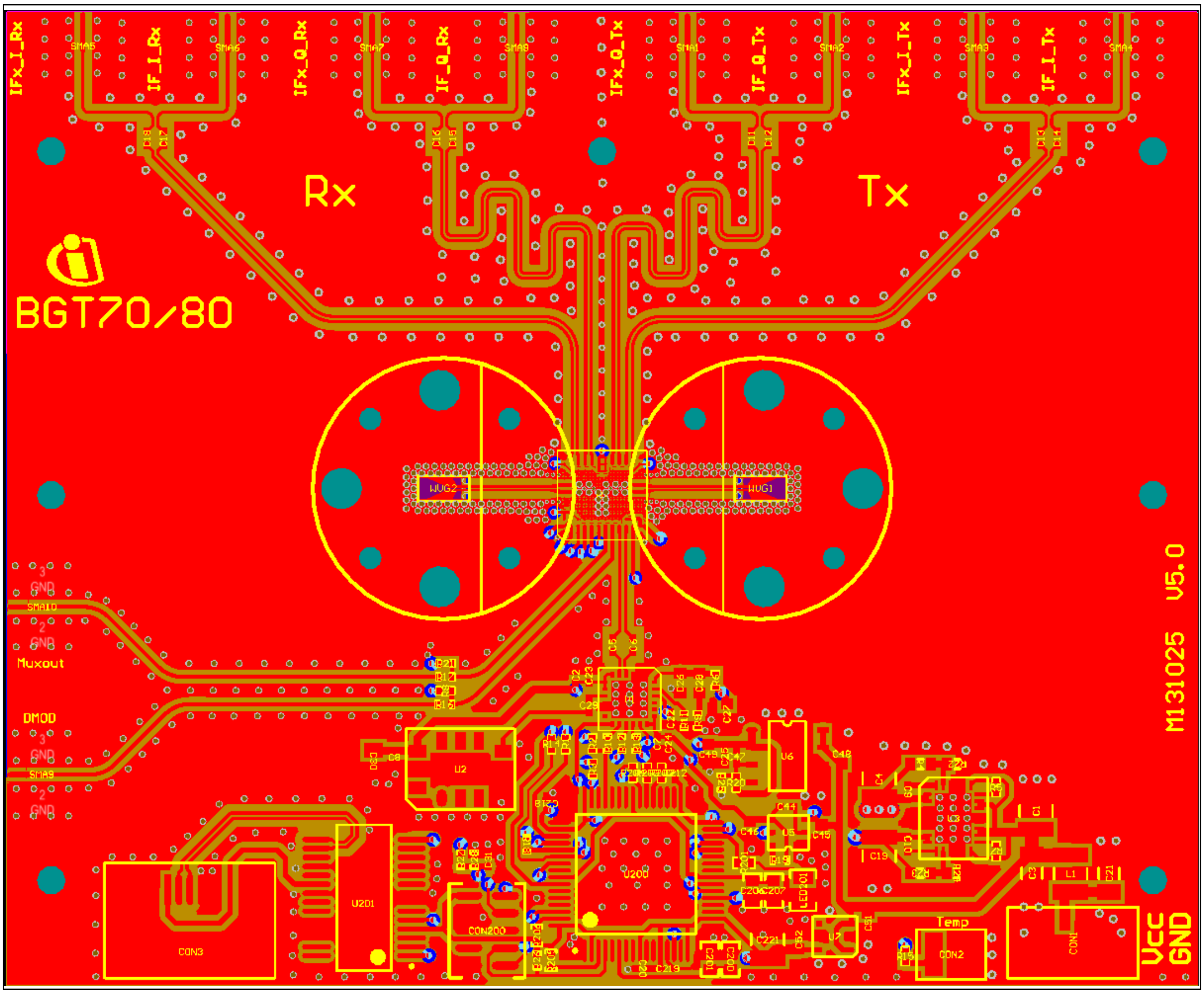


Figure 5 Top layer and component designators for BGT70 evaluation board

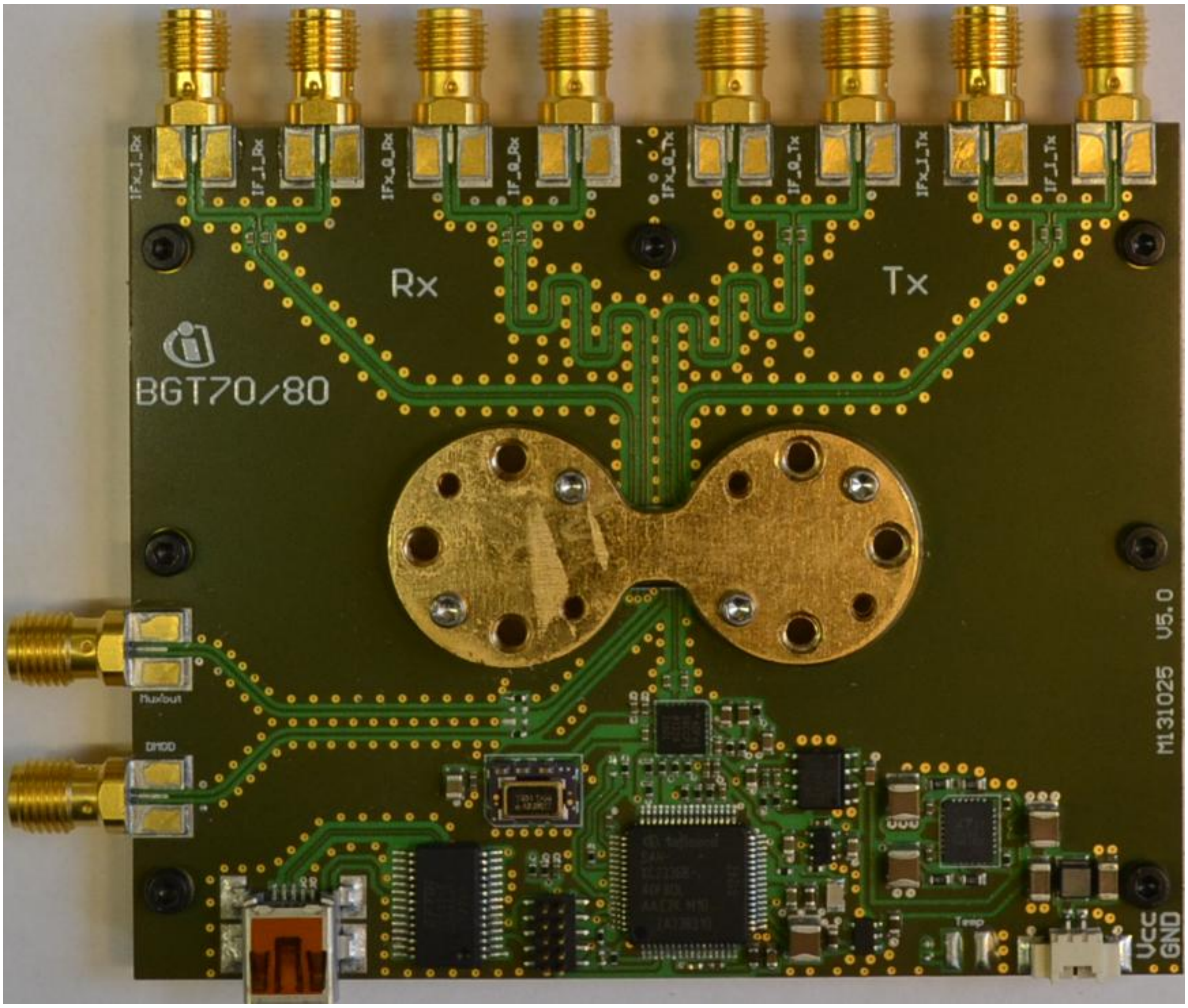


Figure 6 Evaluation Board for BGT70 – Top View

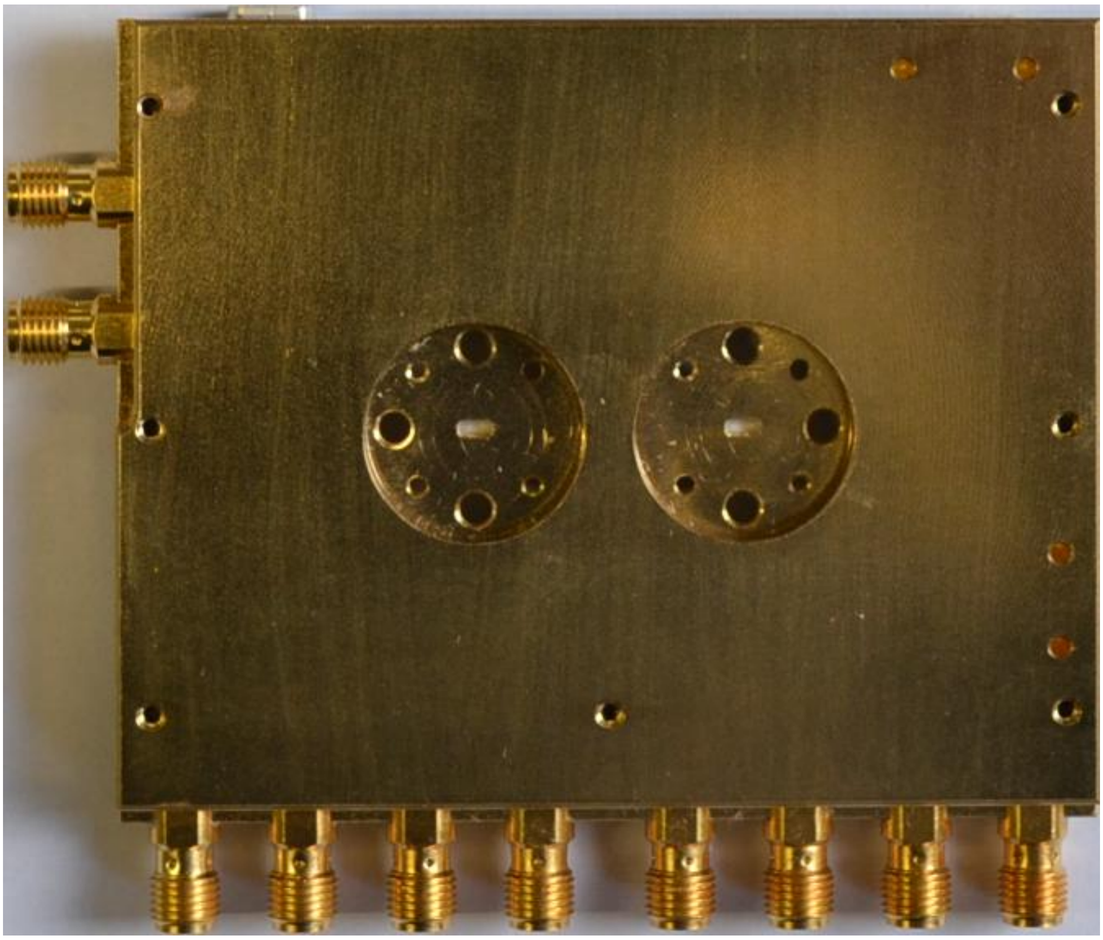


Figure 7 Evaluation Board for BGT70 – Bottom View

Table 7 Interface Description of BGT70 Application Board

Pin	Function	Description
SMA Connectors		
DMOD	Wideband PPD MOD output	Envelop tracking detector
Muxout	Provides DC voltage corresponding to PPD PA or PPD MOD	PPD PA or PPD MOD selectable through SPI control
IF_I_TX/ IF_Ix_TX	Inphase/Complementary I input of transmitter	Source impedance at input: differential 100 Ω
IF_Q_TX/ IF_Qx_TX	Quadrature/Complementary Q input of transmitter	Source impedance at input: differential 100 Ω
IF_I_RX/ IF_Ix_RX	Inphase/Complementary I output of receiver	Load impedance at output: differential 400 Ω
IF_Q_RX/ IF_Qx_RX	Quadrature/Complementary Q output of receiver	Load impedance at output differential 400 Ω
RF interface		
TX/RX Port	Transmitter/Receiver WR-12 waveguide	WR-12 waveguide

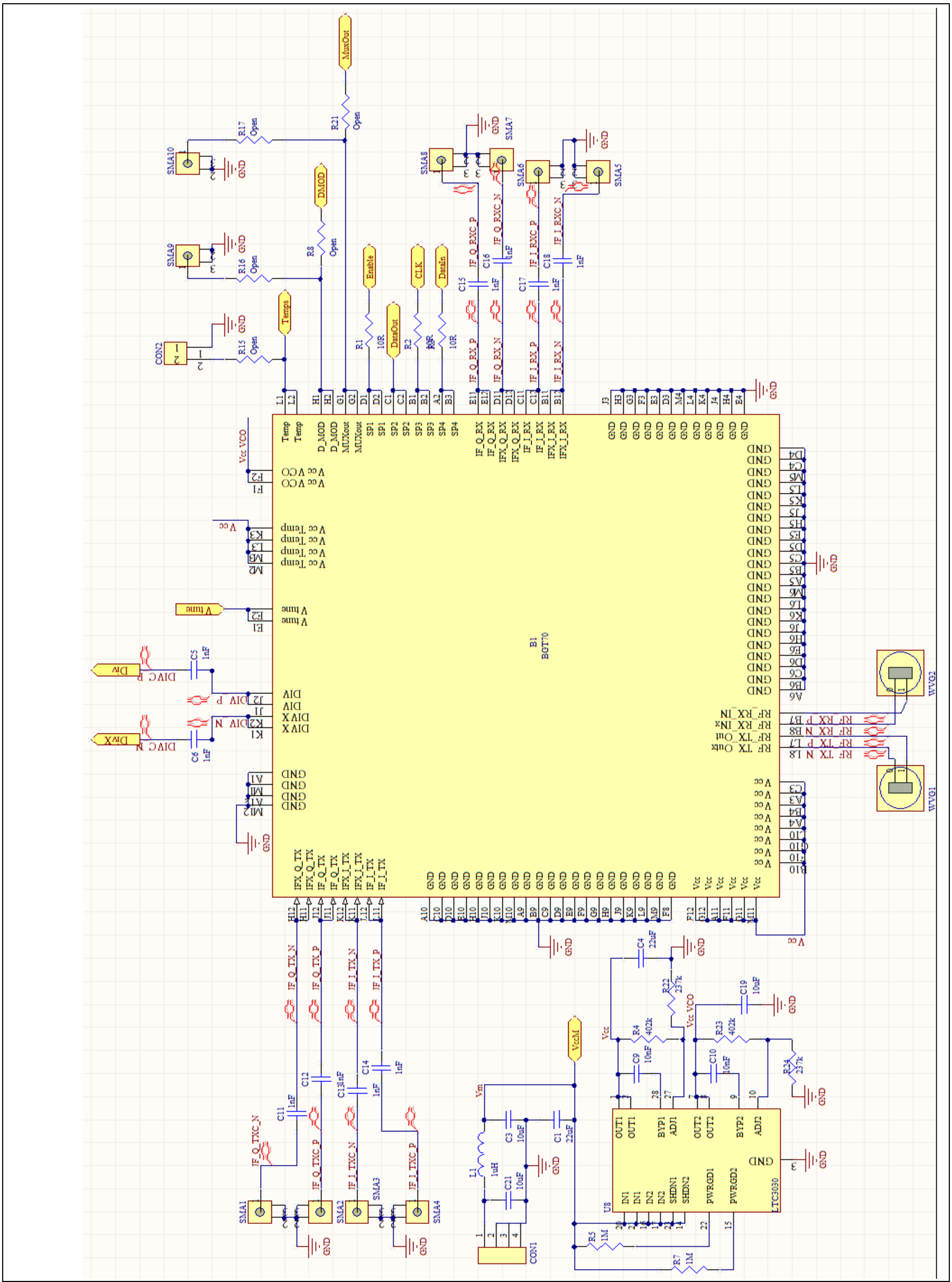


Figure 8 Schematic of BGT70 Evaluation Board

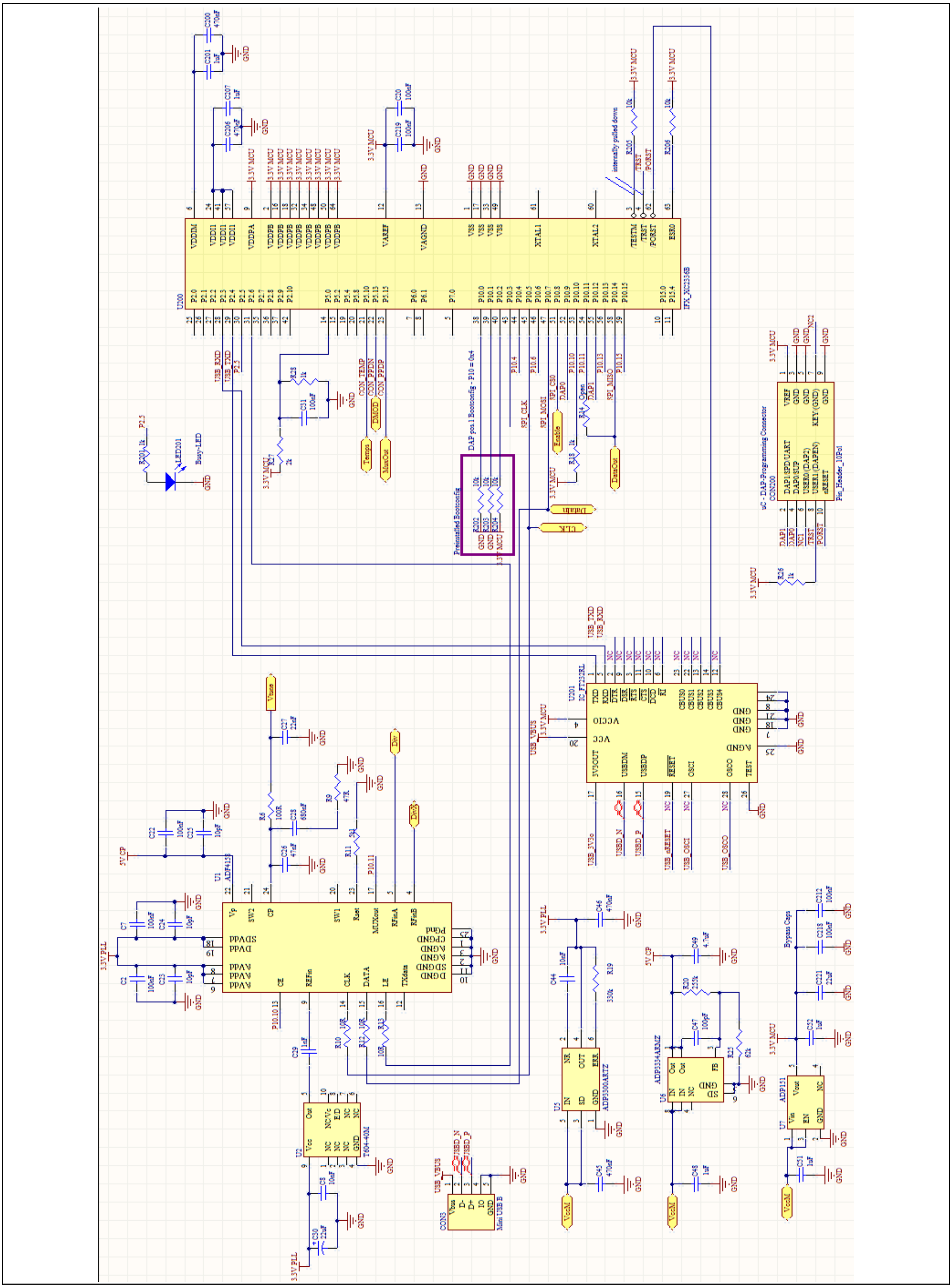


Figure 9 Schematic of PLL and Microcontroller circuitry of BGT70 Evaluation Board

6.2 Measurement of the Loss of the PCB Microstrip Lines and Microstrip-Waveguide Transition

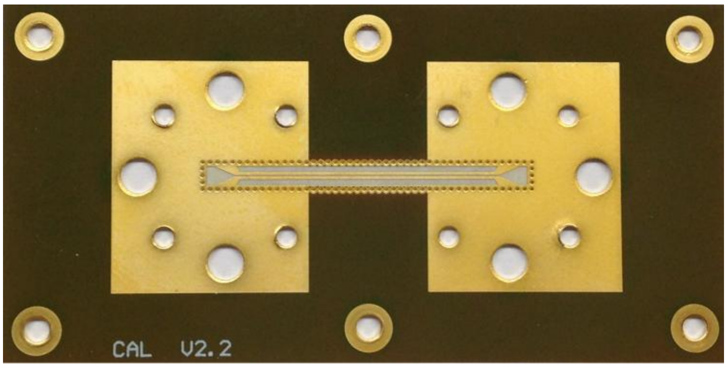


Figure 10 **Calibration board for BGT70 transition loss measurements. Backshort used on top of the transition is not shown here.**

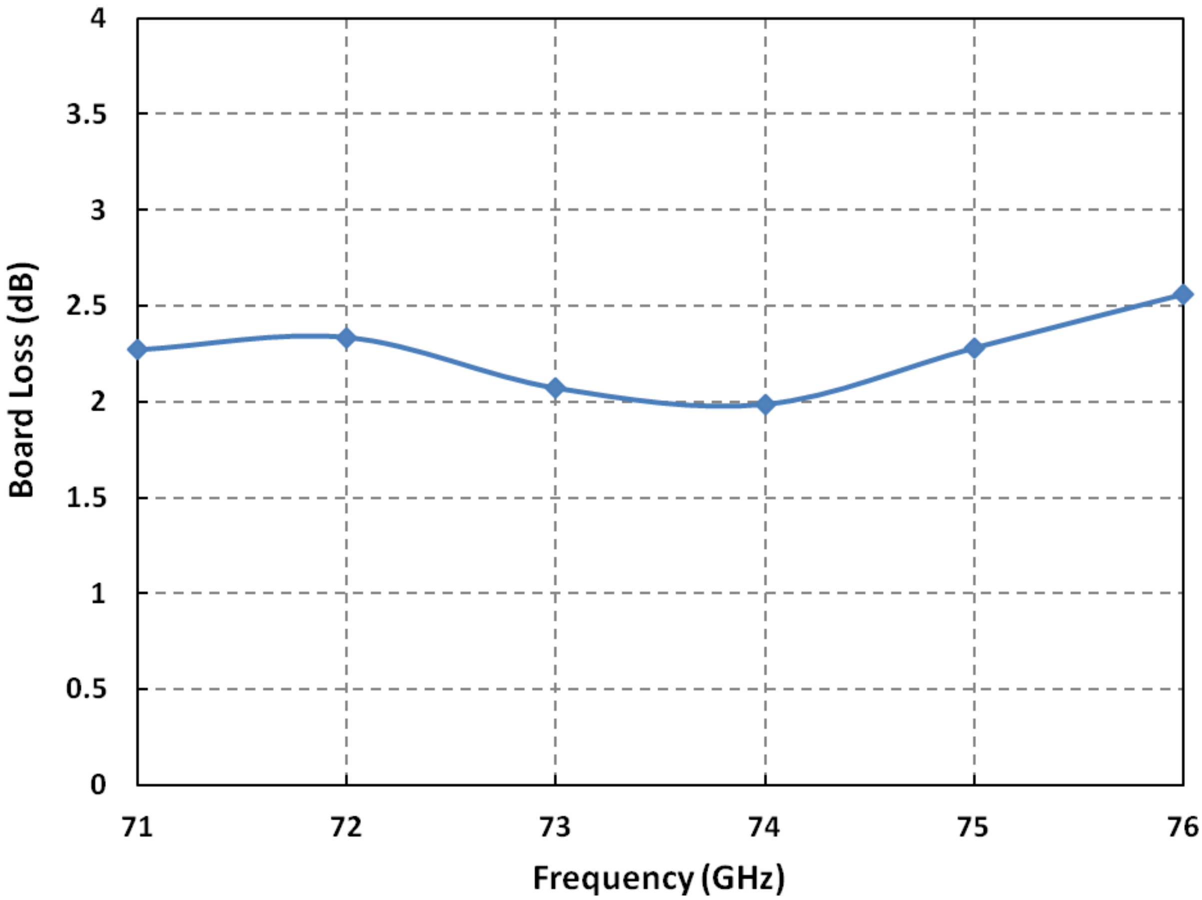


Figure 11 **Measurement Results of PCB Microstrip Lines and Microstrip-Waveguide Transition (Results are from BGT70 ports to the waveguide transition, one way)**

6.3 Bill-of-Materials of BGT70 Evaluation Board

Table 8 shows the bill-of-materials (BOM) of the evaluation board.

