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RECONFIGURABLE DUAL BAND POWER AMPLIFIERS FOR TELEMETRY APPLICATIONS

Urmila Nath

University of Dayton

**JULY 2019
Final Report**

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14. ABSTRACT Telemetry is a highly automated communication process by which measurements are made, data collected at remote or inaccessible sites and transmitted to receiving equipment for monitoring, displaying or recording. Originally, wired transmission had been used but now most commonly radio transmissions are used in the telemetry system. Some of the major applications of telemetry are monitoring electric power plants, collecting meteorological data, monitoring manned and unmanned space flights, and oceanography.					
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.ABSTRACT

RECONFIGURABLE DUAL BAND POWER AMPLIFIERS FOR TELEMETRY APPLICATIONS

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Radio Frequency power amplifiers (PAs) are used in a wide variety of applications that includes cell phones, wireless communications, radar, and electronic warfare systems. Reconfigurability is the key factor to meet the future need of the wireless systems where the same hardware can be used for different frequency bands. The challenge of multiband and multi-standard operation can be met with reconfigurable technologies like ferroelectric varactor devices and Metal-Insulator Transition (MIT) material known as Phase Change Materials (PCMs). The performance and proper functionality of these devices greatly depend on the proper design and efficiency of PA. In this research, the use of tunable components, such as Barium Strontium Titanate (BST) based varactors and vanadium dioxide (VO_2) based switches are investigated in designing reconfigurable PA circuit. The focus of this research is a concurrent dual-band radio frequency (RF), high-efficiency ($\geq 50\%$) power amplifier (PA) employing $0.25\ \mu\text{m}$ gallium nitride (GaN) technology for multi-band transmitter applications. Various reconfigurable highly efficient PA circuits for the telemetry band have been presented

using different technologies based on the designed concurrent dual-band circuit.

Dedicated to my parents, my husband, and my son.

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Beside my advisors, I'd like to thank my husband and my son for their sacrifice and patience for the last 5 years.

Finally, I'd like to thank my Mom and Dad (Late) for their love and support. The major reason I have gone back to school after a long break is the encouragement

from my father. I wish he were here to enjoy this achievement and see me graduate with a Ph.D.

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CHAPTER I

INTRODUCTION

1.1 : Introduction

Telemetry is a highly automated communication process by which measurements are made, data collected at remote or inaccessible sites and transmitted to receiving equipment for monitoring, displaying or recording. Originally, wired transmission had been used but now most commonly radio transmissions are used in the telemetry system. Some of the major applications of telemetry are monitoring electric power plants, collecting meteorological data, monitoring manned and unmanned space flights, and oceanography[1]. New applications of telemetry are constantly evolving. An important area is biomedical field, rocket-motor testing, and remote observation of operation with highly radioactive material[2]. There are specific frequency bands allocated for telemetry use in the USA. Telemetry band is somewhat different than IEEE band. Among the telemetry bands, the lower L band (1435–1525 MHz), is commonly used by targets and drones as well as aircraft and other “manned “ flight tests that require telemetry support. Upper L Band (1755–1850 MHz) could be used for new flight test program with the appropriate approval. C (4.4–6.7GHz) band has long history in Satcoms & radar. More recent applications or uses includes Airport support & Unmanned Aerial Vehicles UAVs[1]. Considering the importance of telemetry, specifically, L & C bands, the

concurrent dual-band, reconfigurable power amplifier have been designed to fulfill the lack of high efficiency amplifiers available for these bands.

1.2 : Motivation

The important matter to note here is that Department of Defense (DOD) is auctioning off the L (1.435–1.85 GHz) & S (2.2–2.395 GHz) band toward commercial applications and moving toward C (4.4–6.7 GHz) band. But most of the systems still use legacy schemes. Thus it necessitates the use of a dual-band power amplifier capable of functioning in both legacy and new systems. Telemetry transmitters need to be interchangeable between the bands with no modifications to the aircraft and PAs are the most important part of the transmitters. The rapid growth of the commercial wireless market has created new demands and standards for communication technologies. Hence, radio frequency spectrum is becoming more and more congested due to new products being introduced into the market. This necessitates the allocation of new spectrum to meet the requirements of future DoD applications.

1.3 : Objectives

The objectives of this work is to

1. Design a concurrent dual-band PA for the telemetry band using commercial off-the-shelf high power GaN devices.
2. Modify the concurrent dual-band to operate as reconfigurable PA to switch/select between one of the two bands employing switched capacitors or variable capacitors (varactors).