Table 8 Bill-of-Materials of BGT70 EVB

Designator	Value	Unit	Package	Manufacturer	Comment
B1	BGT70	-	eWLB	Infineon	RF transceiver chip
C1, C221	22	uF	1210	Murata	DC Filtering
C19	10	uF	1210	Murata	LDO Stabilization
C2, C7, C20, C22, C212, C218, C219	100	nF	0402	Murata	RF Bypass
C45, C46, C200, C206	470	nF	0603	Murata	RF Bypass
C48,C51,C52	1	uF	0603	Murata	LDO Stabilization
C201, C207	1	uF	0603	Murata	RF Bypass
C23, C24, C25	10	pF	0402	Murata	RF Bypass
C26	47	nF	0603	Murata	PLL Loop Filter
C27	22	nF	0603	Murata	PLL Loop Filter
C28	680	nF	0603	Murata	PLL Loop Filter
C5, C6, C11, C12, C13, C14, C15, C16, C17, C18, C29	1	nF	0402	Murata	AC Coupling
C3,C21	10	uF	1206	Murata	DC Filtering
C30	22	uF	0805	Murata	DC Filtering
C31	100	nF	0402	Murata	RF Bypass
C47	100	pF	0402	Murata	Noise Reduction LDO
C49	4.7	uF	0603	Murata	LDO Stabilization
C8, C9, C10, C44	10	nF	0402	Murata	RF Bypass
C9, C10	10	nF	0402	Murata	Noise Reduction LDO
C44	10	nF	0402	Murata	Noise Reduction LDO
CON1	53261-0271	2 Way, 1.25mm, Header	Surface Mount Right Angle	Molex	DC Supply Evaluation Board – 6V
CON2	-	-	-	-	-
CON200	M50-3600542	2 x 5Way, 1.27mm, Header	Surface Mount Right Angle	Harwin	Programming connector for Microcontroller
CON3	56579-0576	Mini USB Receptacle	Surface Mount Right Angle	Molex	Controlling BGT70 and PLL via GUI
L1	1	uH	1210	Murata	DC Filtering
LED201	LG R971	LED	0805	Osram	Read/Write status SPI
R1, R2, R3, R10, R12, R13	10	Ω	0402	Any	SPI stability
R11	5.1	kΩ	0402	Any	Charge Pump current
R18, R26	1	kΩ	0402	Any	Pull-up Resistors

Table 8 Bill-of-Materials of BGT70 EVB

Designator	Value	Unit	Package	Manufacturer	Comment
R28	1	kΩ	0402	Any	Filtering at Analog Reference
R201	1	kΩ	0402	Any	Current Limiter for LED
R19	330	kΩ	0402	Any	Error Detection LDO
R20	255	kΩ	0402	Any	Voltage Setting LDO
R202, R203, R204	10	kΩ	0402	Any	Load Preinstalled Bootconfig
R205, R206	10	kΩ	0402	Any	Pull-up Resistors
R21	0	Ω	0402	Any	Muxout to Microcontroller
R22, R24	237	kΩ	0603	Any	Voltage Setting LDO
R25	62	kΩ	0402	Any	Voltage Setting LDO
R27	2	kΩ	0402	Any	Filtering at Analog Reference
R4, R23	402	kΩ	0603	Any	Voltage Setting LDO
R5, R7	1	MΩ	0402	Any	Error Detection LDO
R6	100	Ω	0402	Any	PLL Loop Filter
R8, R14, R15, R16, R17	Open	-	0402	-	-
R9	47	Ω	0402	Any	PLL Loop Filter
SMA1, SMA2, SMA3, SMA4, SMA5, SMA6, SMA7, SMA8, SMA9, SMA10	SMA	-	End Launch SMA	Emerson	IF Signals for TX-RX, Muxout and DMOD connections
U1	ADF4158	-	LFCSP	Analog Devices	Fractional-N Frequency Synthesizer
U2	T604-040.0M	-	Surface Mount	Connor Winfield	TCXO for PLL
U200	SAK-XC2336B-40F80L AA	-	QFP127P600-8N	Infineon	Microcontroller for PLL and BGT70
U201	FT232RL	-	SSOP-28	FTDI	USB Interface chip for Microcontroller
U5	ADP3300ARTZ-3.3RL7	-	SOT-23	Analog Devices	Voltage Regulator – 3.3V for PLL
U6	ADP3334ARMZ	-	SOIC-8	Analog Devices	Voltage Regulator – Charge Pump of PLL
U7	ADP151AUJZ-3.3-R7	-	TSOT-5	Analog Devices	Voltage Regulator – 3.3V for Microcontroller
U8	LT3030EUFD#PBF	-	20-TSSOP	Linear Technology	Dual Channel Voltage Regulator for Vcc and Vcc VCO

7 Performance of BGT70 Transmitter

The output spectrum at the TX port of BGT70 is shown in **Figure 12**. The measurement setup is shown in **Figure 13**. A Direct Digital Synthesizer (DDS) from Analog Devices (AD9959) is used to generate the IF signals for the transmitter. By adjusting the phase of the I and Q output signals from the DDS an image rejection greater than 50 dBc is achieved at the transmitter output. An E-band smart harmonic mixer is used to measure the output signal. The transmitter output power level is kept low by setting the DAC VGA value to 27 in order not to drive the smart harmonic mixer in compression. The carrier feedthorugh suppression is achieved by sweeping the values of DAC_MOD_I and DAC_MOD_Q registers. LO suppression of >50dB is achieved with this particular setup.

Figure 14 shows the linear and saturated output power at the transmitter output between 71-76 GHz. The transmitter gain over frequency and output power is plotted in **Figure 15** and **Figure 16** respectively, and **Figure 17** shows the measured output 1-dB compression point over frequency. **Figure 18**– **Figure 21** shows the measured third order intermodulation performance of the transceiver over frequency and various DAC VGA settings. The transmitter output power can be varied by changing the DAC VGA and enabling/disabling the VGA buffer. **Figure 22**- **Figure 26** shows the transmitter performance vs different DAC VGA settings.

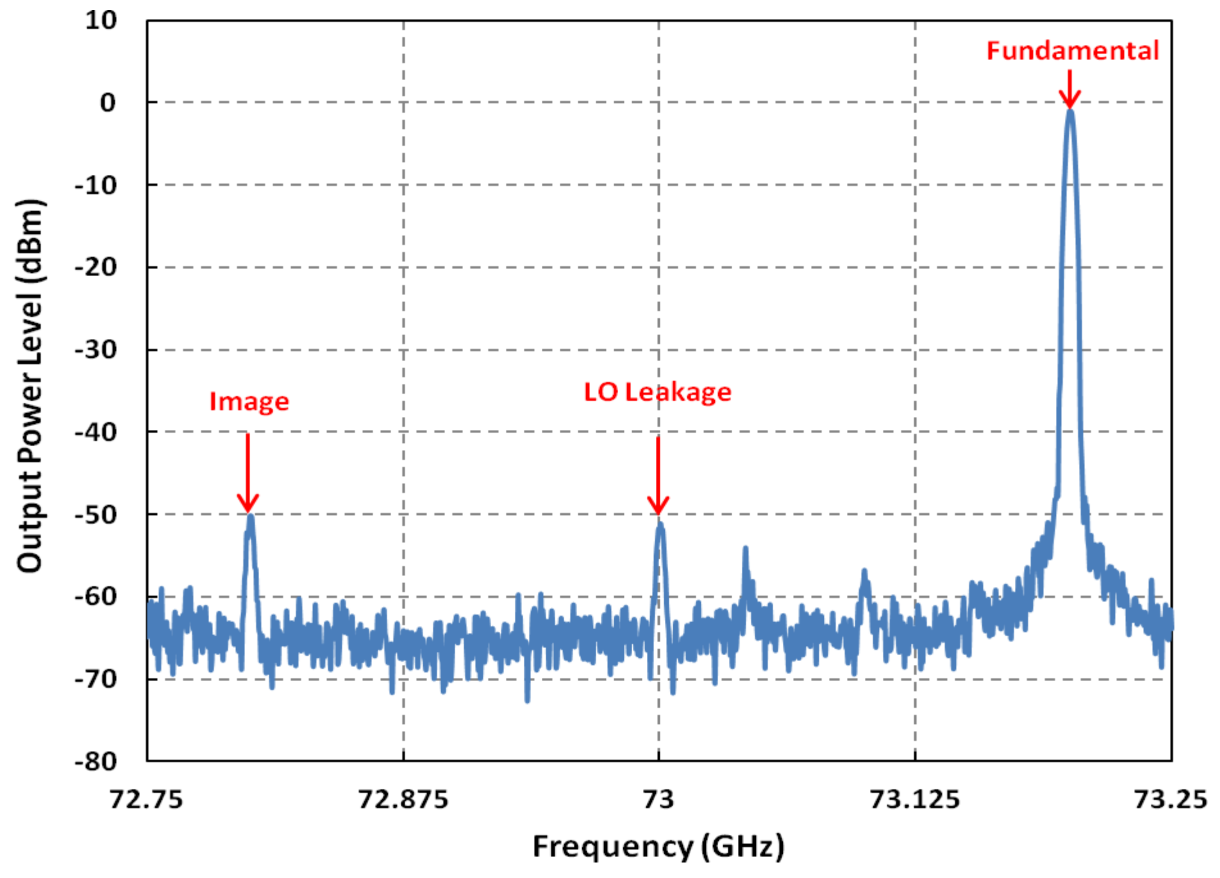


Figure 12 Output Spectrum of BGT70 at TX Waveguide Port on the evaluation board @ f_{TX}=73.22 GHz (DAC VGA=27)

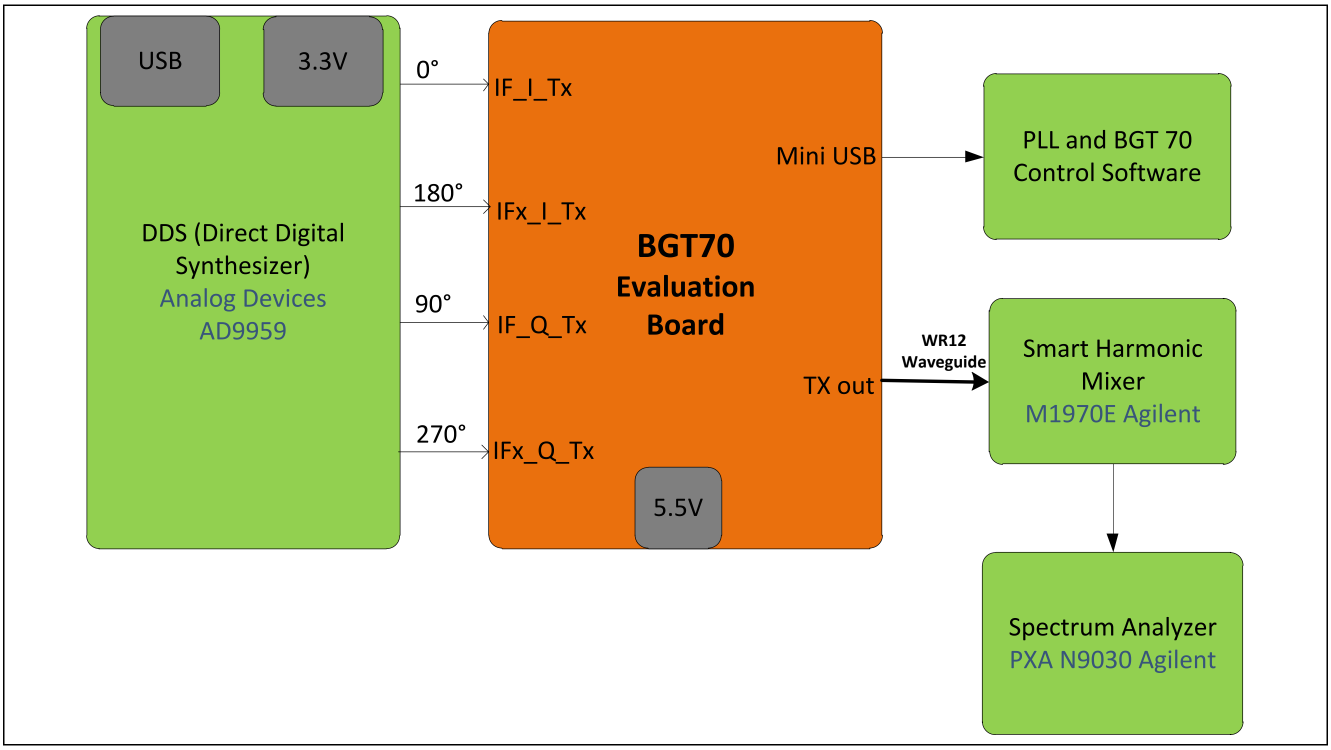


Figure 13 Measurement Setup used to measure TX Output Spectrum of BGT70 @ f_{TX}=73.22 GHz

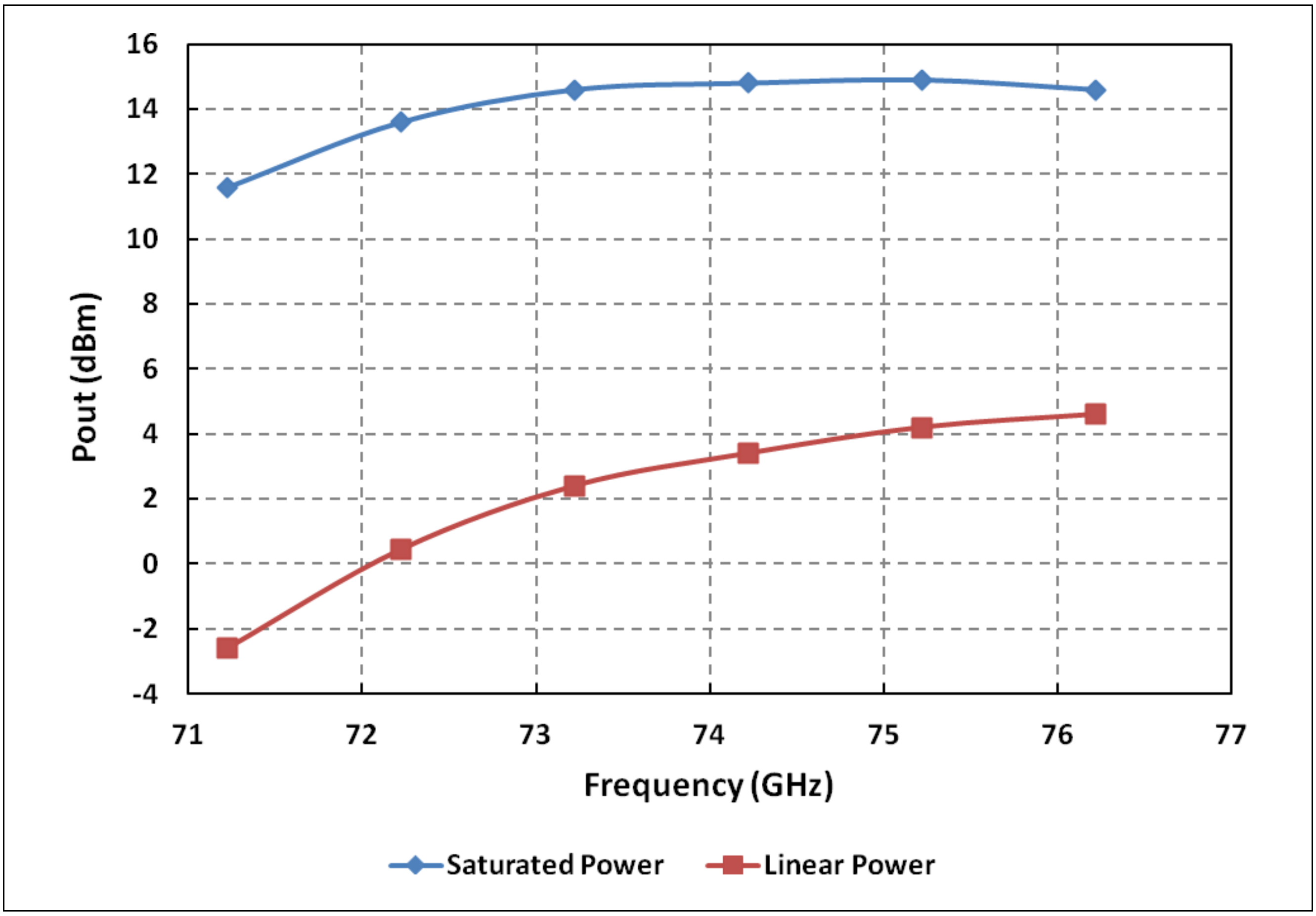


Figure 14 Linear ($P_{IF/TX}$=-27 dBm) and Saturated Power variation over Frequency of BGT70 (DAC VGA=63)

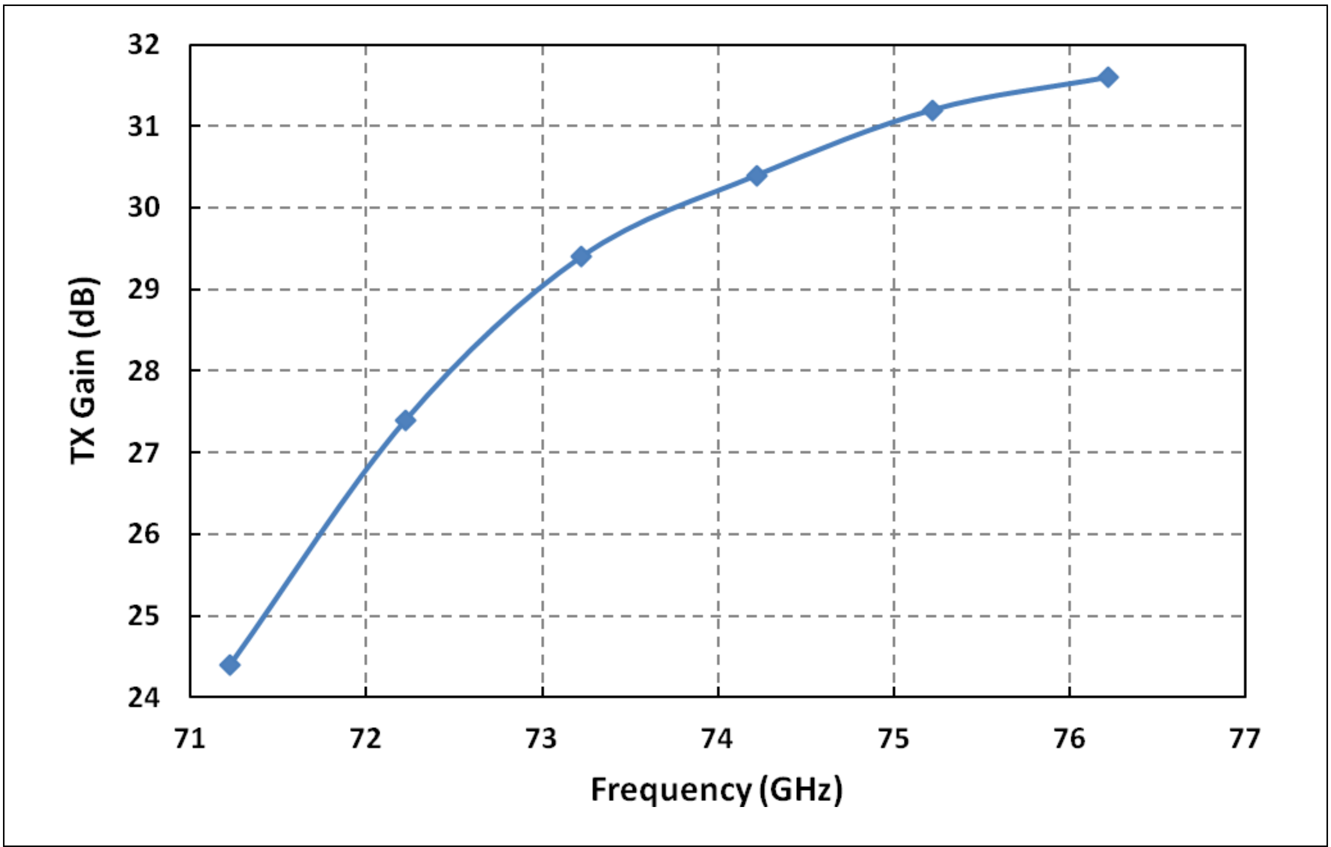


Figure 15 Linear Gain ($P_{IF/TX}$=-27 dBm) over Frequency @ DAC VGA=63

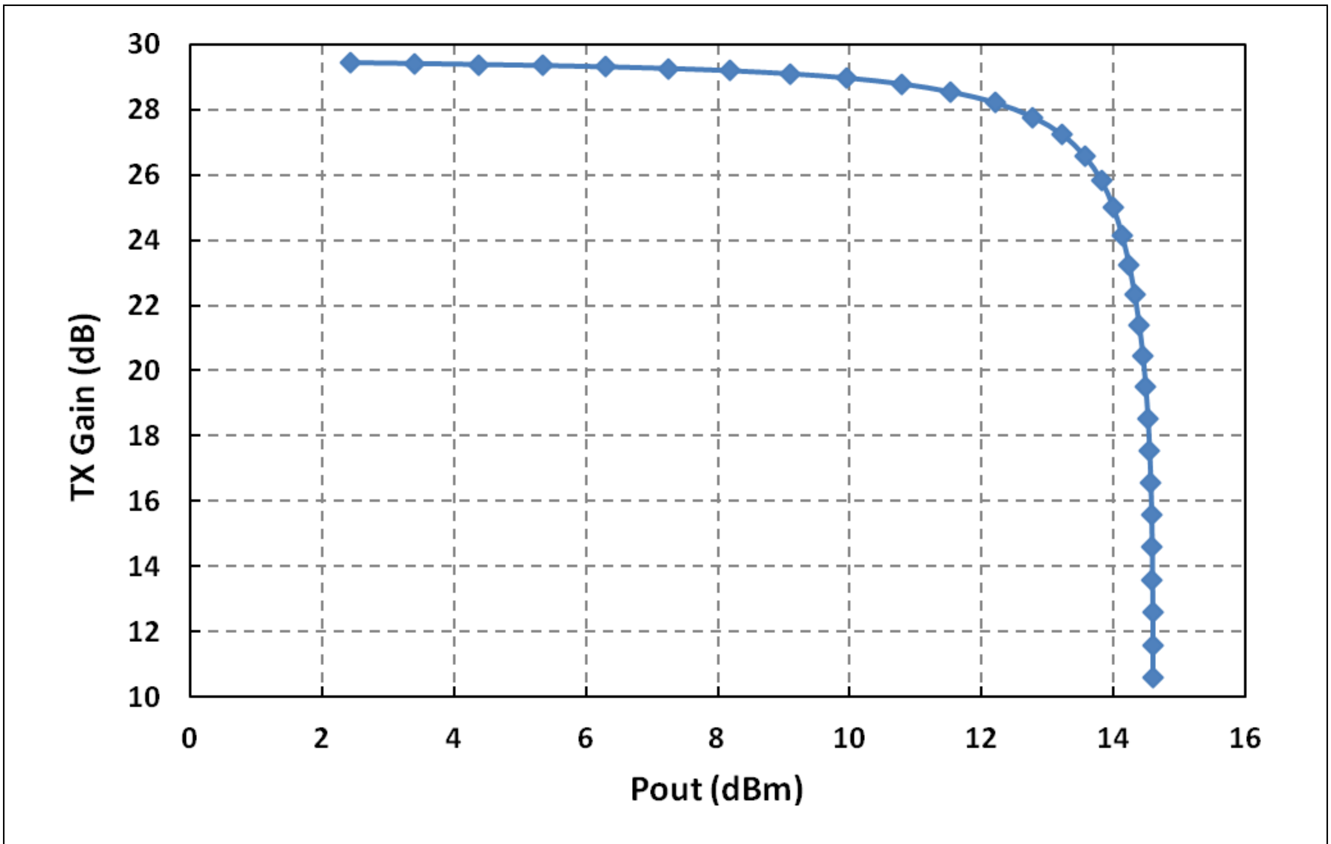


Figure 16 Transmitter Gain vs Output Power @ f_{TX}=73.22 GHz (DAC VGA=63)

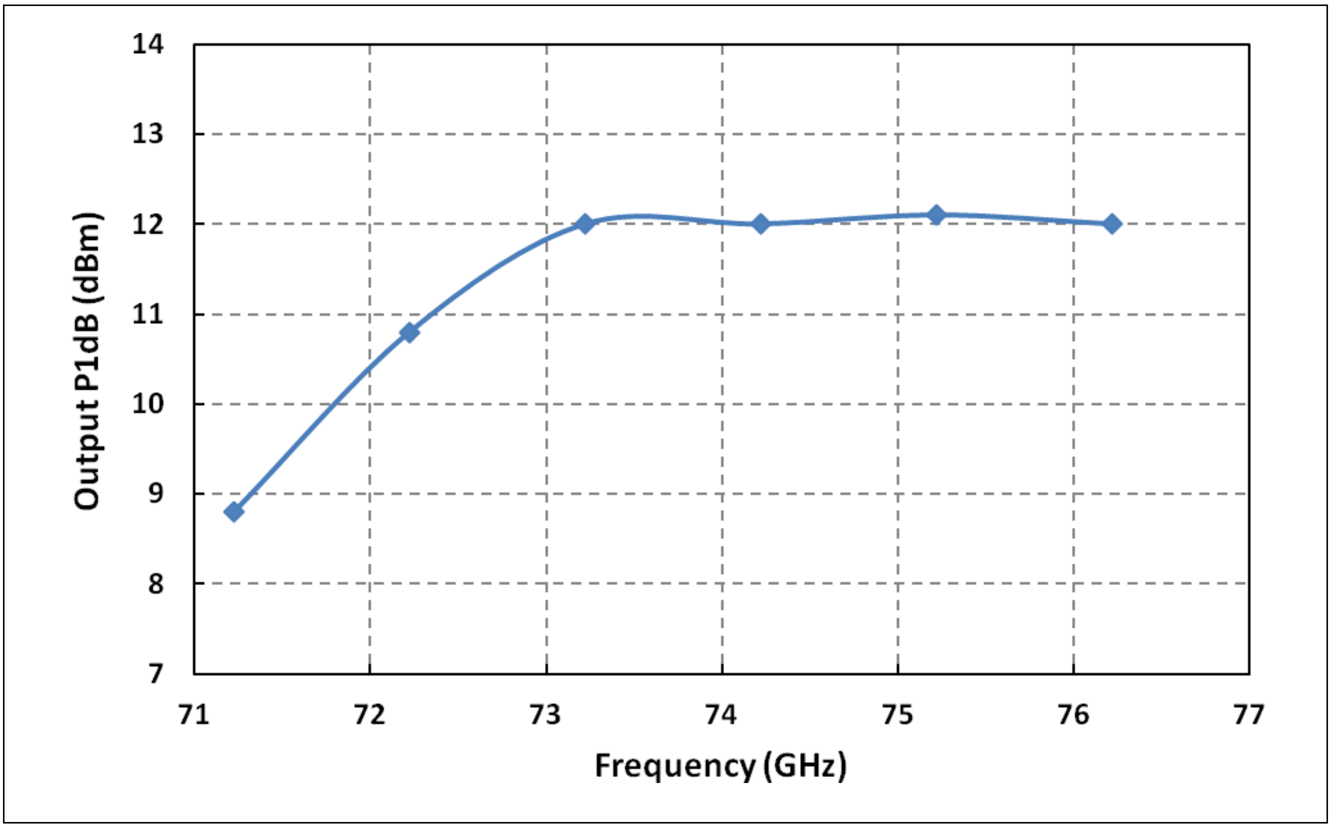


Figure 17 Output P1dB over Frequency @ DAC VGA=63

7.1 Measurement Results of 3rd-Order Intermodulation Products

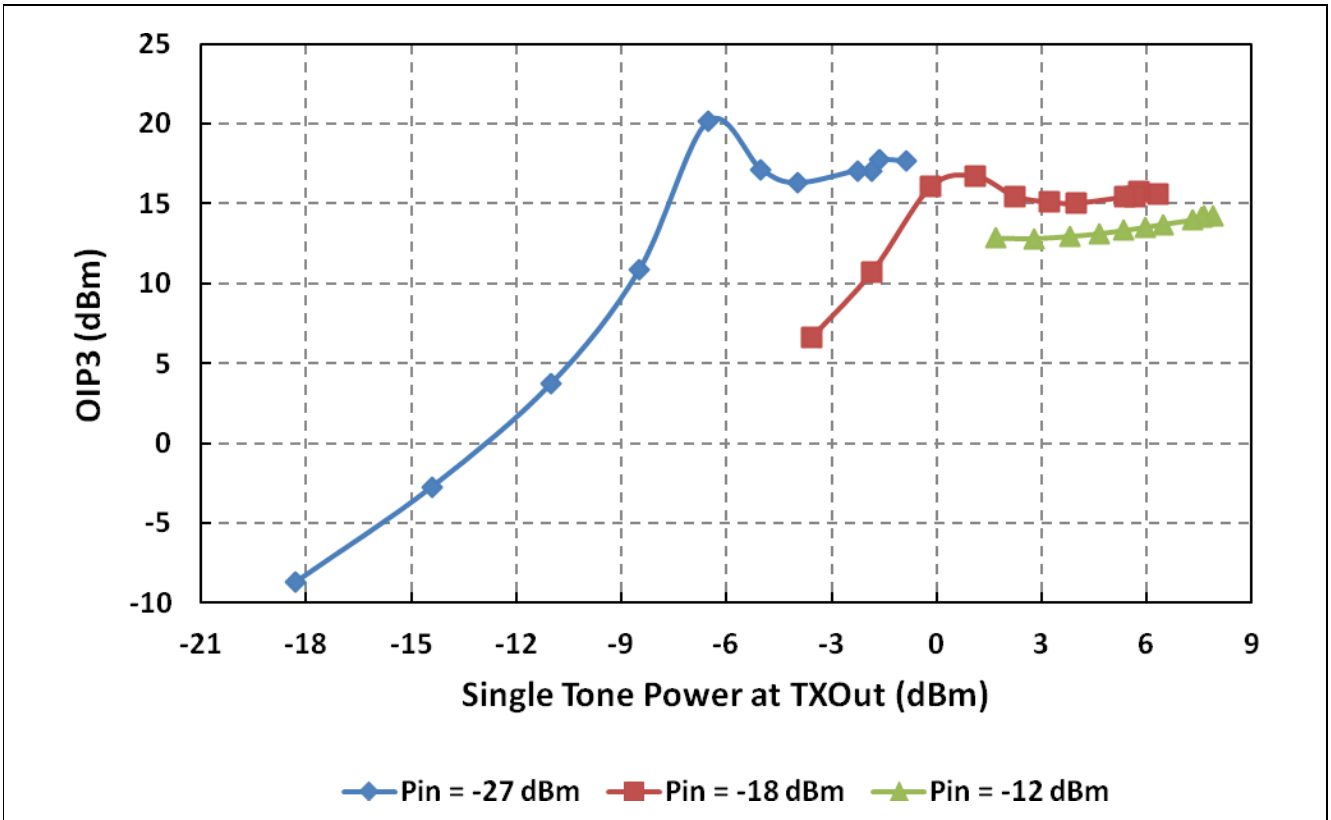


Figure 18 OIP3 and Output Power at various IF Input Power Levels @ f_{TX}=73.25 GHz

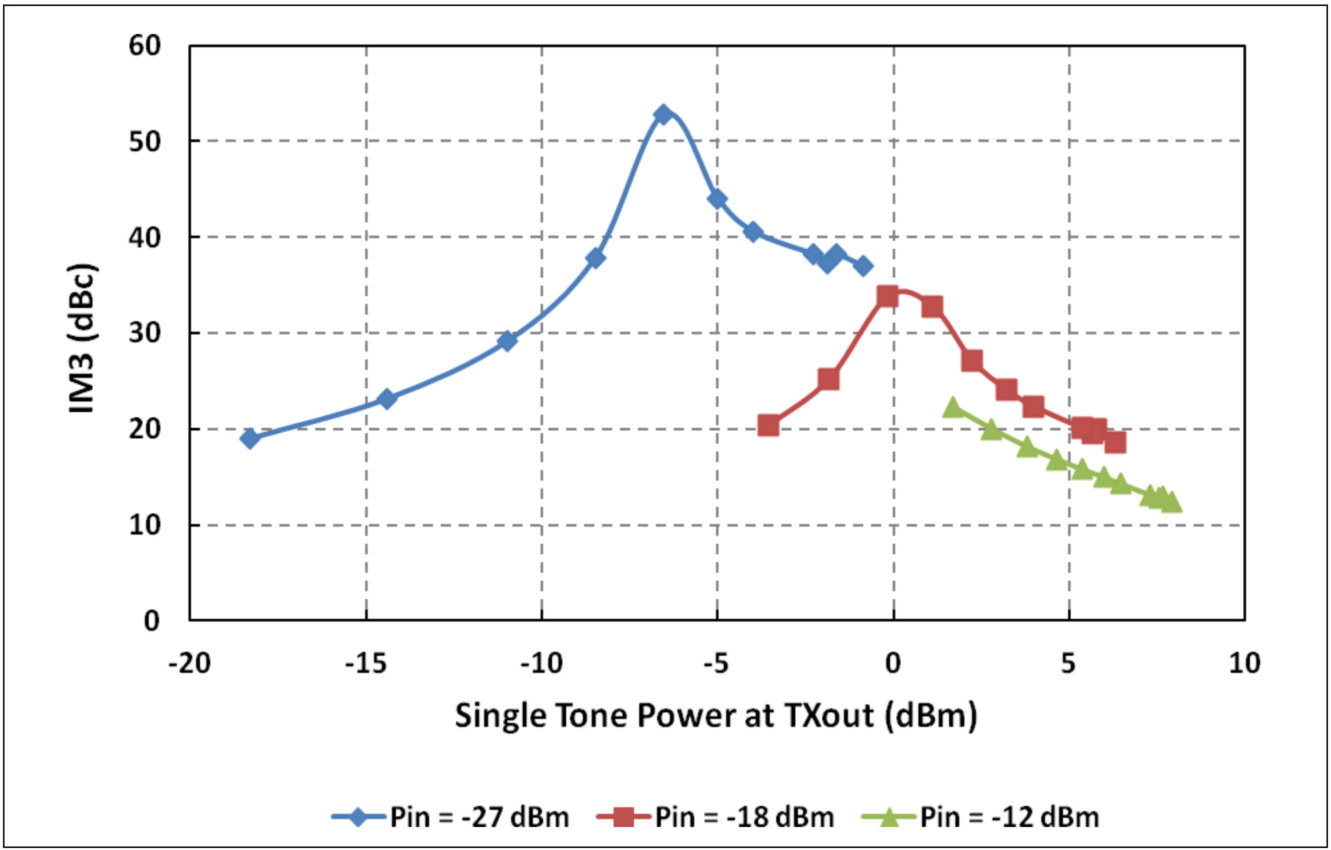


Figure 19 IM3 product versus TX output Power at various IF Input Power Levels @ f_{TX}=73.25 GHz

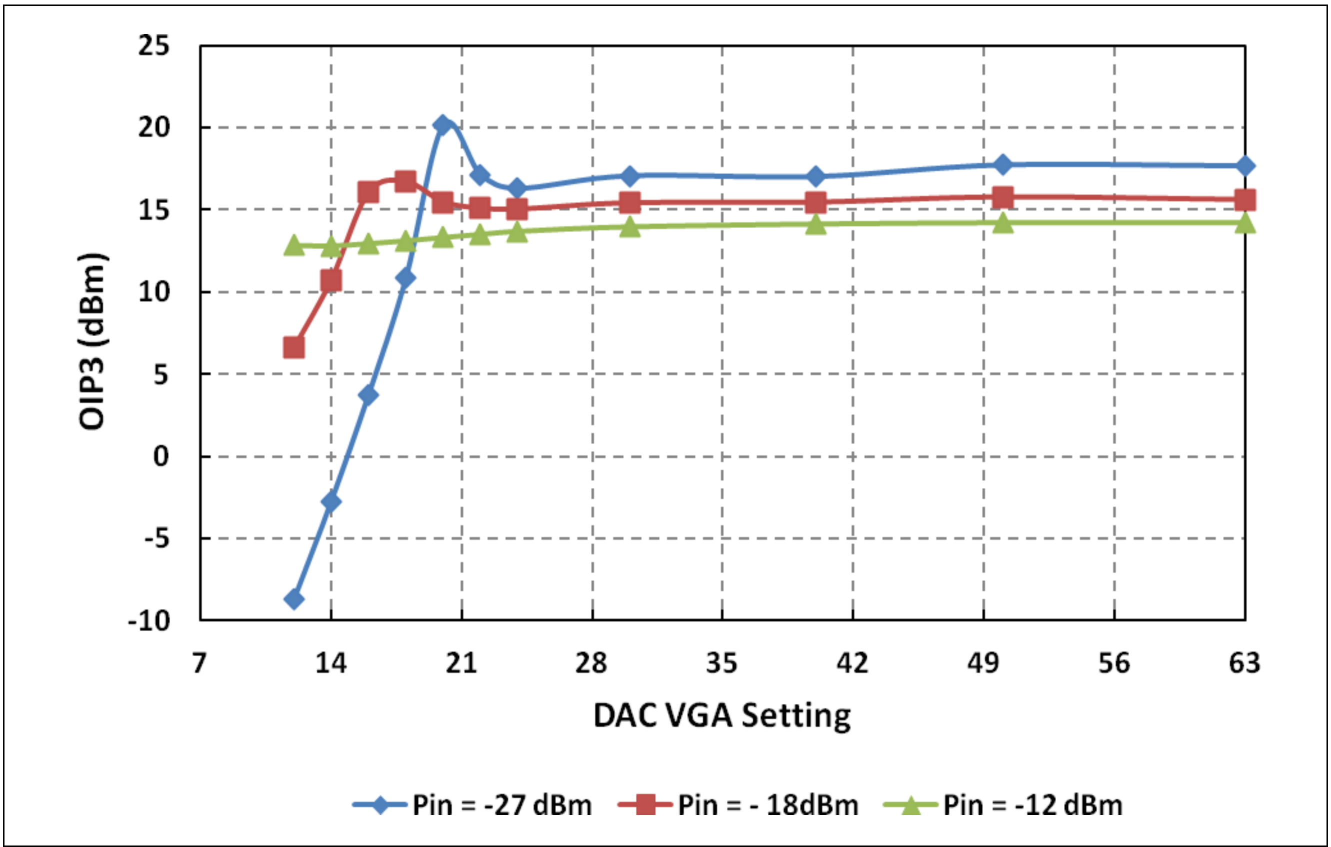


Figure 20 OIP3 versus VGA DAC settings at various IF Input Power Levels @ f_{TX}=73.25 GHz

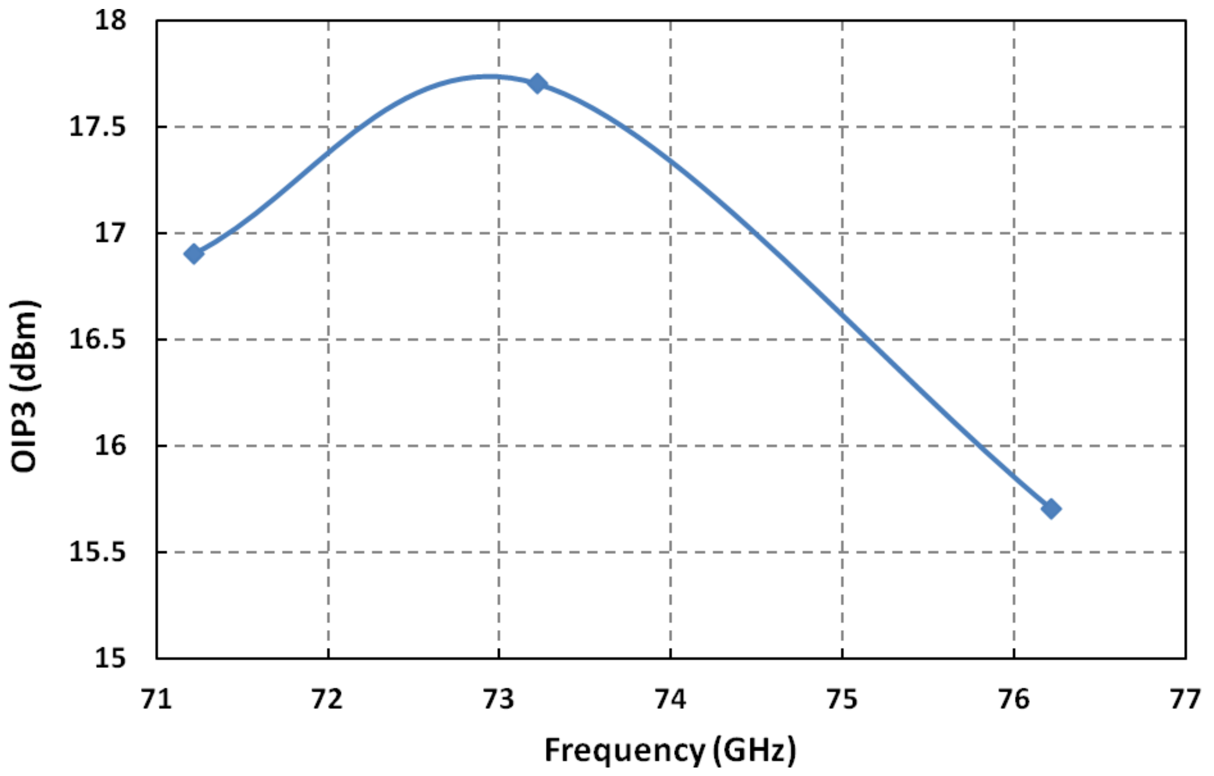


Figure 21 OIP3 versus Frequency at IF Input Power Level=-27 dBm

7.2 Measurement Results of VGA and Buffer Amplifier

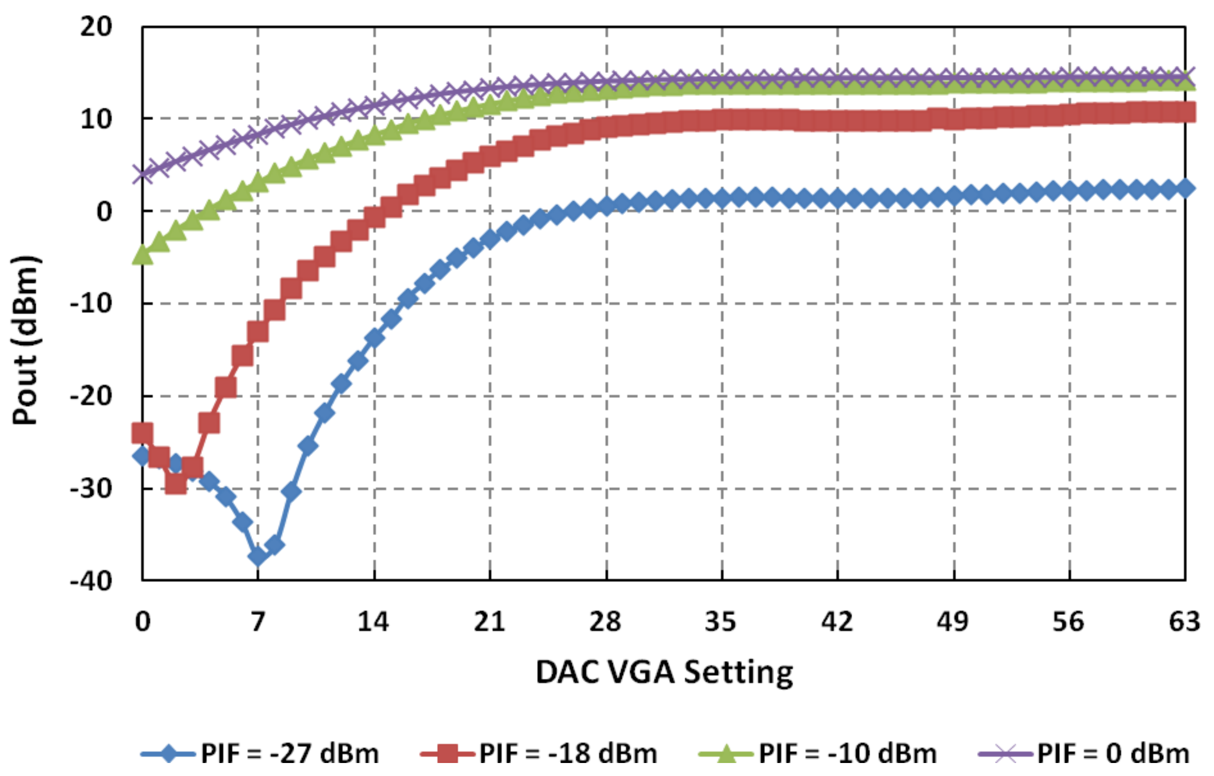


Figure 22 DAC VGA Setting versus Output Power at different IF Input Power levels (f_{TX} = 73.22 GHz)