3. Investigate the use of ferroelectric thin-film-based varactor to transform the fixed dual-band design to reconfigurable dual-band power amplifier.
4. Investigate the use of vanadium dioxide-based switches to digitally switch the fixed dual-band design to reconfigurable power amplifier.
5. Investigate the use of both ferroelectric thin-film-based varactor and vanadium dioxide-based switches together to alter/ transform the fixed dual-band design to reconfigurable power amplifier. Improving or adding the reconfigurable features such as fine tuning (choosing between Lower L & Upper L Band or selecting between Lower C & Middle C Band), in addition to coarse tuning (selecting between L & C band) has also been examined.

1.4 : Contributions of this research

- a) This dissertation provides a step-by-step guideline for designing reconfigurable power amplifiers starting with the characterization of the transistor.
- b) A paper based on concurrent dual-band power amplifier design “Concurrent dual-band hybrid power amplifier in 0.25 μ m GaN technology”, has been presented in **2017 Texas Symposium on Wireless and Microwave Circuits and Systems (WMCS)** and later on added to IEEE explore in October, 2017.
- c) The simplicity of the designed circuit and the band it has been designed for has made this research work unique. As mentioned above, most of the existing systems still use legacy schemes (L and/or S band). Thus, to ensure the compatibility with both

the new and legacy systems, design of a system that can accommodate the dual-band is essential. The concurrent dual band paper using 0.25 μ m GaN technology exactly meets that requirement providing very high efficiency at upper L band (1.75–1.85GHz) and middle C (5–5.1GHz) frequency bands.

d) Detailed analysis of the methods for finding the proper location or placement of a tunable element to control or completely eliminate a band has been presented. This will provide a systematic methodology for future designs of similar devices.

e) Complete rejection of one of the bands from concurrent dual-band is also a unique design effort, which, to the best of my knowledge, has not been published yet.

f) A paper “Reconfigurable concurrent dual band power amplifier for Telemetry applications” will be submitted to the “Microwave and Optical Technology Letters” journal as soon as it receives the approval from AFRL Public Release Approval Office.

CHAPTER II

BACKGROUND OF THE RESEARCH AND LITERATURE REVIEW

Power Amplifier (PA) can be defined as a circuit to convert dc power into a significant amount of Radio Frequency (RF) or Microwave output power[3]. RF power amplifiers are an essential part of our day-to-day life. They are used in a wide variety of applications that includes cell phones, wireless communications, magnetic resonance imaging, semiconductor wafer processing for chip manufacturing, and RF heating etc. They play a significant role in electronic warfare systems such as jamming, imaging, and Radar systems. Several industrial and military applications also need high-power and efficient but low-profile power amplifiers. Output power of the power amplifier varies from few hundred milliwatts for cell phones to tens of watts for a base station. For example, a 100W microwave link or a TV transmitter generally radiates hundreds of watts of RF power. Irrespective of the applications, the basic underlying principles of the design of power amplifier are generally similar[3]. Since different applications has its own requirement of frequency, bandwidth, power, efficiency, load, linearity, and cost, there are many parameters that need to be considered when designing RF power amplifiers for a particular application. The ever-increasing need for enhanced power in RF/Microwave frequencies has resulted in compound semiconductor (known as III–V semiconductors) material based

transistors such as GaN and GaAs transistors. When we combine a class III (Boron, Aluminum, Gallium, Indium, and Thallium) with Category V elements (such as Nitrogen, Arsenic, Antimony, Phosphorous, and Bismuth), they create a covalent bond with eight electrons. This bond makes them a unique semiconductor with significantly higher electron mobility than Silicon. For this reason, GaAs and GaN are very useful for microwave power amplifiers[4].

Table 1: Microwave semiconductor material properties[5]

Material	Mobility, $\mu, cm^2 /V.s$	Delectric constant, ϵ	Bandgap, Eg,eV	Break down field, Eb, $10^6 V/cm$	Tmax, °C
Si	1300	11.9	1.12	.3	300
GaAs	5000	12.5	1.42	.4	300
4H-SiC	260	10	3.2	3.5	600
GaN	1500	9.5	3.4	2	700