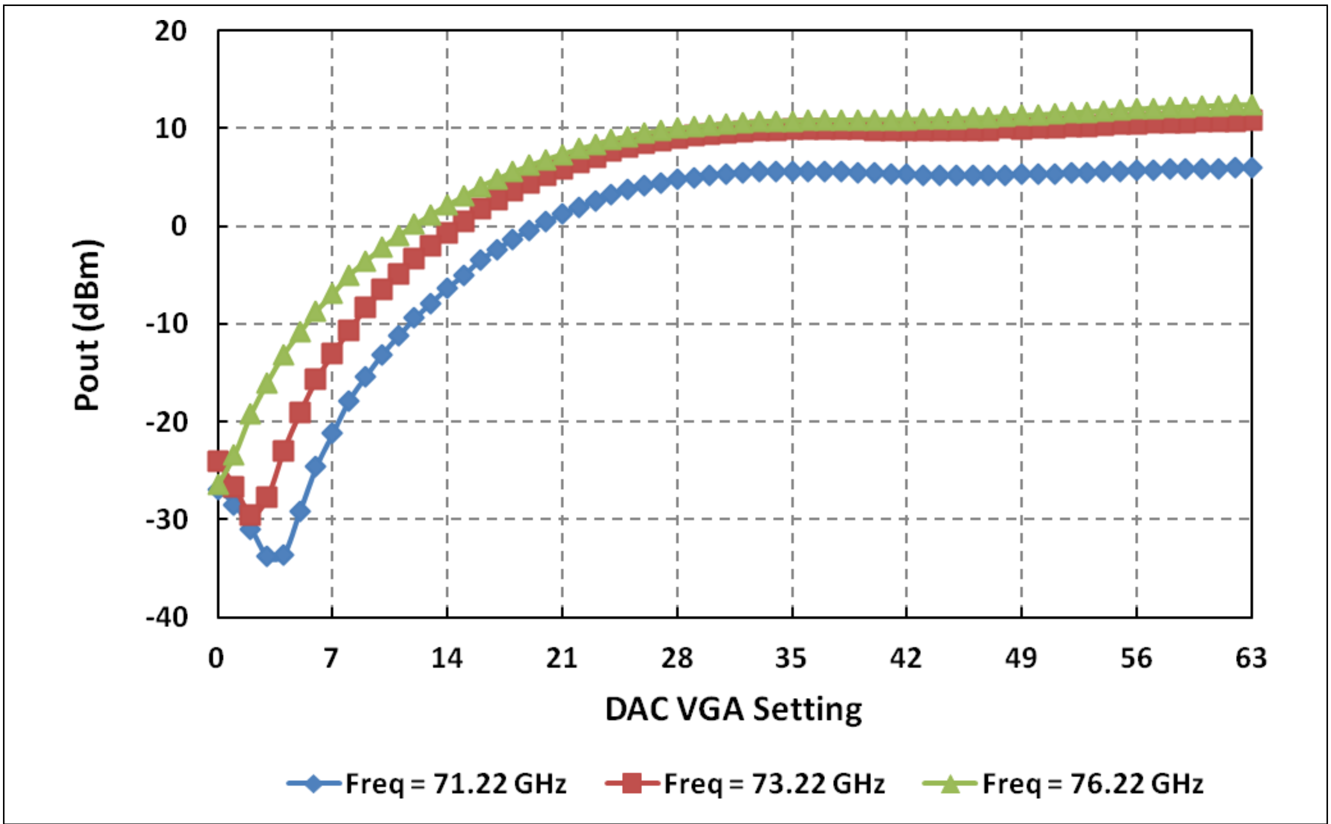


Figure 23 DAC VGA Setting versus Output Power over Frequency ($P_{IF/TX}$ = -18 dBm)

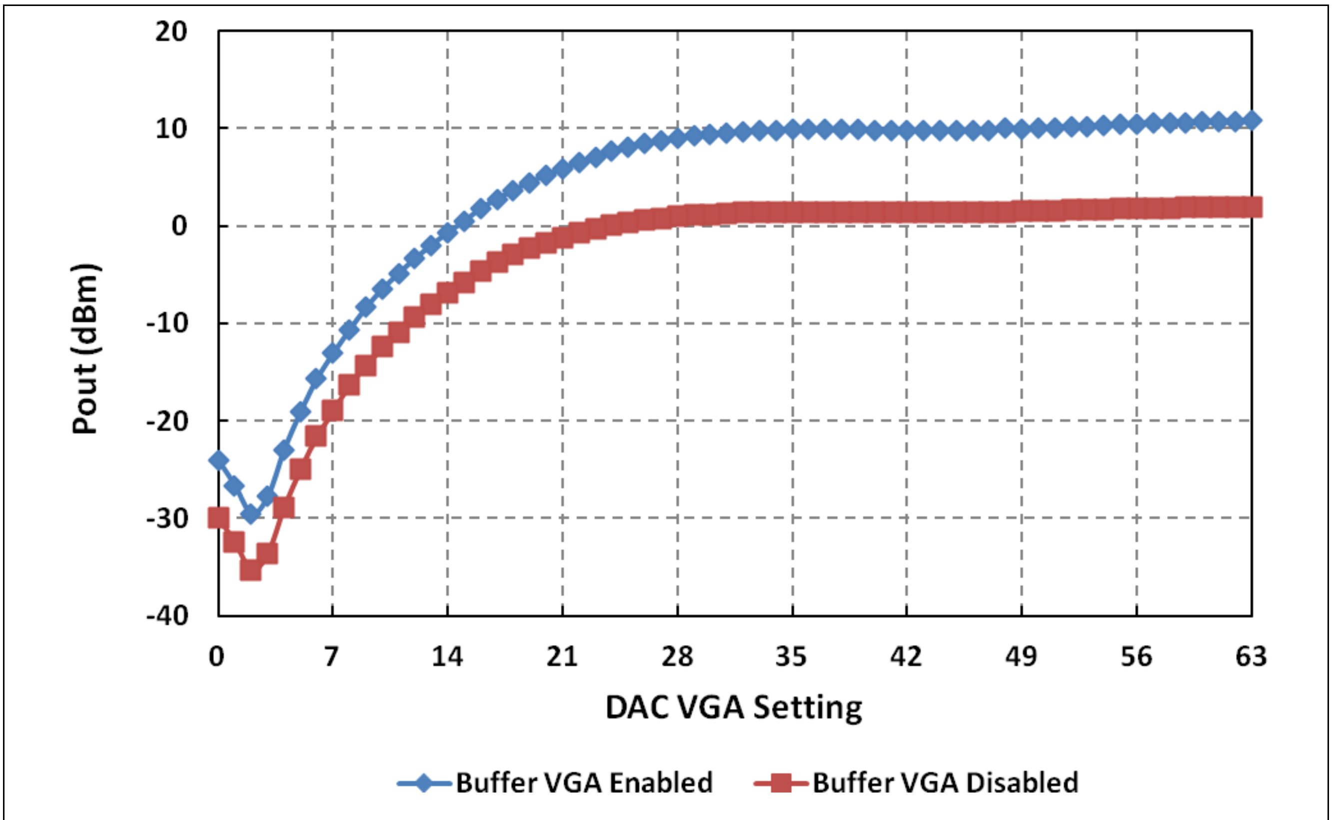


Figure 24 DAC VGA Setting versus Output Power when Buffer VGA in enabled/disabled ($P_{IF/TX}$ = -18 dBm; f_{TX} = 73.22 GHz)

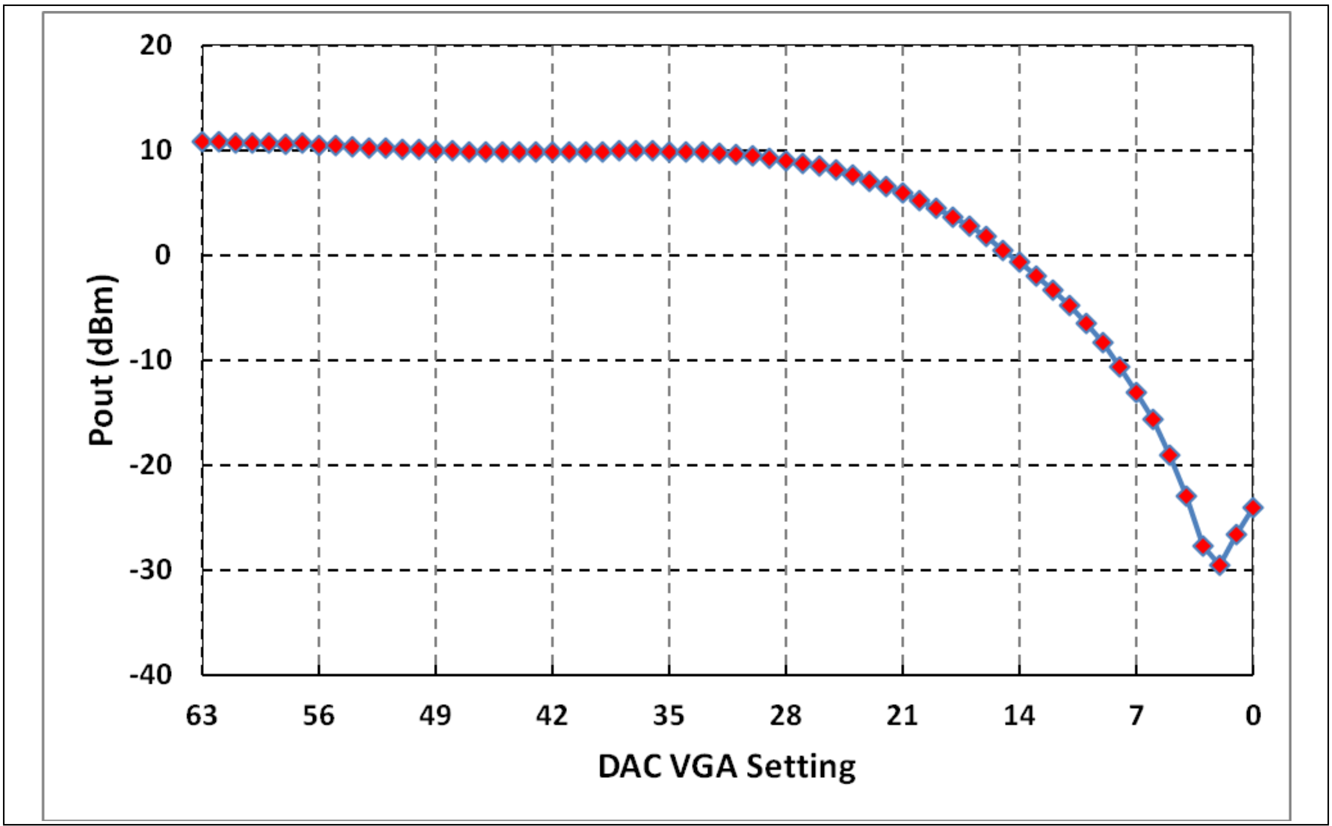


Figure 25 Output Power versus DAC VGA Setting (Buffer VGA=Enabled;$P_{IF/TX}$=-18 dBm; f_{TX}=73.22 GHz)

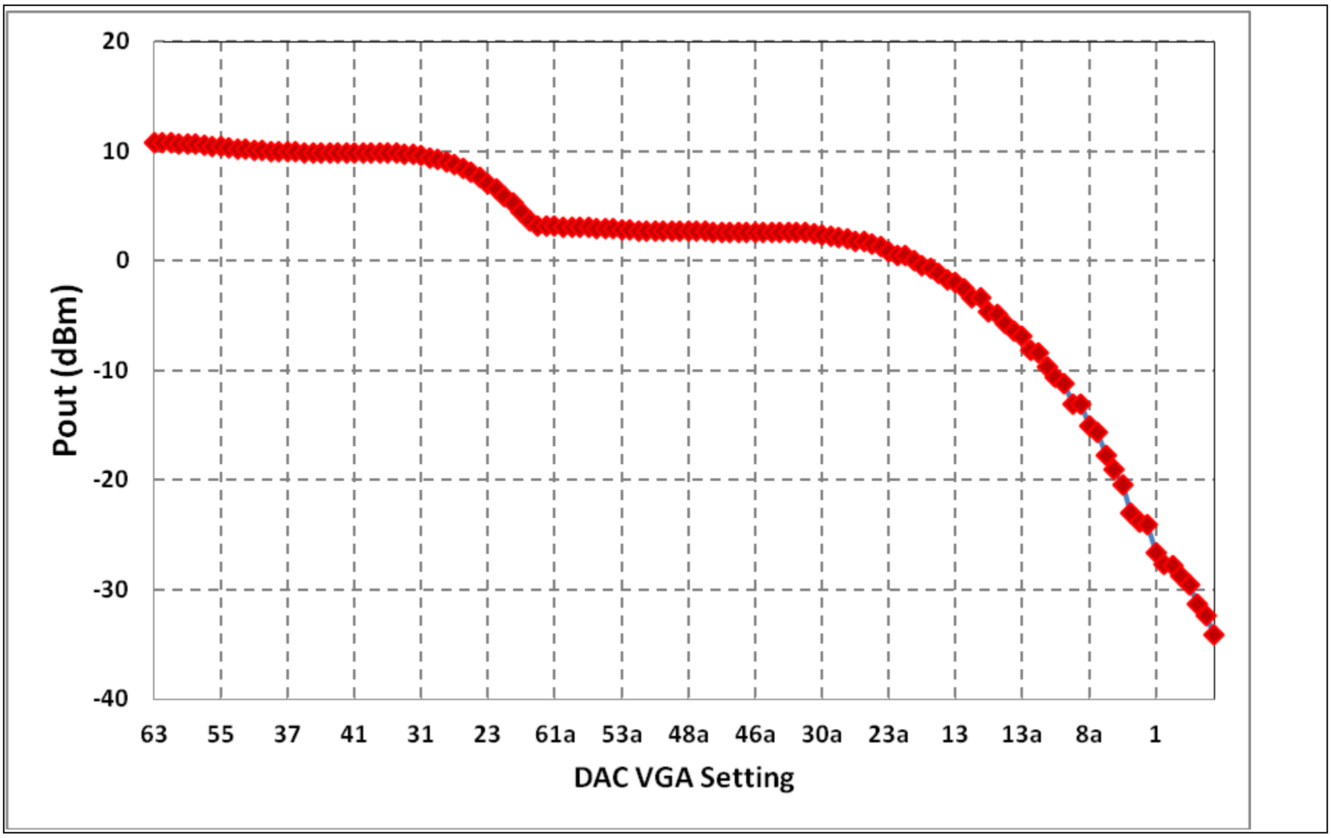


Figure 26 Pout vs DAC VGA setting when Buffer VGA=Enabled/Disabled @ $P_{IF/TX}$=-18 dBm and f_{TX}=73.22 GHz (*Buffer VGA Disabled denoted by VGA setting followed by letter "a" e.g. 46a*)

7.3 PPD Modulator – DMOD Out

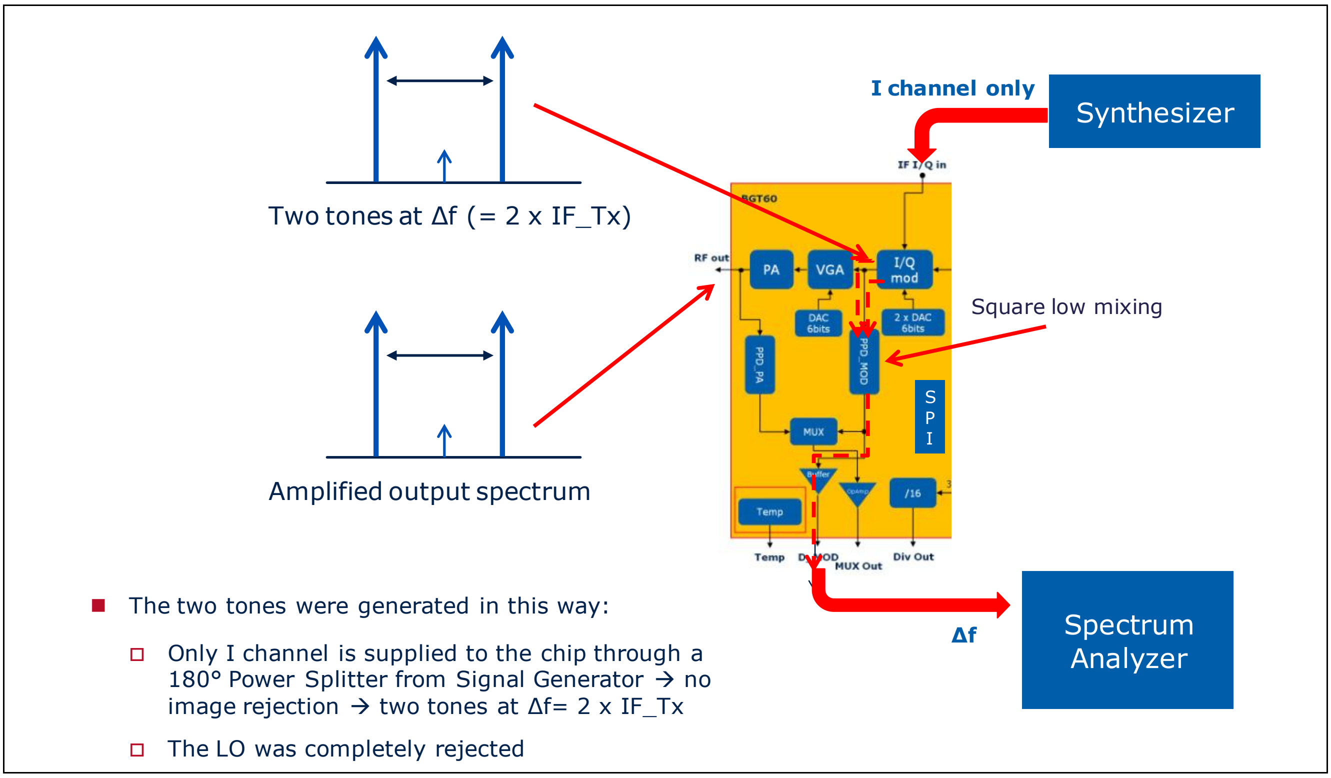


Figure 27 Test Setup for Measurement of PPD Modulator Response

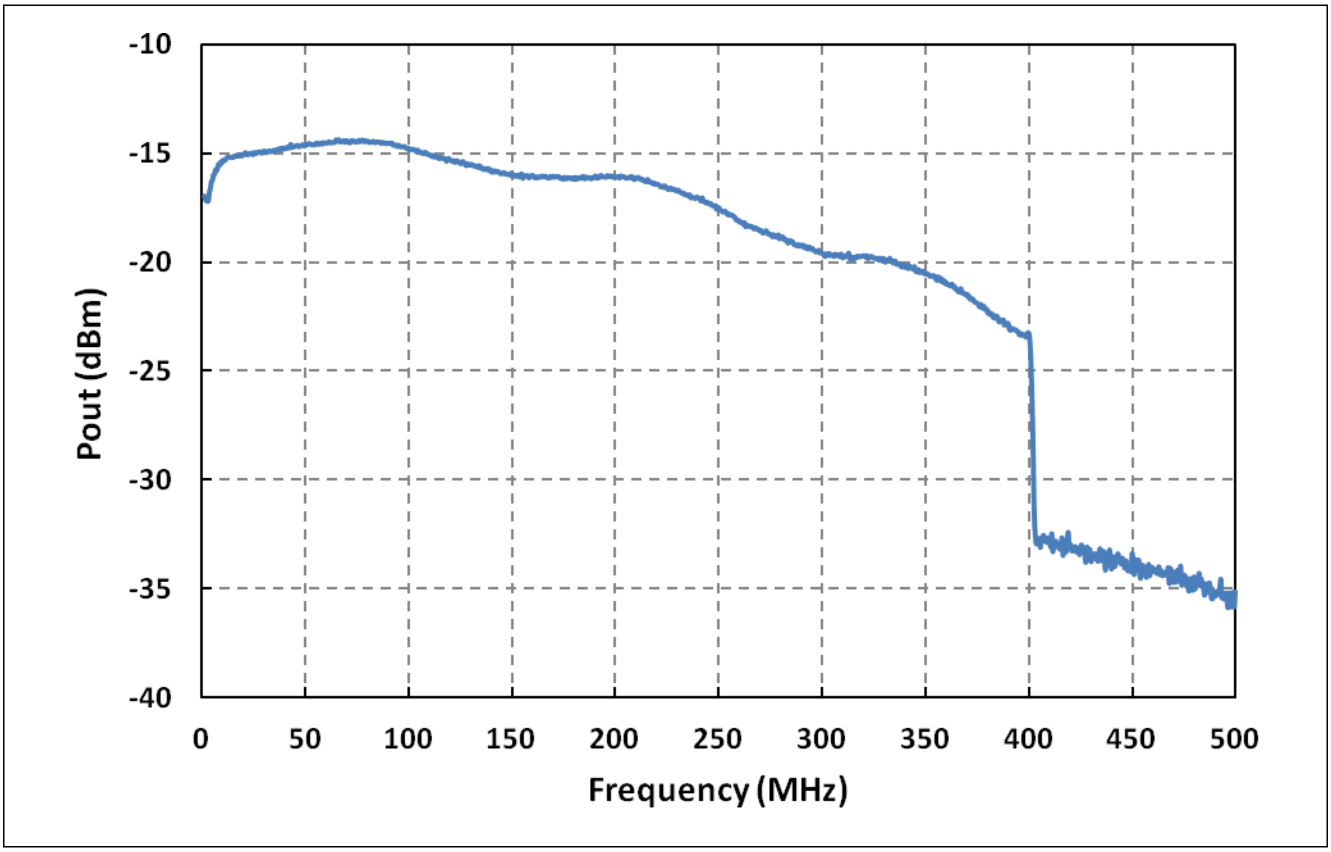


Figure 28 Bandwidth Measurement of DMOD

7.4 PPD Power Amplifier – MUX out

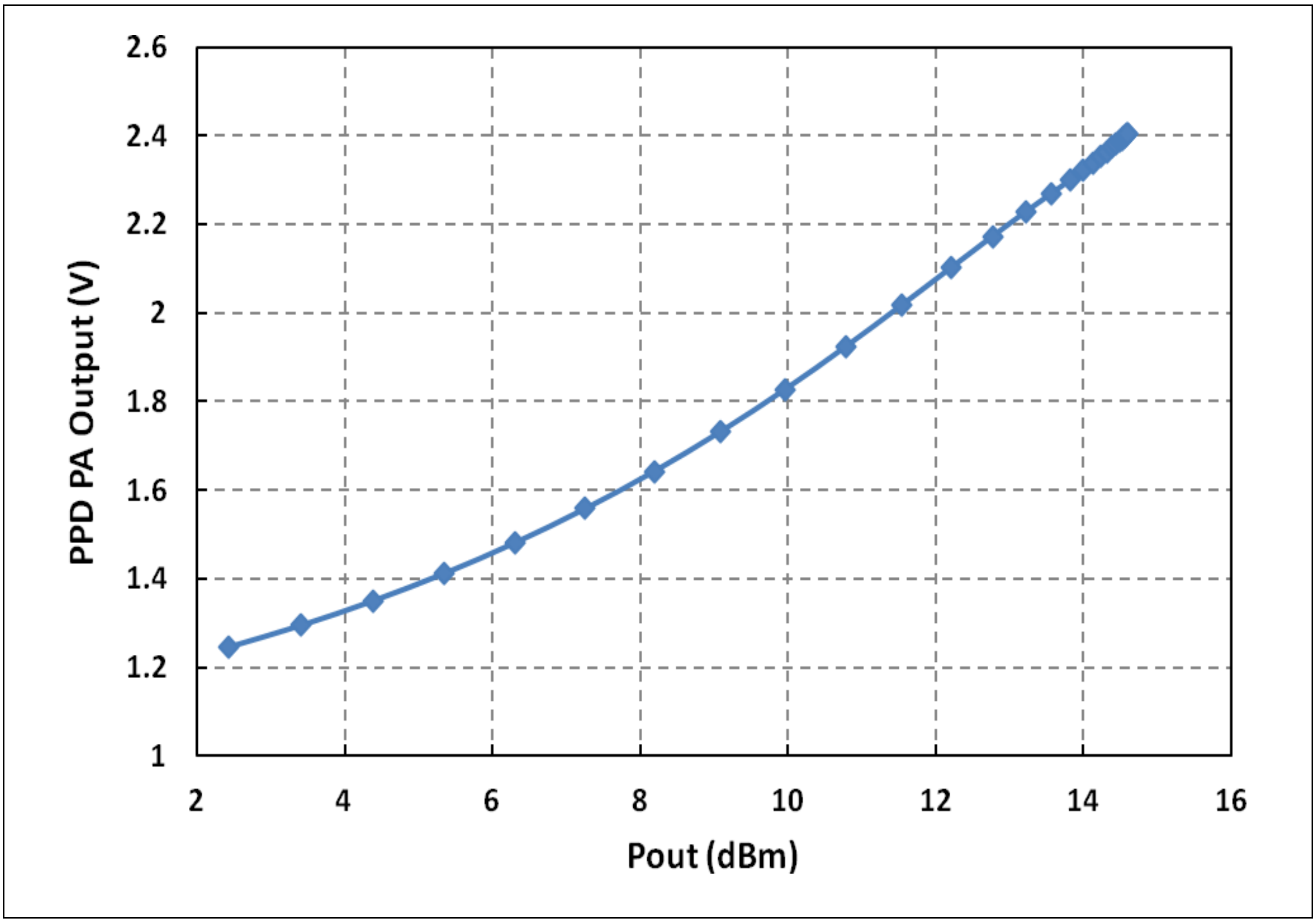


Figure 29 PPD PA Output Voltage versus Output Power @ f_{TX}=73.22 GHz

8 Performance of BGT70 Receiver

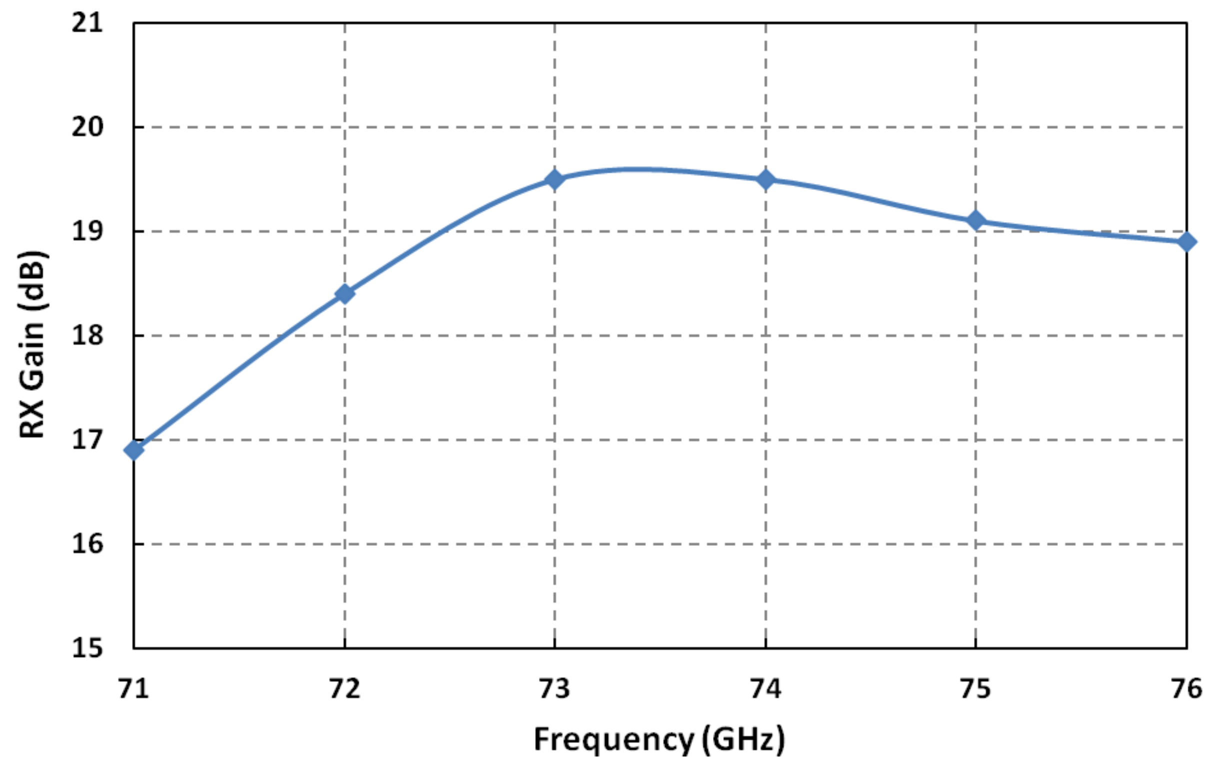


Figure 30 Receiver Gain over Frequency for BGT70

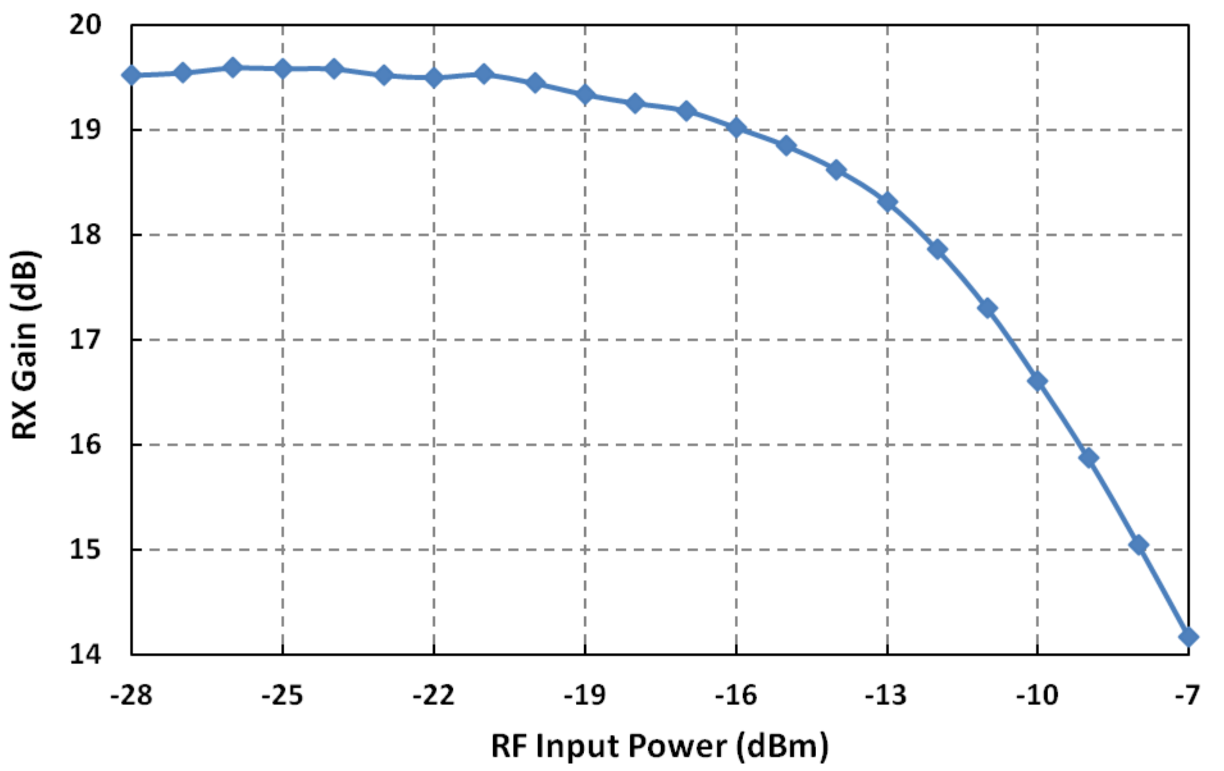


Figure 31 Input P1dB of Receiver @ f_{RX}=73 GHz

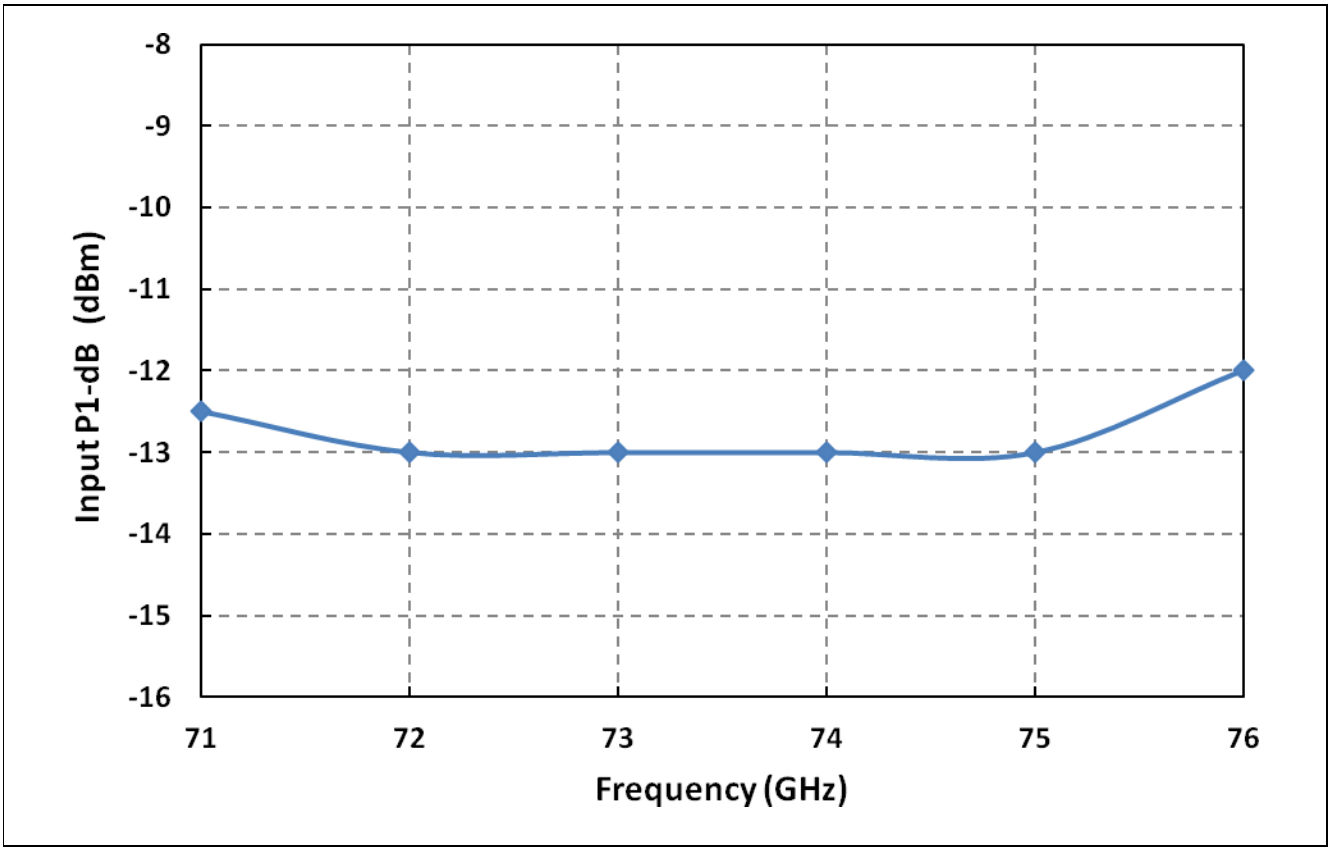


Figure 32 Input P1dB over Frequency of BGT70 Receiver

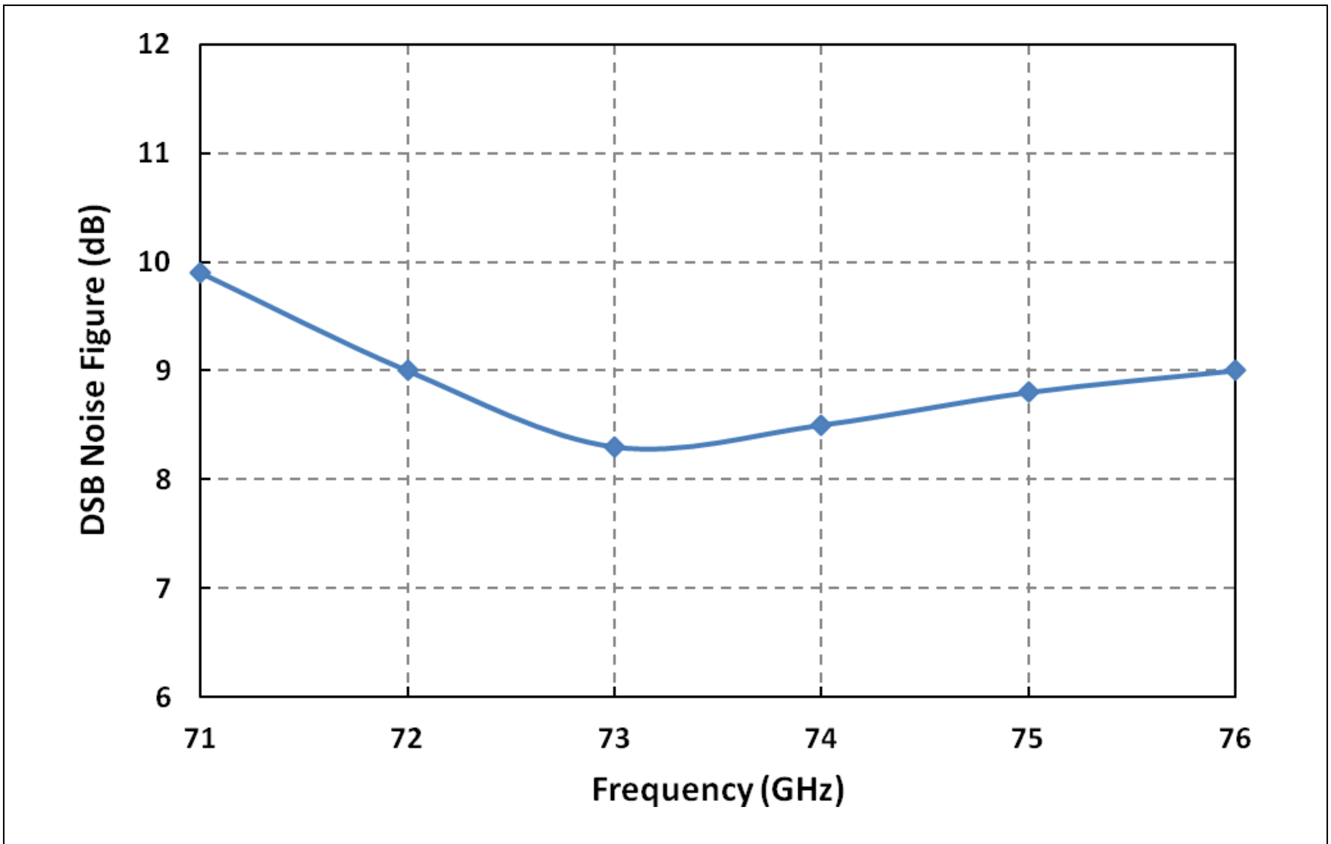


Figure 33 Noise Figure variation over Frequency for BGT70

8.1 Intercept Point Measurement of Receiver

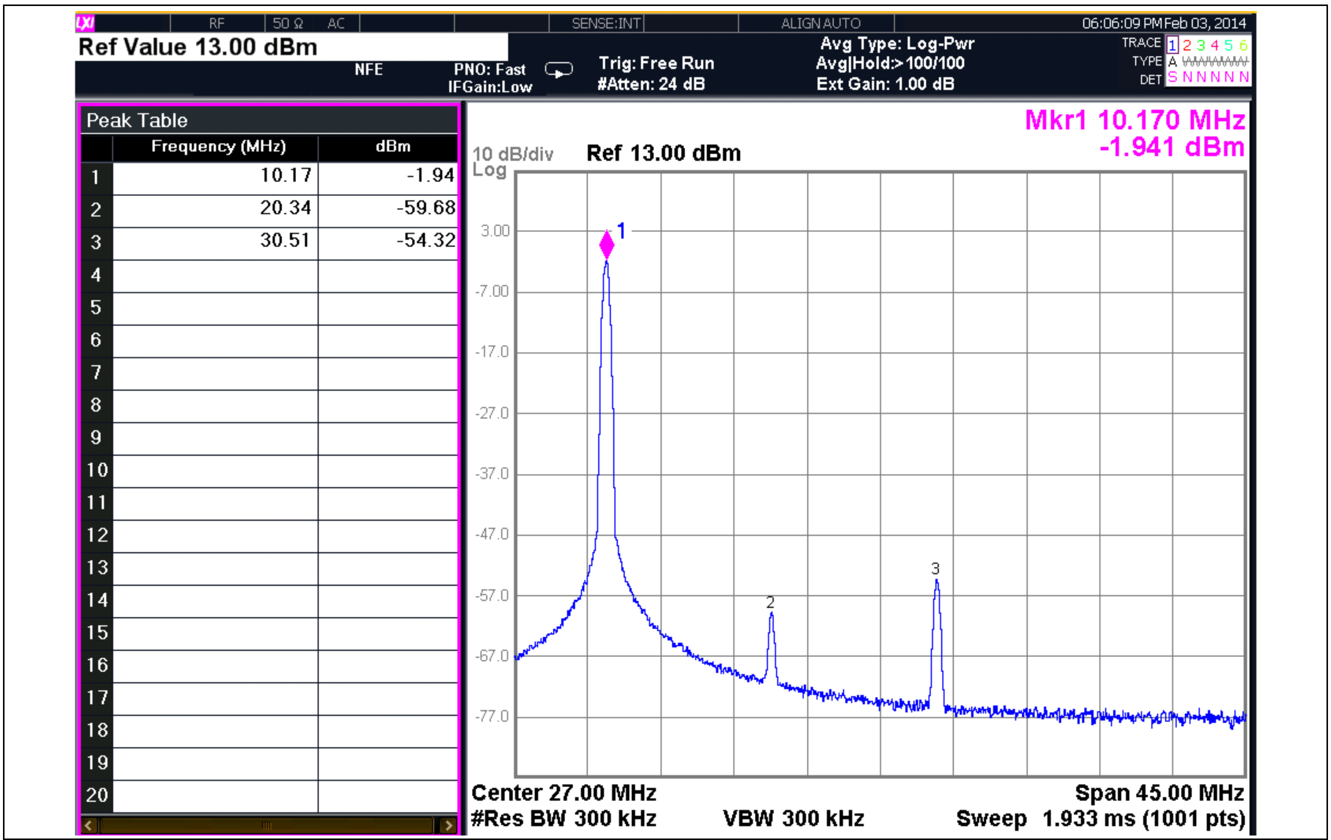


Figure 34 IIP2 of Receiver at $P_{RX\text{-}RF}$=-22 dBm, f_{RF}=73.01 GHz (setup losses not de-embedded)

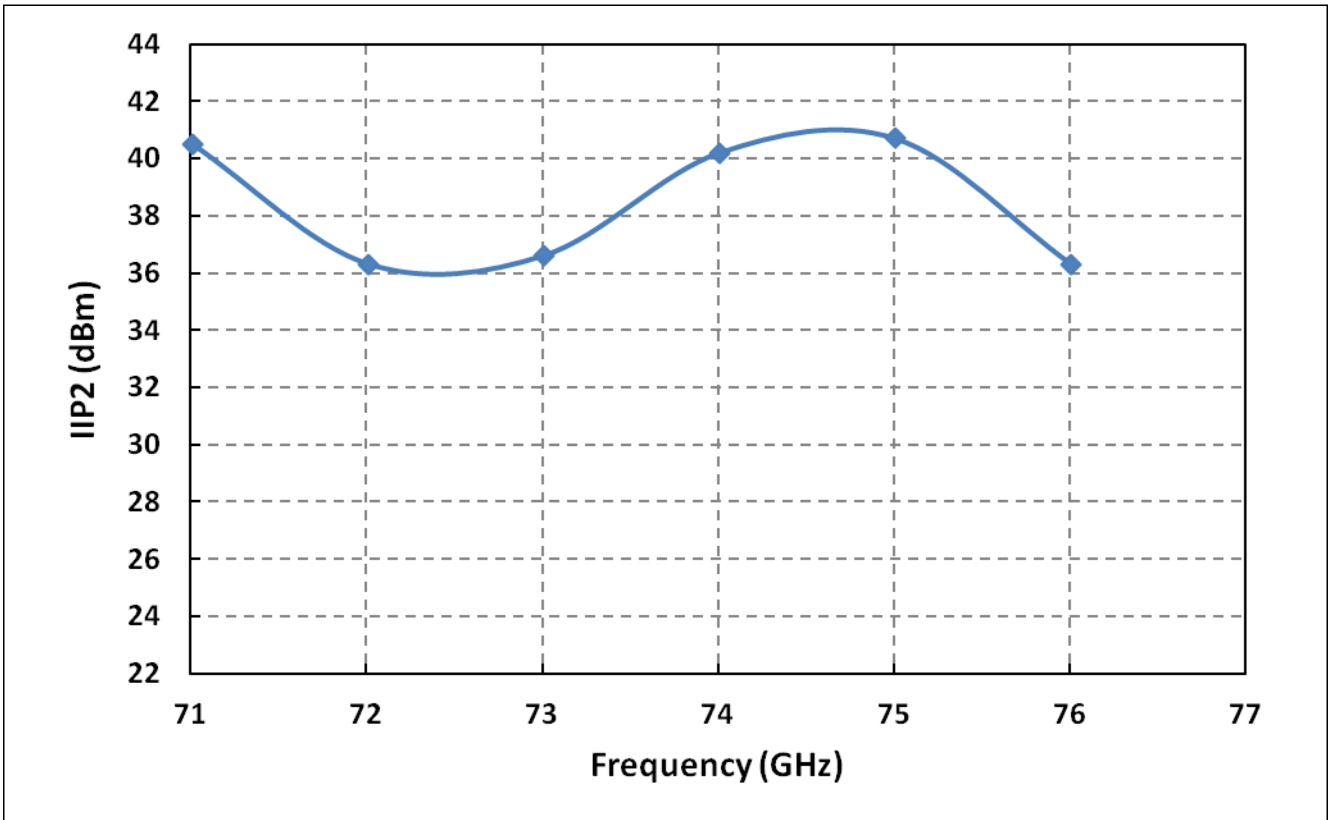


Figure 35 Input IP2 of Receiver over Frequency at $P_{RX\text{-}RF}$=-28 dBm

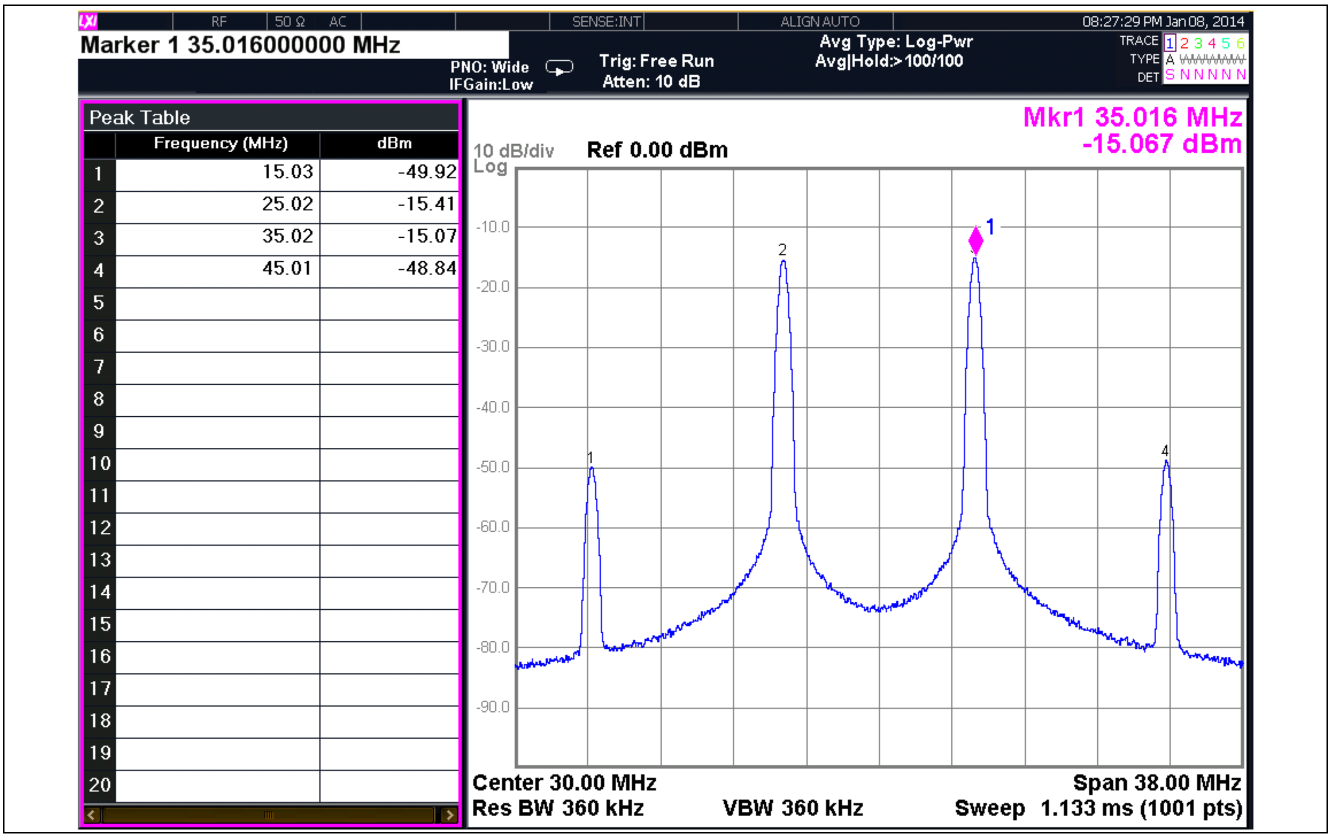


Figure 36 Input IIP3 of Receiver at $P_{RX\text{-}RF}$=-22 dBm, f_{RF}=73.025 GHz (setup losses not de-embedded)