Comparing all the characteristics of GaN technology with the other available technologies, a Triquint 5W device which is a GaN HEMT on SiC substrate, was used for this research effort. Gallium-Nitride HEMT and integrated circuit technology, because of their exceptionally high power densities and breakdown voltages are getting adopted at a rapid pace in various applications ranging from pulsed radars, counter IED (Improvised Explosive Devices) jammers, CATV (Cable television) modules to fourth generation infrastructure base-stations. High thermal conductivities of SiC helps dissipating the excess heat efficiently for high-power-density devices which prevents extreme channel

temperature. The material properties of GaN compared to the other material are analyzed in the Table 1 above[5]. If we consider different types of PA concepts or configurations and compare between silicon or GaN on SiC technology, it can be observed that GaN on SiC has significant impact on the PA configurations such as, in Class E/F/J concepts, higher f_T and breakdown voltages can be observed for GaN on SiC configurations. For Doherty concepts, higher off-state capacitance and lower output capacitances are measured. Lower thermal time constant and larger bandwidth has been recorded for the digital pre-distortion type concepts [5].

2.1: HEMT(High Electron Mobility Transistor)

A new type of electronic device which depends on heterojunction semiconductors for their operation had been introduced due to the recent developments in the growth technology of III–V semiconductors mentioned above such as GaAs and GaN[7]. Instead of p–n junction, in these cases, a metal semiconductor junction is used, which is a reverse-biased Schottky barrier. HEMT offers low noise operation along with enhanced performance at higher frequencies [7]. The main focus of this effort is to design and develop power amplifiers for the telemetry band (L and C) using GaN HEMT transistor and extend it for reconfigurable power-amplifier design using BST (Barium Strontium Titanate) based varactors and a phase-change material vanadium dioxide.

2.2:Telemetry

Some of the bands and their uses are described in detail below. Table 2 shows all the telemetry bands and their frequency range. The frequency allocations and other services change occasionally for the telemetry band[1].

Lower L band (1.435–1.525 GHz): Telemetry is the primary service, however, it has also been used as part of mobile service in USA.

Lower L band (1.525–1.535 GHz): Mobile Satellite service is the primary service in USA and telemetry is secondary.

Upper L band (1.755–1.85 GHz) & Lower S band (2.2-2.29 GHz): Used for missile, spacecraft, and other unmanned flight tests that requires telemetry support.

Upper S Band (2.36–2.395 GHz): Slowly being reallocated for other non-DOD uses. For this band, either manned or unmanned use is applicable as it has not been designated specifically[6].

Lower C Band (4.4–4.94 GHz): Prior to WRC (World Radio Conference) 2007, this band was available for aeronautical telemetry by federal government in US. After WRC 2007, the allocation has been extended to all of ITU Region 2 and decision has been made not to allow the non-government users for the time being.

Middle C Band (5.091–5.15 GHz): In USA, middle C band is available to aeronautical telemetry by both federal and non-federal government users.

Upper C Band (5.925–6.7 GHz): WRC 2007 allows this band on a non-interfering basis for home point-to-point microwave links by users, rail roads, oil companies, and gas companies etc.

The potential for the WRC'07 allocations to alleviate the well-documented congestion at L- and S-bands has generated considerable interest in how telemetry systems might behave at C-band [2].

Table 2: Telemetry bands in consideration [Telemetry charts] [2]

Band Name	Frequency(GHz)
Lower L Band	1.435–1.525
Lower L Band	1.525–1.535
Upper L-Band	1.755–1.85
Lower S-Band	2.2–2.29
Upper S-Band	2.36–2.395
Lower C-Band	4.4–4.94
Middle C Band	5.091–5.150
Upper C Band	5.925–6.7

The next table shows the IEEE bands and their range of frequency which is different than the Telemetry band [2].

Table 3: Frequency bands (IEEE)[2]

Band Name	Frequency Range
HF Band	3–30 MHz
VHF Band	30–300 MHz
UHF Band	300–1000 MHz
L Band	1–2 GHz
S Band	2–4 GHz
C Band	4–8 GHz
X Band	8–12 GHz
Ku Band	12–18 GHz
K Band	18–27 GHz
Ka Band	27–40 GHz
V Band	40–75 GHz
W Band	75–110 GHz
mm Band	110–300 GHz

IEEE bands and it's uses are not discussed here in detail, since the designs in this dissertation are performed for the telemetry band.

2.3:Review of different classes of power amplifiers

Amplifier circuits are generally classified as class A, B, AB, C, D, E and F depending on the relation between the input and output signals. These classes are implemented by designing or considering couple of factors like biasing, input and output matching to meet the systems requirements which can be noise figure, output power, efficiency, linearity, frequency range, size, weight, and cost. Small signal amplifiers are normally implemented using class A operation, and the other classes are mainly used for power amplifiers [8]. Figure 1 and Table 4 will show the classifications of amplifiers based on their conduction angles. Class D amplifiers, mostly used as audio amplifiers are not discussed here.