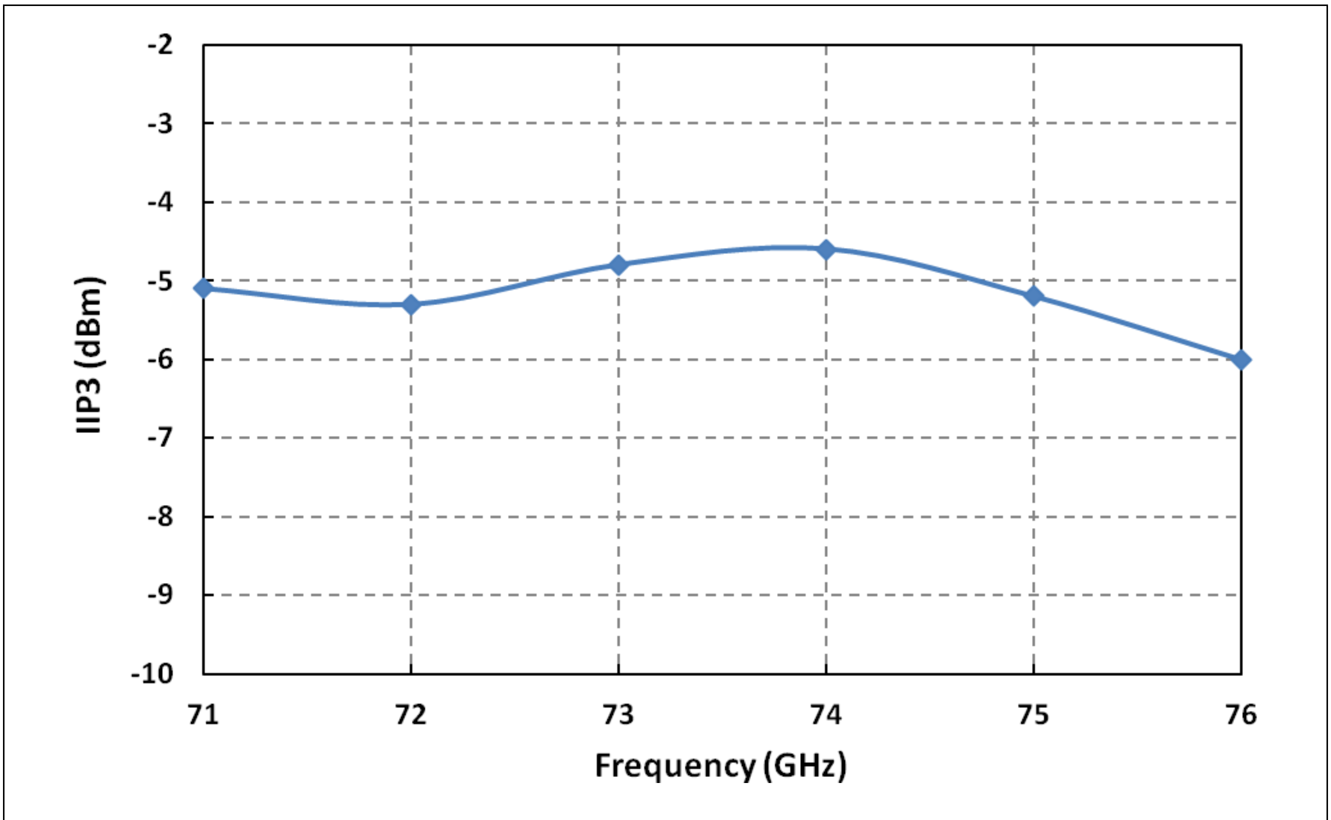


Figure 37 Input IP3 of Receiver over Frequency at $P_{RX\text{-}RF}$ = -31 dBm

8.2 I/Q Imbalance Analysis of Receiver

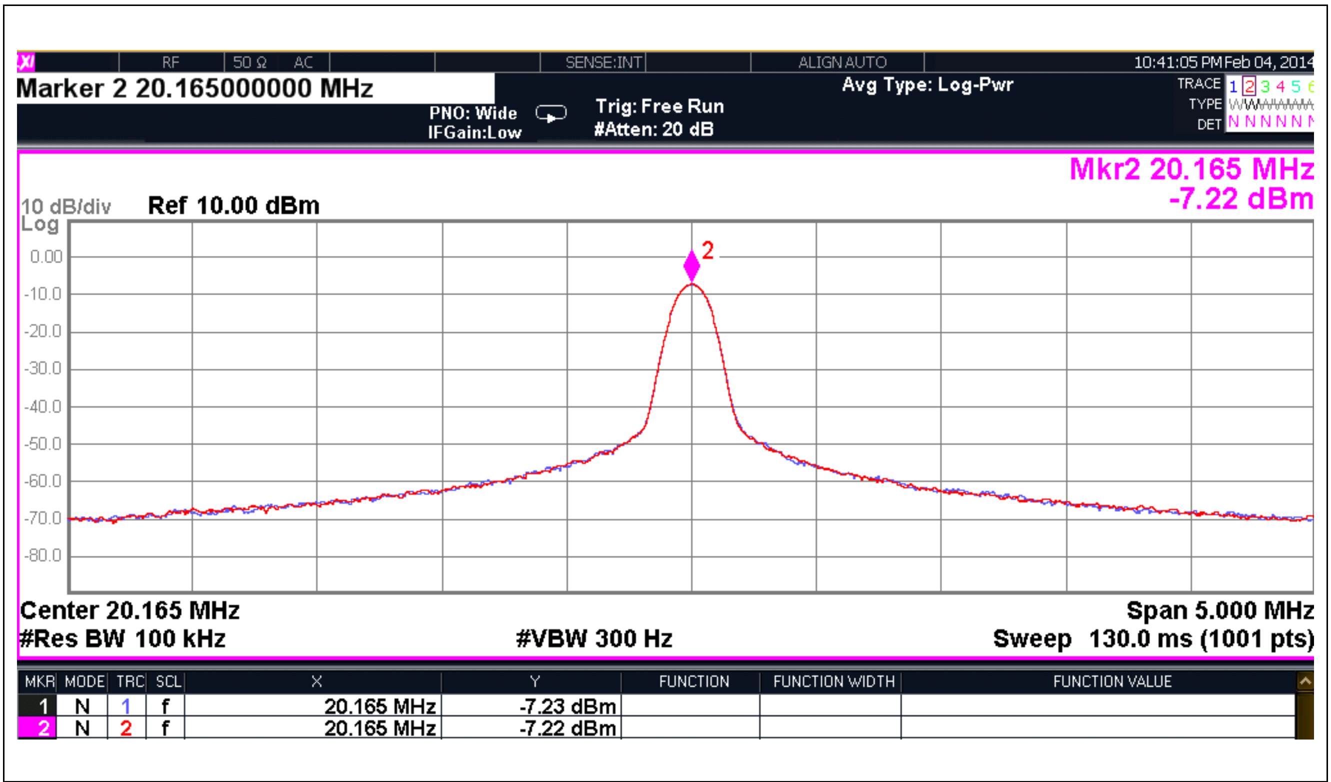


Figure 38 RX I/Q Imbalance in Amplitude (IF Ch-I in blue, IF Ch-Q in red)

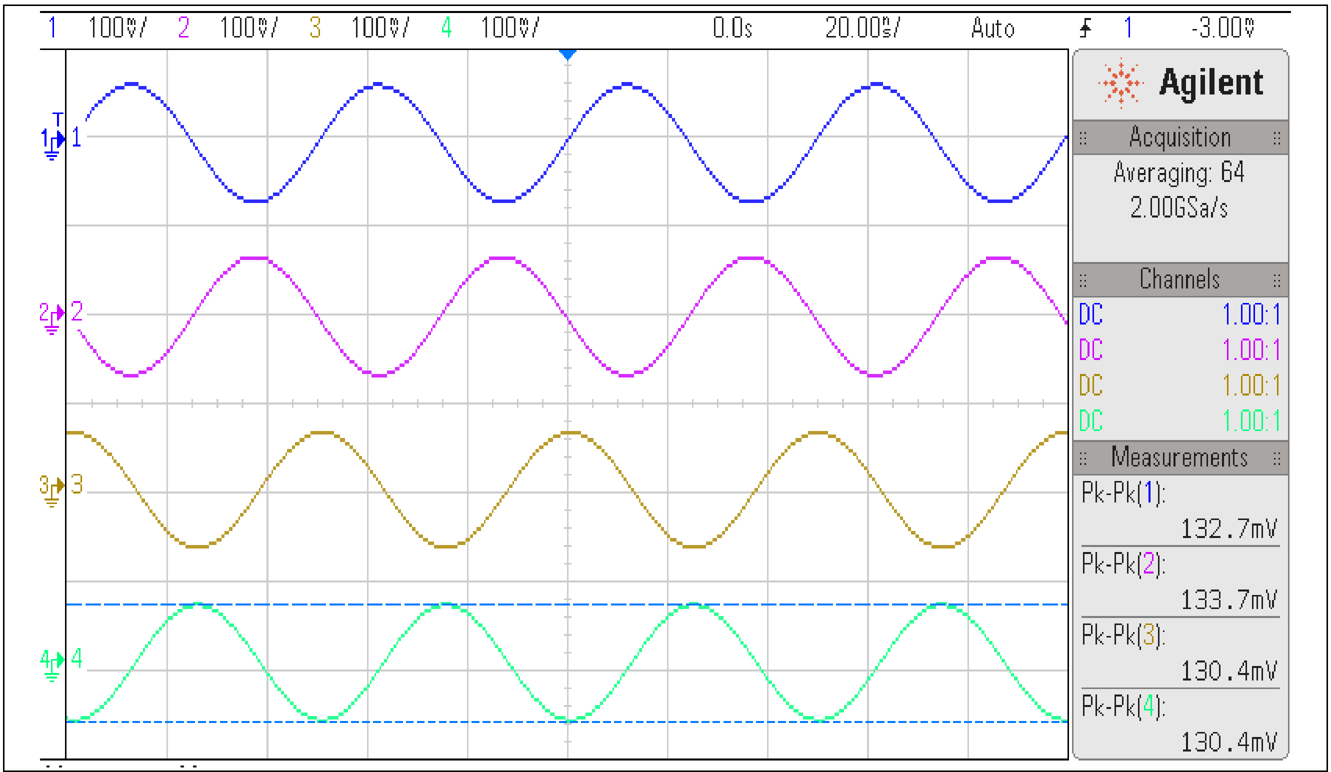


Figure 39 RX I/Q Imbalance in Magnitude (IF Ch-I in blue/pink, IF Ch-Q in brown/cyan)

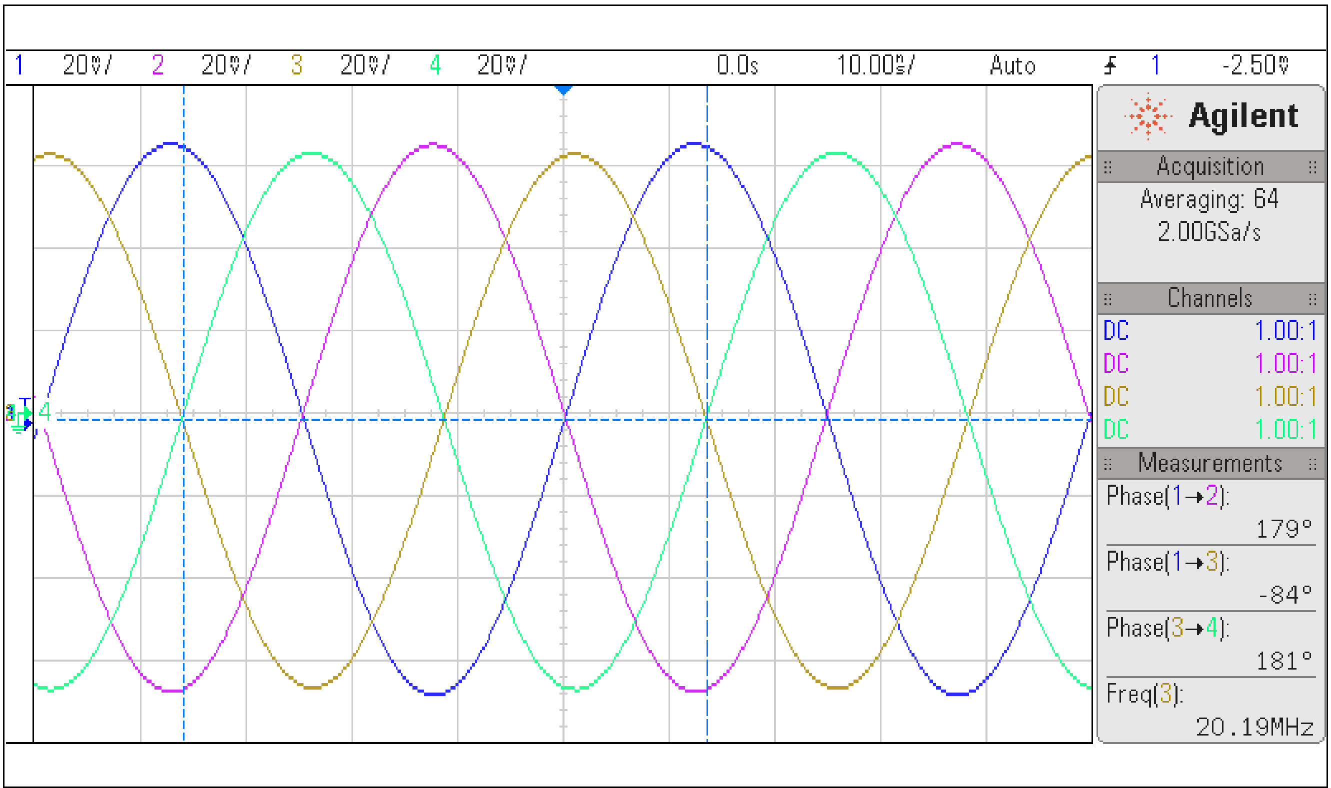


Figure 40 RX I/Q Imbalance in Phase (IF Ch-I-brown/blue, IF Ch-Q-Cyan/Purple)

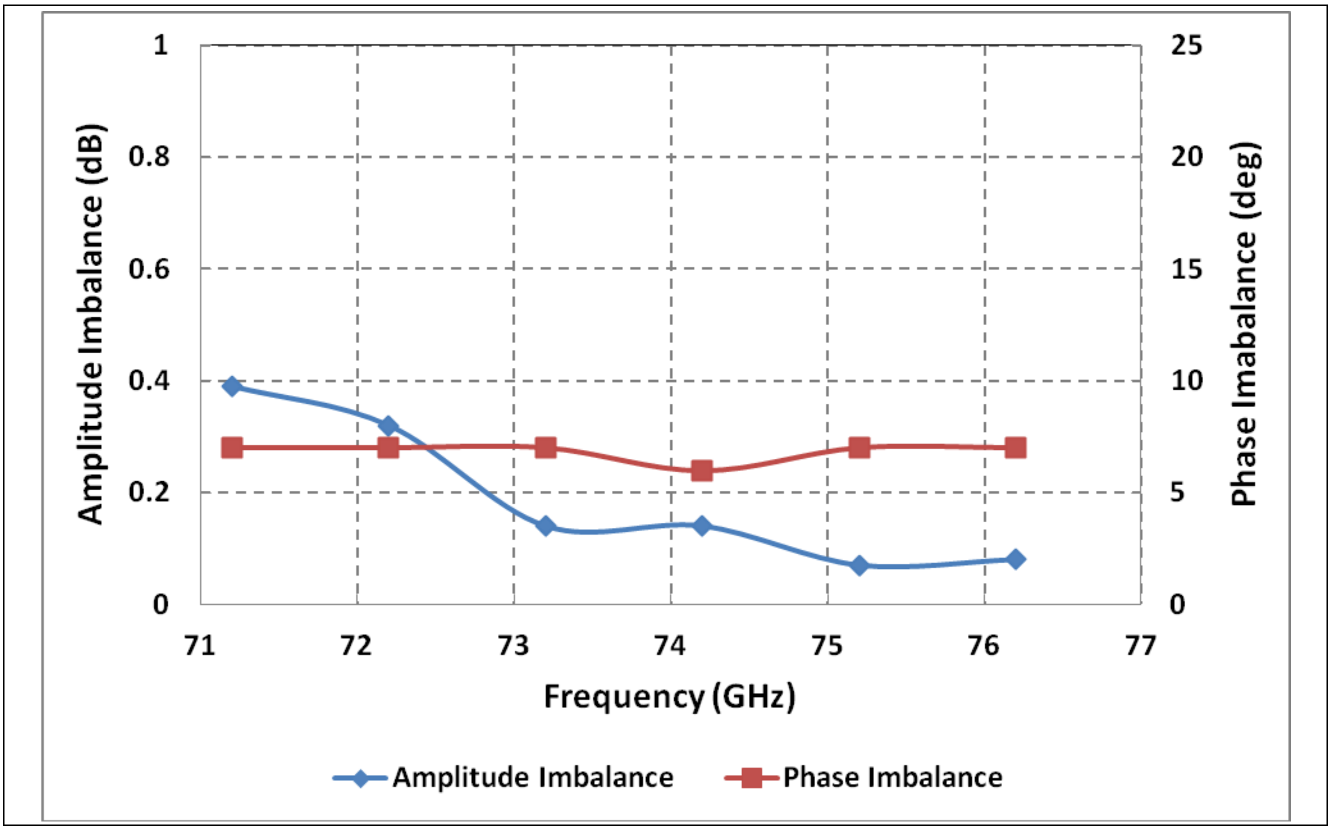


Figure 41 RX I/Q Amplitude and Phase Imbalance over Frequency

9 VCO Signal Generation

BGT70 is designed to cover the complete tuning range of 71-76 GHz with 0-5.5 V of tuning voltage. All the chips are tested during production and VCO is centered with the help of divider output signal. **Figure 42** shows the tuning range of the VCO. The Tuning sensitivity (Kvco) is in the range of 3.4 GHz/V to 0.8 GHz/V being higher at lower tuning voltages and lower at higher tuning voltages. The phase noise shown below is measured directly at TX port of the EVB.

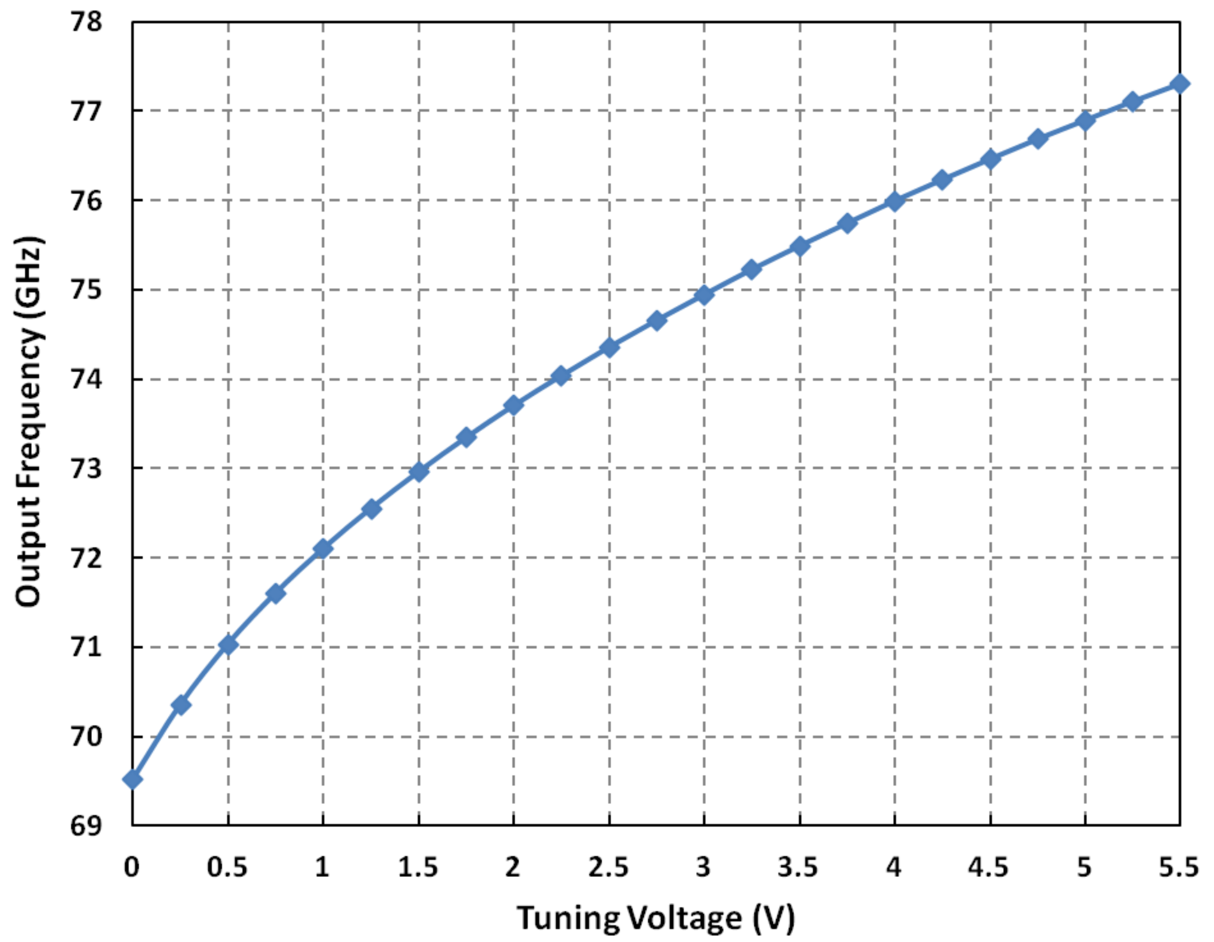


Figure 42 VCO Frequency over Tuning Voltage

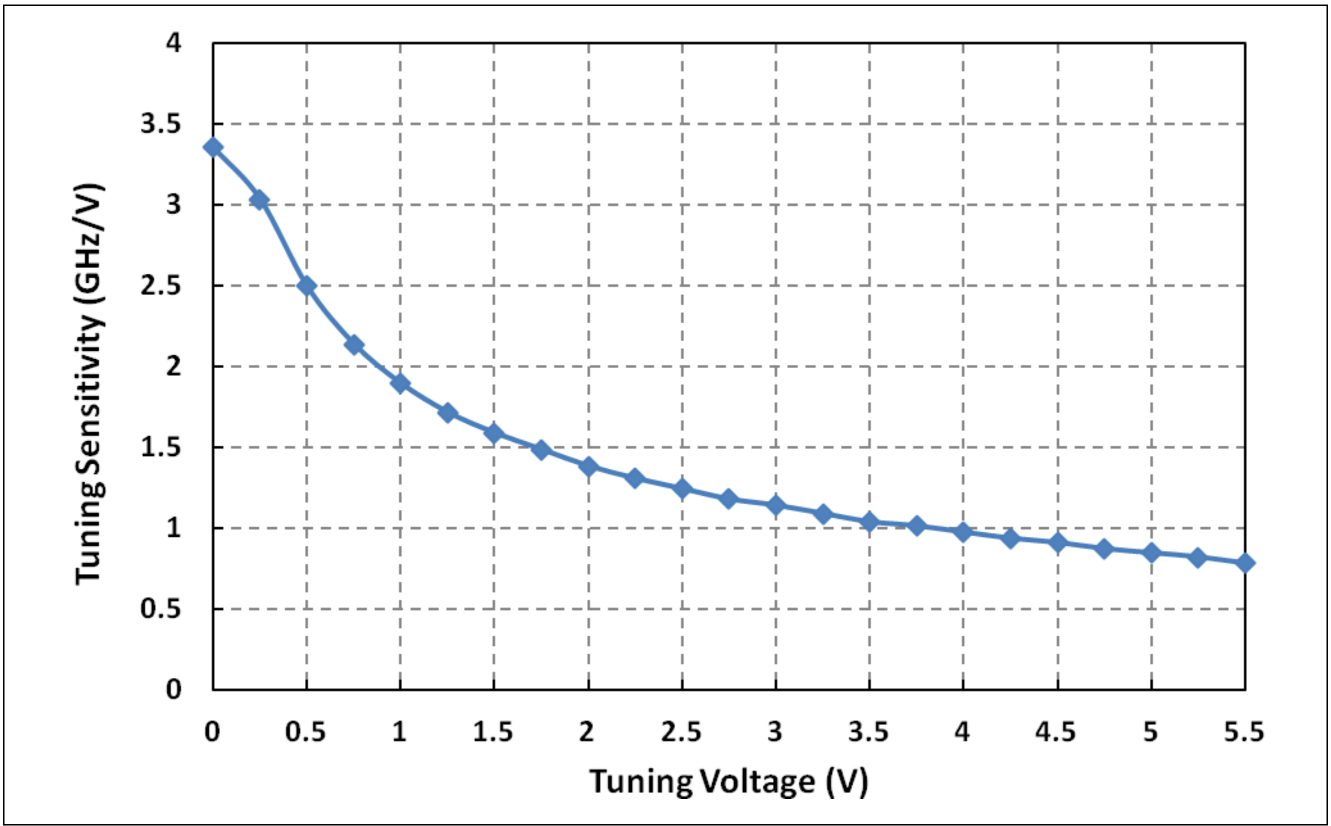


Figure 43 Tuning Sensitivity (Kvco) versus Tuning Voltage

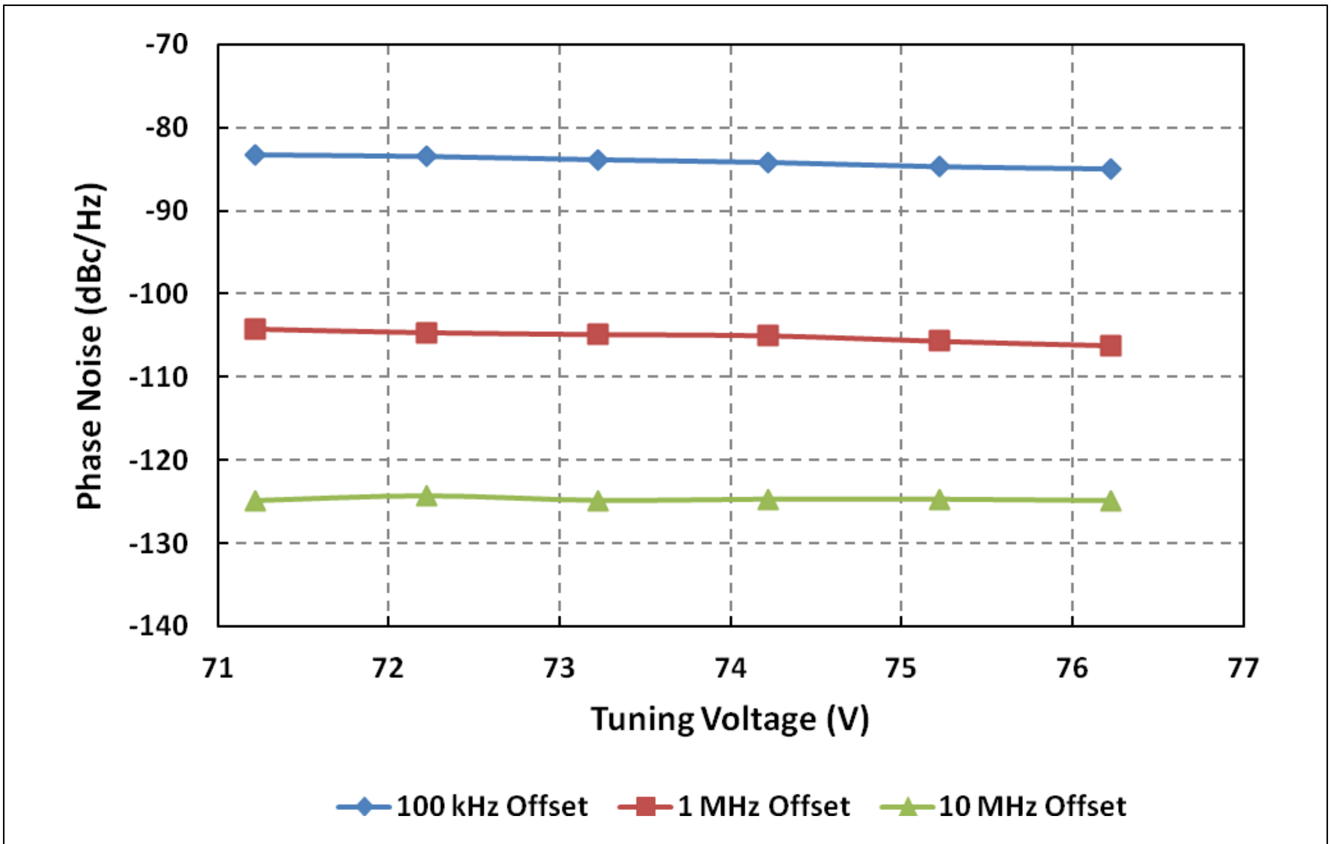


Figure 44 BGT70 Phase Noise Performance over Frequency

9.1 LO Feedthrough

The LO feed-through is measured at both the TX and RX port on evaluation board as shown in the **Figure 45** and **Figure 46** below. For this test only LO generation portion is switched "ON" and TX, RX chains are switched "OFF".

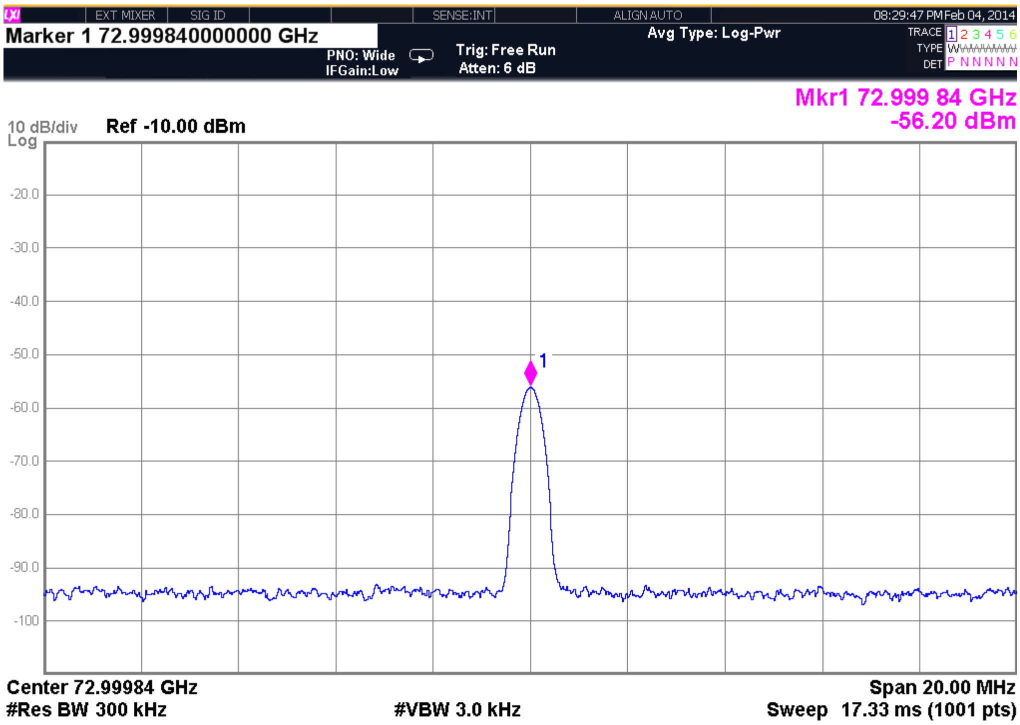


Figure 45 LO Feed-Through at the Transmitter Port (TX & RX Off) @ FLO = 73 GHz

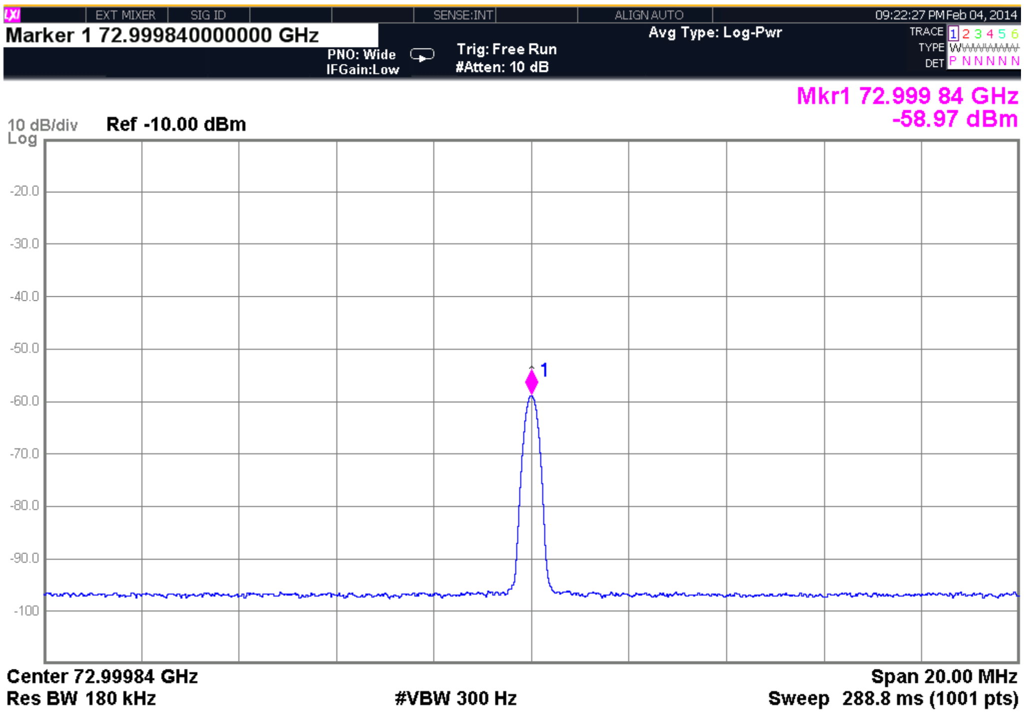


Figure 46 LO Feed Through at the Receiver Port (TX & RX Off) @ FLO = 73 GHz

9.2 Isolation of TX and RX Paths on Evaluation Board

BGT70 chip offers more than 50 dB of Isolation between its TX and RX ports. In order to ensure proper system level tests using BGT70 evaluation board, the isolation of BGT70 on-board is measured below. **Figure 47** and **Figure 48** shows on-board isolation >50 dB.

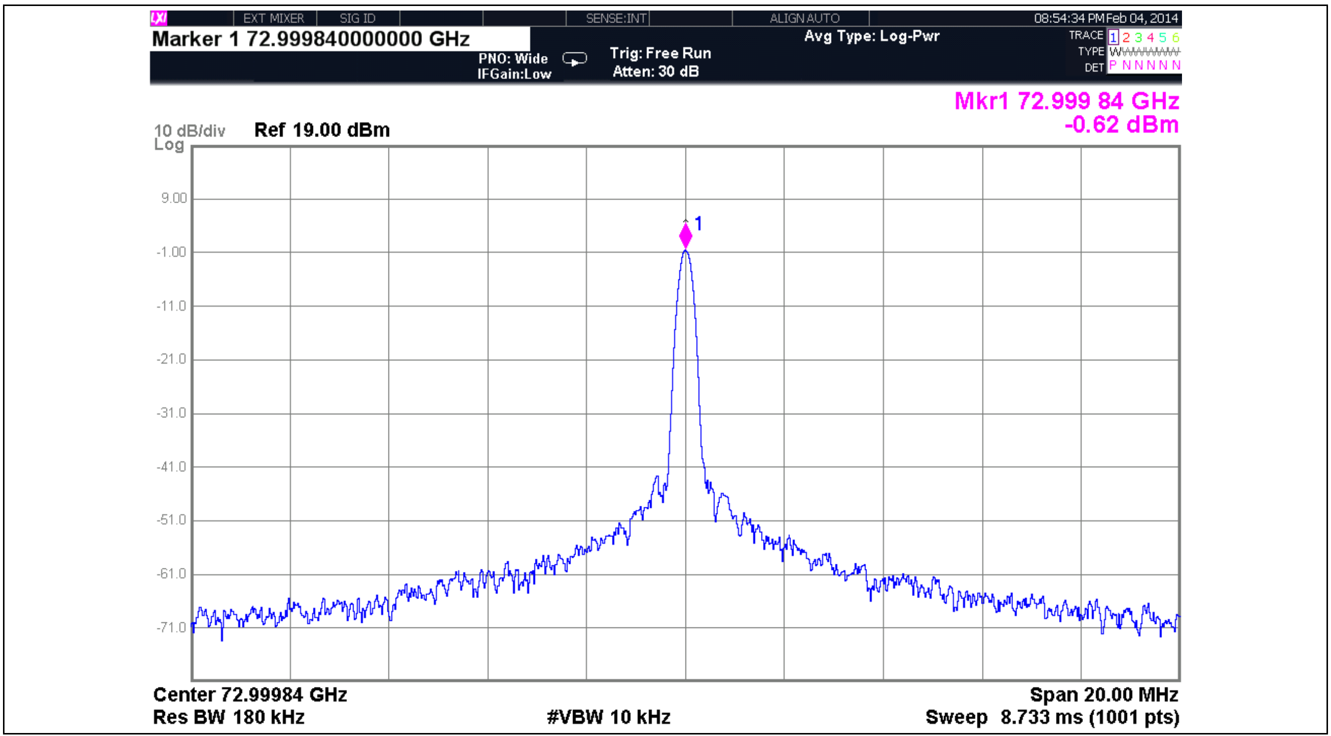


Figure 47 LO leakage at TX Port used in Isolation Test @ FLO = 73 GHz

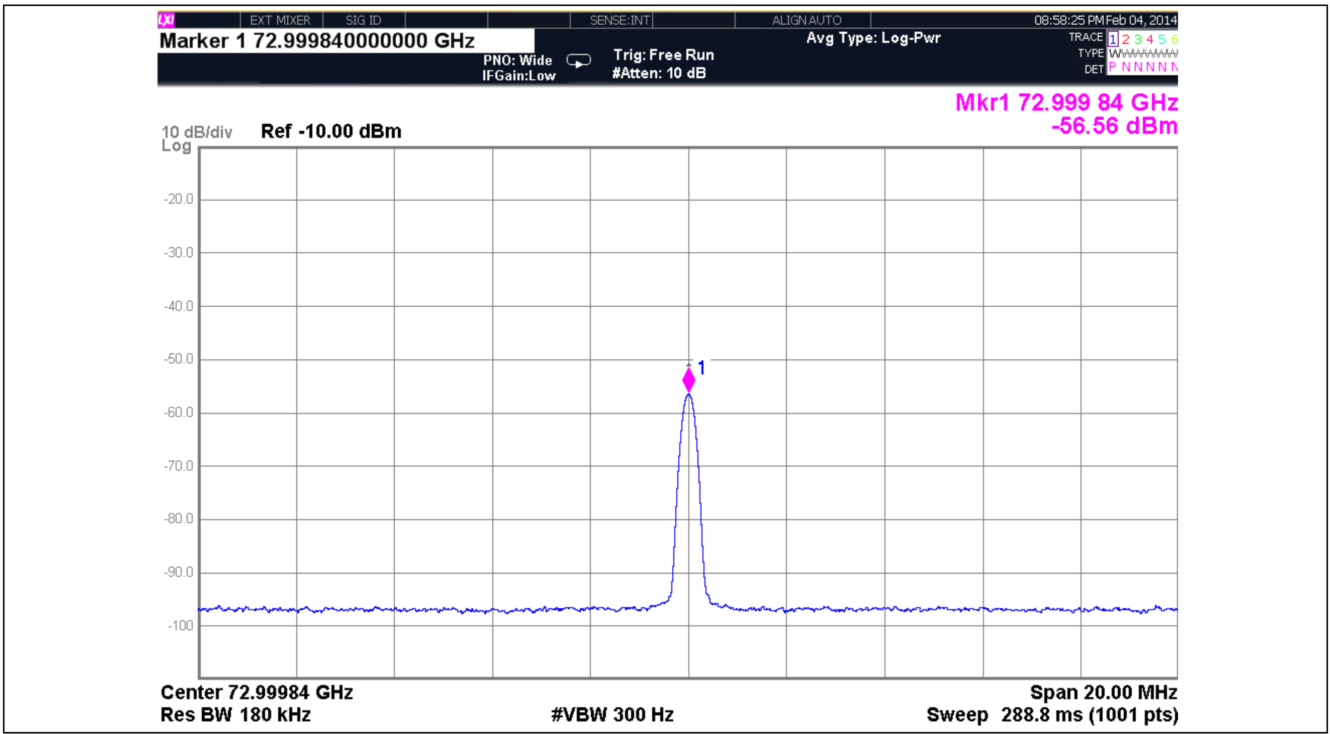


Figure 48 LO leakage measured on RX Port while running TX Port to -0.62 dBm @ FLO = 73 GHz

9.3 Phase-Lock Loop (PLL) Circuit on BGT70 Evaluation Board

The loop filter designed on the BGT70 evaluation board has bandwidth of ~8 kHz when charge pump current is set to 2.5 mA. Based on requirements, the loop filter can be modified on the evaluation board. The component values soldered on the evaluation board are mentioned in **Table 9** and their placement is shown in **Figure 49**.

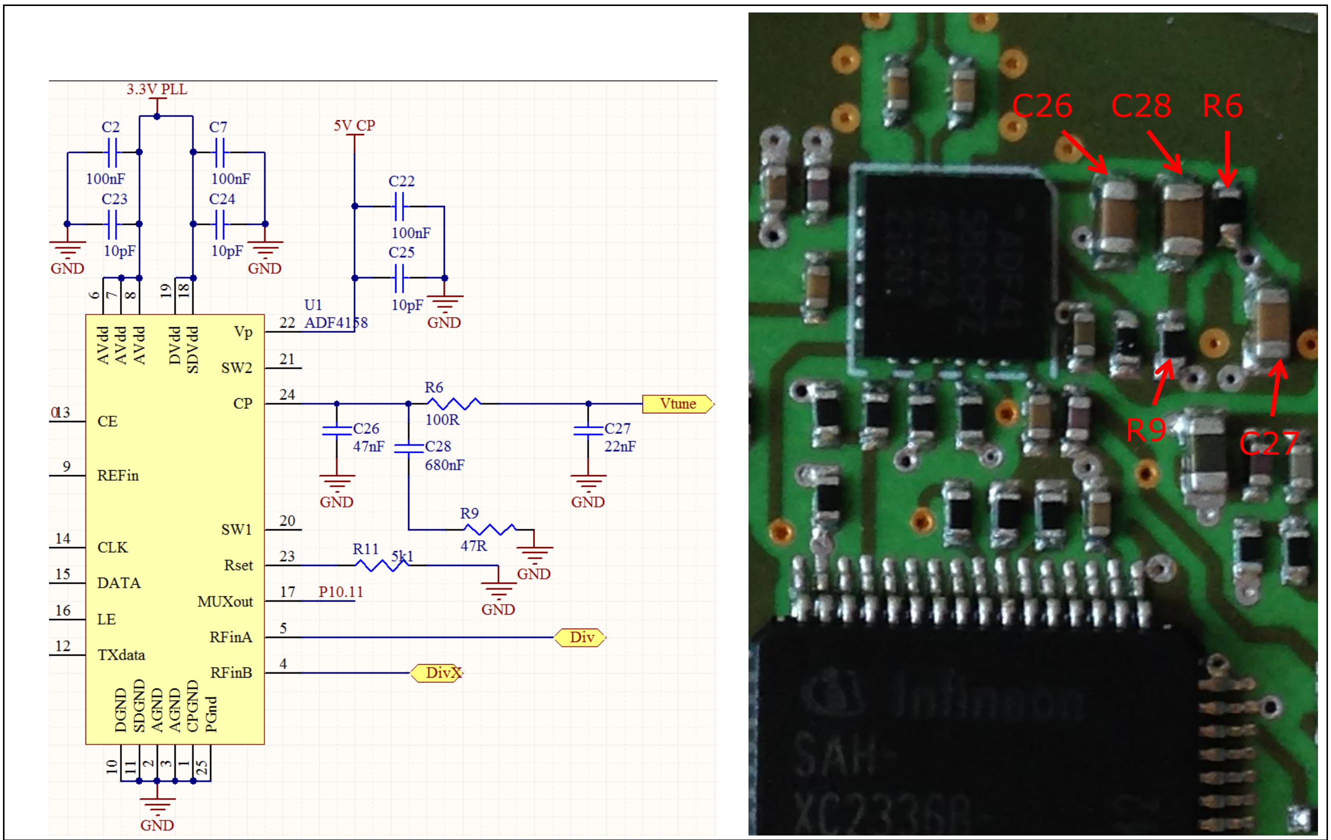


Figure 49 ADF4158 Fractional-N Frequency Synthesizer used on BGT70 Evaluation Board

Table 9 PLL Loop Filter components on BGT70 Evaluation Board

Designator	Value	Unit	Package	Manufacturer	Comment
C26	47	nF	0603	Murata	Loop Filter
C27	22	nF	0603	Murata	Loop Filter
C28	680	nF	0603	Murata	Loop Filter
R6	100	Ω	0402	Any	Loop Filter
R9	47	Ω	0402	Any	Loop Filter

10 Getting Started with Evaluation Board

10.1.1 Configuring as Transmitter

To configure BGT70 as transmitter the following steps should be followed:

1) Apply Vcc=6 V to the BGT60/70/80 board and connect USB cable from PC to the Evaluation Board. The current consumption should be in the range of 315 mA.
2) In the software folder supplied with this transceiver navigate to "E-Band V-Band SPI-Programmer.exe" and double click on it. A window will open as shown in **Figure 50** below.