Class A: In class A amplifier, the transistor conducts over the entire input sinusoidal cycle (360°). The quiescent point is selected approximately at the center of the device current. The quiescent current is large enough to keep the transistor always in the active region and acts as a current source which is controlled by the drive. The efficiency of class A amplifier is at around 30% due to continuous loss of power generating tremendous amount of heat. Class A PAs are generally used in application that require low power, high linearity, high gain, and broadband operation[9].

Class B: This class of amplifier had been invented as a solution to the efficiency and heating problem related with class A. In this case, the Q-point is set at the cut-off of the device current, so the active device conducts only for one half cycle or 180° . In RF frequencies, class B amplifiers are realized in push-pull configurations (two complimentary transistors, either Bipolar or FET) because of the single ended transistor's poor linearity performance. Since each device is turned on only for one half cycle, the efficiency of this class of amplifier is much higher about 78.5%. This arrangement provides higher output power but the linearity is not as good as class A amplifier. This is due to the non linear transition between the two stages during a full RF cycle[10].

Class AB: As it's name suggests , class AB amplifiers is a combination of class A and class B amplifiers. The conduction angle of this amplifier is somewhere between 180° to 360° . In this type of amplifier, both transistors are allowed to conduct at the same time around the waveforms crossover point so that it can eliminate the distortion problem of class B amplifier.

The two transistors have a very small bias voltage, typically 5 to 10 % of the quiescent current which is just above the cut-off point used to bias the transistors. This allows the conducting transistor to be on for more than one half-cycle. In the push–pull configuration, each transistor will conduct for more than half cycle but less than full cycle. This class is commonly used in single-ended power amplifiers and has better efficiency than class A and displays higher linearity than class B[10].

Class C: The conduction angle for this type of transistor is significantly less than 180° and normally it is around 90 degrees. Because of the fact that the output waveform is quite different from the input waveform, these amplifiers are very nonlinear. The transistor is turned on for less than a half cycle, so the efficiency of class C is higher than class A, B, and AB class amplifiers. The output filter of true class C is parallel tuned type which helps bypassing the harmonic components of the drain current to ground without generating harmonic voltages. Class C amplifiers are often used at RF and lower microwave frequencies in the modulation schemes such as CW(Continuous Wave), pulse, FM, AM, and PM (Frequency, Amplitude and Pulse Modulation) [10].

Class E: This type of amplifier is a compromise between linear class AB amplifier and a switched power amplifier. It uses a single transistor to operate as a switch. The drain waveform is the result of the sum of DC and RF currents. In optimum class E, the drain voltage drops to zero and has zero slope when the transistor is turned on. So it has zero overlap between voltage and current over and through the transistor. The result is an ideal efficiency of 100%. Class E eliminates the losses associated with charging the drain capacitance, reduces switching loss, and has a good tolerance of component variation[12].

The output network of class E uses a shunt capacitor which absorbs the shunt capacitance of the transistor. When the switch is closed, current passes through the capacitor. The resonator circuit (LC) is designed in a way to ensure that only fundamental frequency tone can flow in the output network to load. By this, it ensures a single tone in the load. The flywheel effect of resonator circuit drives the current either through the transistor switch or through the capacitor [12]. The capability of efficient operation in the presence of significant drain capacitance makes it attractive for a large number of applications. As with class D mode (not described here), high peak voltage is a drawback of this mode of amplifier.

Class F: This mode of operation uses multiple resonators for controlling the harmonic contents of the drain voltage and current. For the ideal case of class F amplifier the drain voltage waveform is square and the current is half-sinusoidal[12].

Alternately in an inverse class F, the voltage is half sine wave and the current is square waveform [11]. In class F amplifier, the efficiency is improved by using multiple resonator output matching circuit to control the harmonic power levels. Thus shaping drain voltage or current waveform. The load network in class F amplifier resonates at fundamental frequency as well as at one or more harmonic frequencies [13]. For example, the combination of fundamental and third harmonic components (which is 180 degree out of phase) can result in a flattened voltage waveform with depression in the center of the waveform. So the proper ratio between the amplitudes of the fundamental and third harmonic component can produce the flattened voltage waveform with minimum depression and maximum difference between the peak amplitude and the amplitude of the fundamental harmonic. Similarly combining the fundamental and second harmonic

component, as they are in phase at the center point, flattens the current waveform corresponding to the maximum values of the voltage waveform. In this way it sharpens the current waveform corresponding to the minimum values of the voltage waveform [14]. So the multiresonant load network in this mode of amplifier helps controlling the harmonic content of the drain voltage and current and thus helps shaping the waves for minimizing the overlap region between them. It helps reducing power dissipation and improvement of both efficiency and power capacity. In theory, an ideal class F amplifier can control infinite number of harmonics and has a square voltage waveform and also can give 100% efficiency. But in practical applications it is very difficult to control more than the fifth harmonics. All these makes the implementation of the network somewhat difficult [13].

Table 4: Amplifier classes comparison [10]

Amplifier Class	Description	Conduction Angle
Class A	Full Cycle 360° of Conduction	$\theta=2\pi$
Class B	Half Cycle 180° of Conduction	$\theta=\pi$
Class AB	Slightly more than 180° of Conduction	$\pi<\theta<2\pi$
Class C	Slightly less than 180° of Conduction	$\theta<\pi$
Class D to T	ON-OFF non-linear switching	$\theta=0$

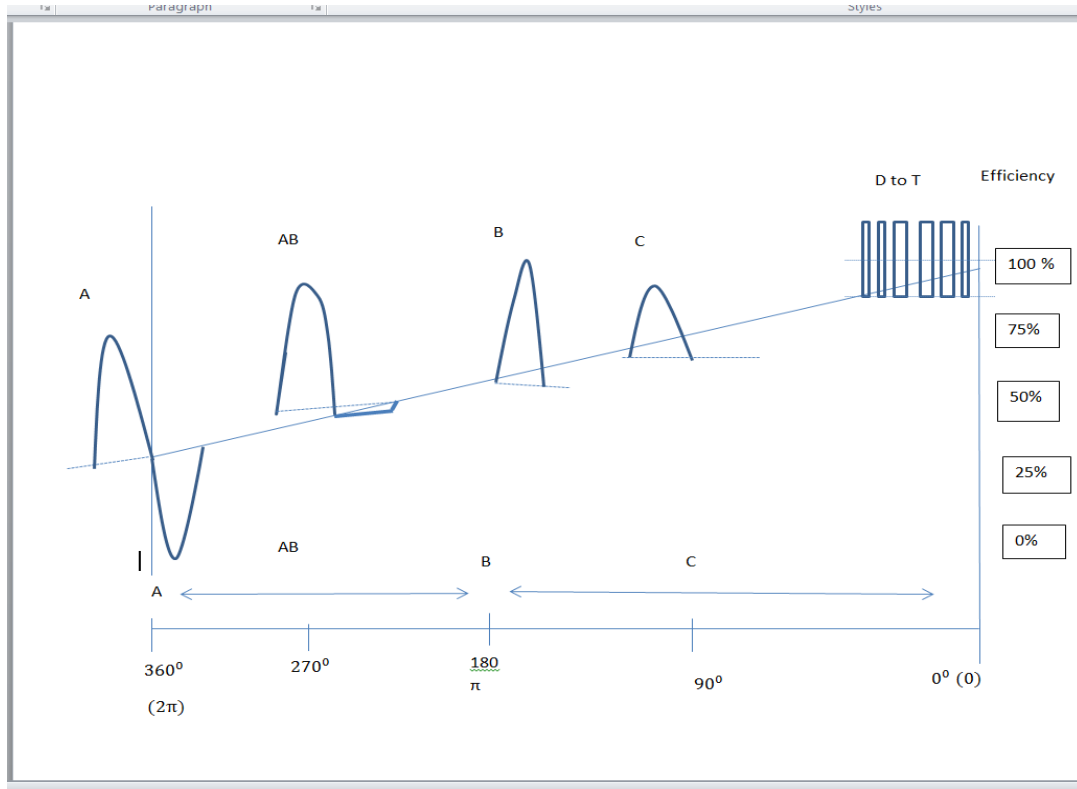


Figure 1: Amplifier classes based on conduction angles [10]

Class **G, I, S and T** are all switching amplifiers and will not be discussed here. The classes of operation of the amplifier with regard to its DC operating point can be realized in Table 4 and Fig.1.

Comparison of some of the key works on dual-band PA have been presented in Tables 5 and 6. Majority of the efforts compared in the tables did not employ concurrent dual-band PAs and none of those has been designed for the telemetry band which presents relatively high efficiency ($>50\%$) and output power ($>35.5\text{dBm}$) for the frequency band of interest. The table below shows the literature review on dual-band PA.