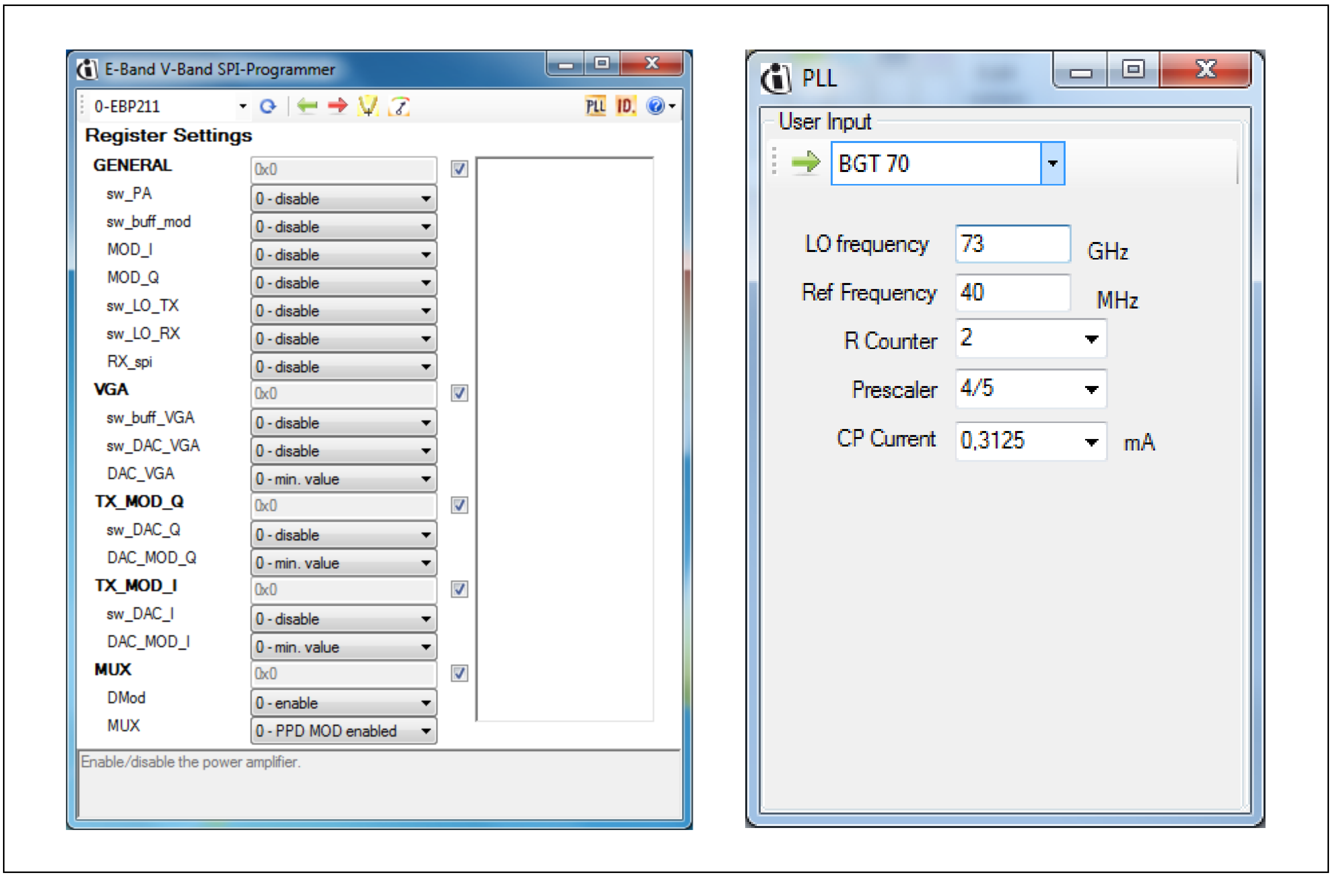


Figure 50 E-Band V-Band SPI-Programmer Main Window and PLL Window

3) Click on the "PLL" button in top right corner of this window. Another window will open which looks like as **Figure 50**.
4) In this PLL window one can select the appropriate chip i.e. BGT60 or BGT70 or BGT80 from the drop down list. Then enter the required frequency in "LO frequency".
5) In "Ref Frequency" box just enter the oscillation frequency of the reference used for PLL. In our case its 40 MHz reference. But exact frequency is also mentioned in the datalog or written on the backside of the board.

6) In “R Counter” box one can choose between different divider values >1. It should be noted that the PLL IC ADF4158, which is assembled on the Evaluation Board, accepts maximum PFD frequency of 32 MHz. “Prescaler” should be set to 4/5 and “CP Current” can be set to 2.5 mA. “CP Current” value will change the bandwidth of the loop filter used on the board.

7) After setting everything one should click on the “Green Arrow” in top left side of the PLL window.

8) Before you proceed to this step make sure that there is **no IF signal applied to the TX IF inputs**. Then in the main window press button. This step will automatically execute the LO leakage calibration and set the right value to the **DAC_MOD_Q** and **DAC_MOD_I** registers. The current consumption in this case will jump to 550mA. The typical setting for the Transmitter would look like as shown in **Figure 51**. After LO calibration is done, IF can be applied to TX IF inputs of BGT70.

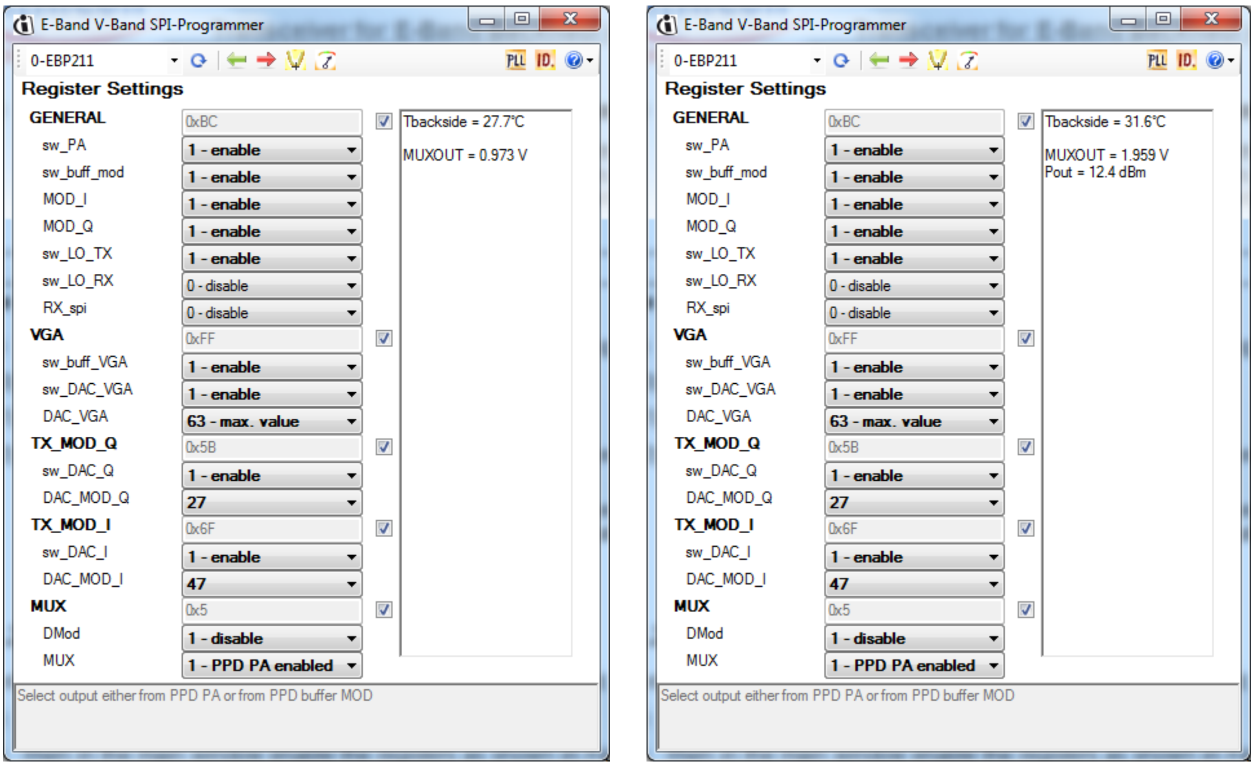


Figure 51 Typical Transmitter Settings for the BGT70

9) Pressing the “Red Arrow” button will update the chip temperature i.e. reading of the integrated temperature sensor and also display DC voltage at Muxout. The DC voltage at Muxout corresponds to the reading of PPD PA or PPD MOD. One of them can be selected at a time from the drop down list under MUX register.

10) Pressing the “Meter” button this button will give you the approximate power output of the device at its landing pad, when IF is applied on the TX input. The measurement is accurate up to -5 dBm of

output power. The power at the output of the transmitter can be controlled by changing the value of DAC_VGA register.

10.1.2 Configuring as Receiver

To configure BGT70 as receiver the following steps should be followed:

1) Follow step 1 to 7 from the above **Section 10.1.1**
2) Then in the main window enable the registers as shown in **Figure 52**. The supply current will jump to 427 mA.

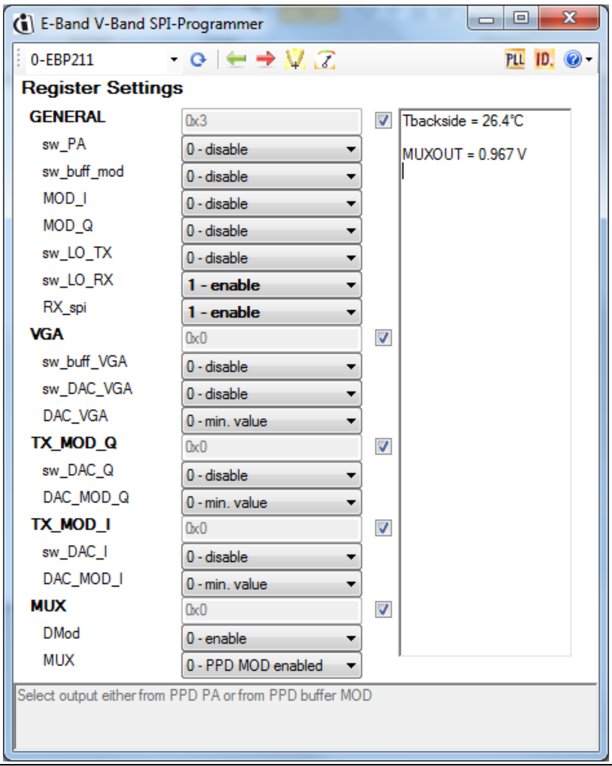


Figure 52 Typical Receiver Settings for BGT70

11 Appendix

11.1.1 Using BGT70 in E-Band Backhaul System with Frequency-Domain-Multiplexing (FDD)

In a FDD E-Band system, each of the two frequency sections 71 – 76 GHz and 81 - 86 GHz are used for transmission or reception. In this case,one BGT80 and one BGT70 chipsets are installed on each side of the radio stations as shown in **Figure 53**. Within one base station, one of the chipsets works in the TX mode and the other one in RX mode. As an example below, in the base station A, BGT70 is set to the receive mode (RX on / TX off) and BGT80 is set to the transmit mode (TX on / RX off). And in the other base station B, BGT70 is set to the transmit mode and BGT80 is set to the receive mode.

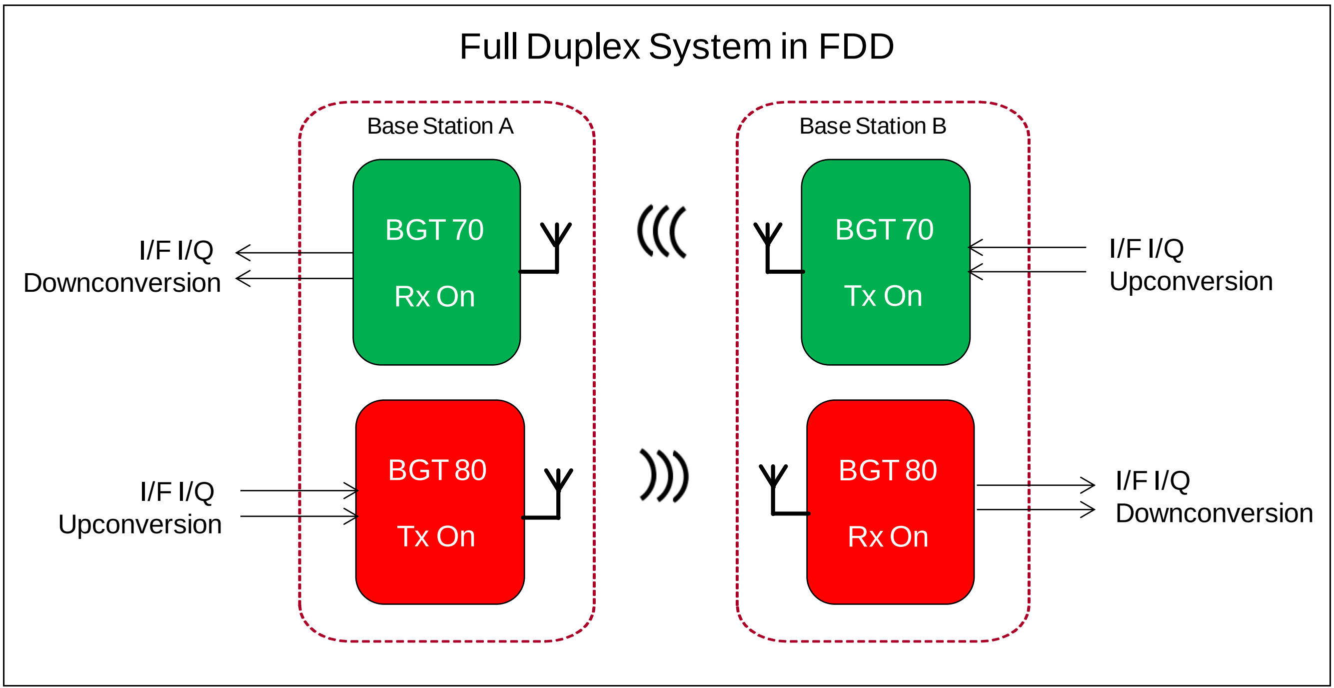


Figure 53 Application Example of BGT70 and BGT80 in a FDD System

11.1.2 Using BGT70 in E-Band Backhaul System with Time-Domain-Multiplexing (TDD)

In a TDD system, one BGT70 and one BGT80 chip is installed on each side of the link stations as shown in **Figure 54**. The two chips within one base station can work in the TX and RX mode independently. The two base stations need to be aligned to set one side to the transmit mode (TX on / RX off) and the other side to the receive mode (RX on / TX off) for the lower E-band (71 to 76 GHz) and for the higher E-Band (81 to 86 GHz) separately.

Because both the TX and RX modes on each chip are used in the application, discrete diplexer needs to be used between the TX, RX ports and the antenna.

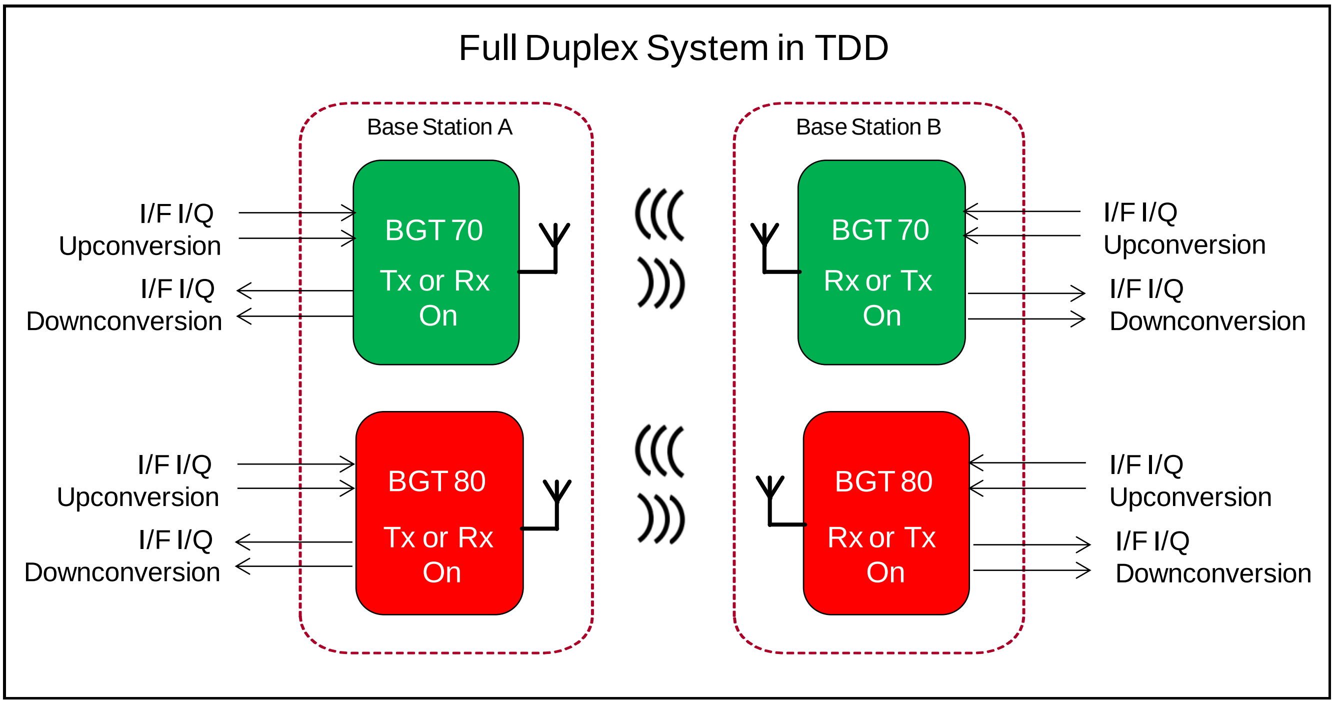


Figure 54 Application Example of BGT70 and BGT80 in a TDD System

11.1.3 Temperature Sensor

$$Temp = \frac{Tsense - a}{b};$$
$$a = 1.36;$$
$$b = 0.005$$

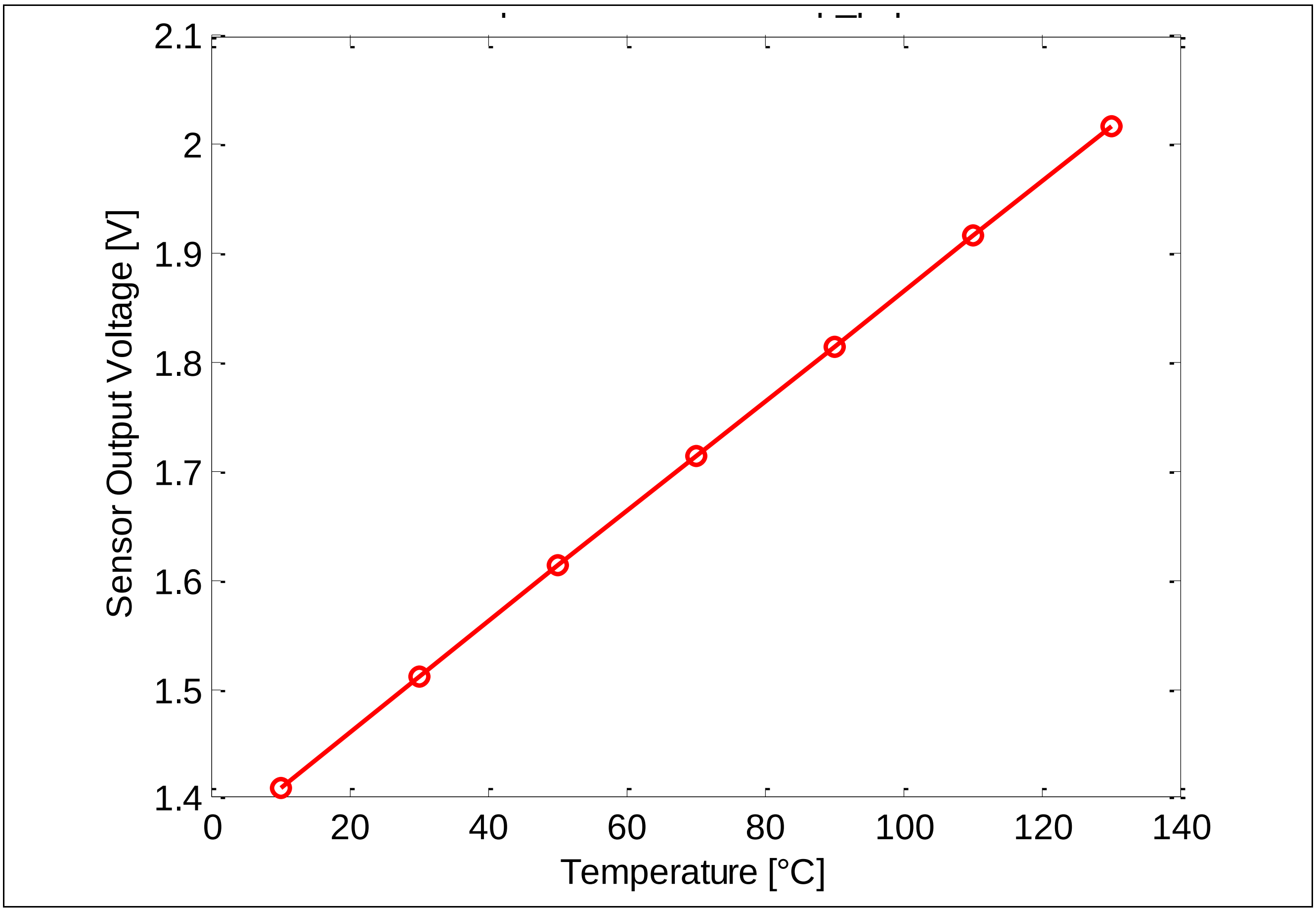


Figure 55 Temperature Sensor Output Voltage versus Temperature

11.2 Questions about BGT70

11.2.1 What maximum IF signal bandwidth can be applied to transmitter?

The BGT70 IF interface is optimized to have IF signal Bandwidth of 1GHz. All the datasheet values are specified up to this bandwidth. Though in lab we are able to demonstrate IF bandwidth up to 4 GHz, it is limited by the real end-use of the device in backhaul application to 250/500MHz.

11.2.2 What is the impedance of IF receiver ports?

The IF receiver path has emitter follower as the last stage buffer amplifier in RX chain. They have low output impedance and have limited drive capability. In order to have maximum voltage swing at the RX IF it is recommended to drive loads with impedance greater than 400 Ω. If one wants to measure RX in lab it is recommended to use an Op-Amp as impedance translation from 400 Ω differential to 50 Ω or to use oscillioscope with 1 MΩ input.

11.2.3 Can power amplifier be connected to the TX output to enhance the output power?

Yes, it is possible to connect an external PA to the BGT70 TX output, to extend range in real application. BGT70 has differential output so one has to make differential to single ended conversion on board to drive single ended PA. Infineon already has some recommendations for such power amplifiers which can be shared after discussions.

11.2.4 Are Gerber files, Differential to Waveguide Transition and Layer stack-up of Infineon Evaluation Board Available?

Yes, it is possible to get all these details. Infineon offers two different business models for advanced technical design-in support. Please contact Sales/Marketing to get further information for this kind of support.

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