Table 5: Review of key works in dual band PA[15-18]

Ref No	Paper Name	Performance	Stage
15	An Efficient , UHF, Dual Band RF Power Amplifier Module on a 22 mm^2 Footprint Designed in First Pass through accurate Modeling and Simulation	Pout: 35dBm (824–915MHz), 33dBm (1710–1910MHz) PAE: 60% (824–915MHz), 57.5 % (1710–1910MHz)	3
16	A High Efficiency and Multi-Band /Multi-Mode Power Amplifier using a Distributed Second Harmonic Termination	PAE:>60% between about 1.8GHz and 2.3GHz (500 MHz BW)	1
17	Concurrent Dual-band Power Amplifier with Different Operation Modes	Pout: Average 36dBm PAE: Average> 40% Frequency Band: 1.4–1.6GHz 3.0–3.9GHz	1
18	Concurrent Dual Band Hybrid Power Amplifier in 0.25 μ m GaN Technology (This work)	Pout: 35.5dBm and PAE: 65% (Upper L Band) PAE> 50% Entire L Band Pout: 36.7dBm and PAE: 61% (C Band)	1

Table 6: Review of more dual-band literatures, performance, and comparison[19-23]

Ref	Freq (GHz)	Pout (dBm)	Gain (dB)	PAE (%)	Drain Eff(%)
19	2.4/5.2	27/24	33/15	40/22	
20	.836/1.95	22/22	4.5/7	43/43	
21	1.5–1.7 2–2.15	29–32.8 32–34.4		20–33 25–45	20–40 43–61
22	1.98–3.42	29/25	8.1/3.5	57/15	
23	2.4–2.6 3.3–3.4	29.4–33 31.4–32.5	3–6.6 5–6.1		40–53 40–46

2.4: Ferroelectrics

Ferroelectric materials are generally complex oxide dielectrics with multiple functionalities. Some of their physical properties such as permittivity and

polarization are susceptible to the changes with the variation of external electromagnetic field, temperature, and mechanical strain. These inherent functionalities can be used for various applications [24]. Some of the recent studies have shown that varactors, fabricated using one of the ferroelectric material, Barium Strontium Titanate (BST), have high power handling capability, good room temperature stability, large capacitance tuning ratios, quality factors that are comparable to varactor diodes, and high permittivity that is tunable through dc voltage. With the application of electric field, the electric dipoles in the ferroelectric material gets oriented. Ferroelectrics could be in either polar or non-polar phases. Non-polar phase is called paraelectric phase and polar-phase is called (ferroelectric phase). The polarization $P(E)$ in ferroelectric is remnant, reversible, and saturates with increasing $[E]$ even after the applied voltage is removed [25].

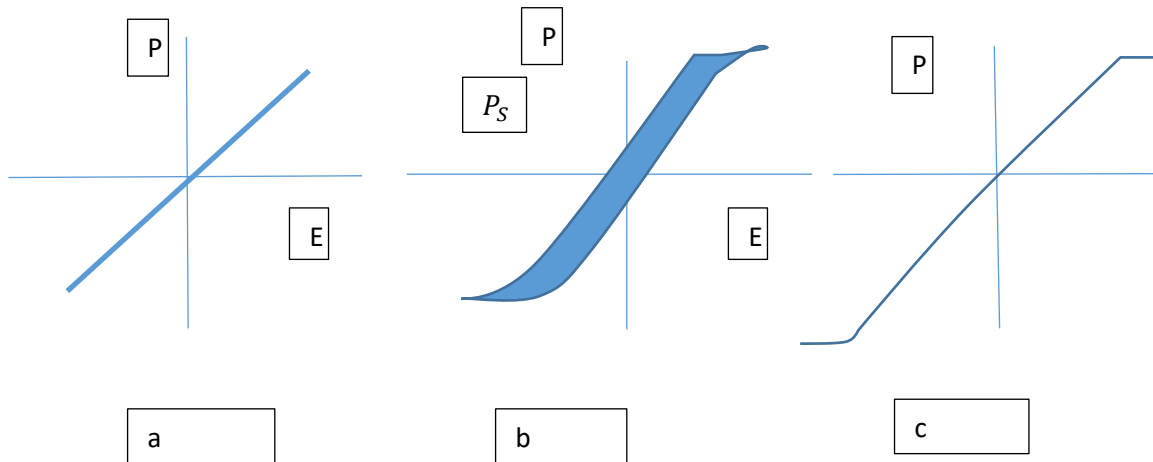


Figure 2: a) $P(E)$ response of linear capacitor, b) Response in ferroelectric phase, c) Paraelectric phase[25].

Ferroelectrics, in polar phases are also piezoelectrics and their transformation generally causes large losses at relatively lower microwave frequencies (frequencies $<10\text{GHz}$). Because of this reason, even though they offer high dielectric constants, ferroelectrics in

polar phases are not normally used in tunable microwave devices. In the non-polar or paraelectric phase, the ferroelectric materials are characterized by high dielectric constant which is strongly dependent on temperature, applied external electric field, and mechanical stress. This unique feature is mostly used in tunable microwave devices [25].

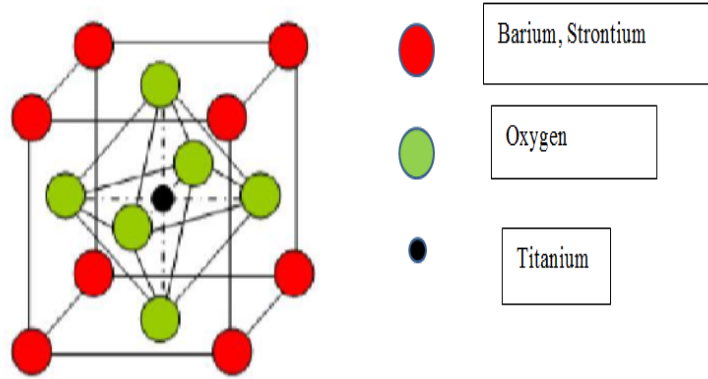


Figure 3: BST in ferroelectric phase structure[25].

BST composition is created by mixing BaTiO_3 with SrTiO_3 . Figure 3 shows BST's phase structure. Titanium (Ti) which is in the center of the Octahedron is relatively free to move. A permanent dipole moment is formed when it (Titanium) moves from the center and the domains are formed [25].

Here, in this work, two BST-based varactors have been used to create tunable band/reconfigurable PA which presents a rejection/notch at fixed frequencies depending on the capacitance values and is switchable from dual to one of the single bands (L or C band). Figure 5 shows the electrical model of BST thin-film varactor. Under fixed-bias condition, the varactor device can be modeled as a conventional parallel-plate capacitor using lumped elements. Here, the parallel capacitor C_1 represents the BST capacitor and the parallel resistor represents the dielectric loss of the ferroelectric material. The series resistance

represents the parasitic conductor and interconnect or electrode resistance. The series inductor represents the parasitics represented by the shunt line of the varactor.

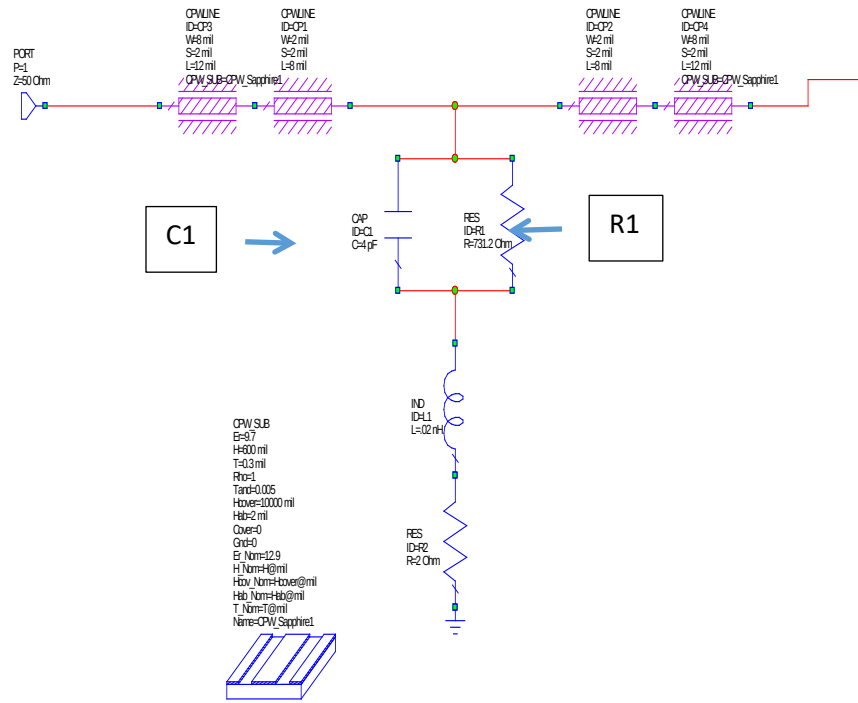


Figure 4: Electrical model

Figure 5 shows the Electromagnetic (EM) model of the varactor. The bias pad was implemented from the bottom layer to avoid the parasitic capacitance issues and to avoid the break point on the top metal ground plane which could have effected the signal and the total effective capacitance value.

BST varactor model layout and 3D view have been presented in the next two figures.

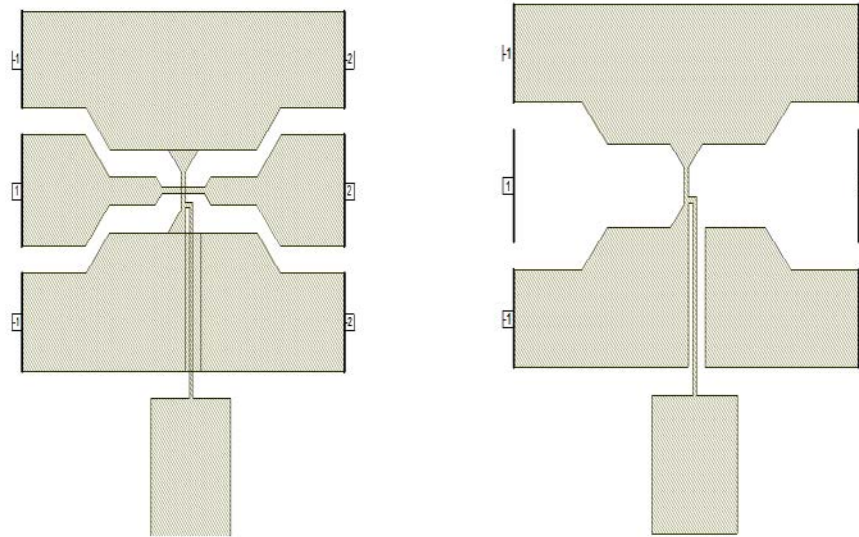


Figure 5: BST varactor layout (a) Entire EM structure (b) Bottom metal & bias pad

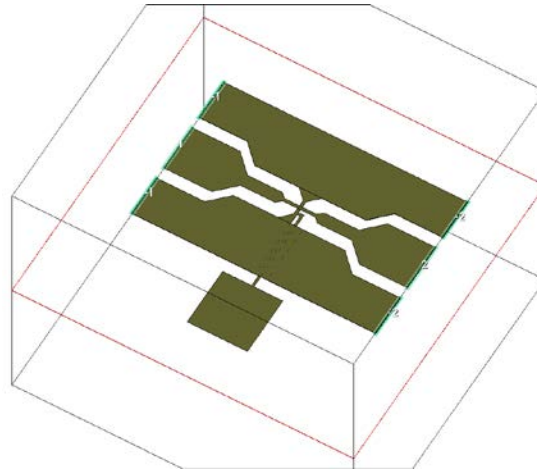


Figure 6: 3D view (BST varactor)

The figure 6 above is a very unique structure where BST is sandwiched between the top and bottom planes. Over the years, BST has been used in many tunable microwave devices

like delay lines, resonators, phase shifters, and varactors. Some of the designs presented in Table 5, 6, and 7 used BST varactors as switch and the others used them as tuning device for different frequency bands.

2.5: Vanadium dioxide

To solve the problem related to the frequency bands overlap for various communication commercial and defense applications several reconfigurable techniques have been proposed. They are semiconductor based diodes or transistors and RF MEMS etc. However, their performance is somewhat limited by their nonlinear behavior, power consumption, reliability, and switching speed. Current research field is leaning toward the development of smart materials whose electrical and optical properties can be tuned by external stimulations like applied voltages or electric field, temperature variation, incident light, mechanical stress or pressure etc. Tunable RF components can be classified based on their properties as tunable resistivity materials (phase-change materials, semiconductors), tunable permittivity materials (ferroelectrics, liquid crystals etc) or tunable permeability materials (ferromagnetics, multiferroics etc). VO_2 is a very attractive smart phase-transition material which shows reversible change in electrical, optical, and magnetic properties at $\sim 68^\circ\text{C}$, close to room temperature [26]. With the temperature change, VO_2 undergoes significant changes in resistance, crystal structure, and optical properties. The device switches to a low resistance state when a finite current is passed through the material using some electrodes. The phase-change properties of VO_2 has been presented in Fig. 7 deposited at 35 mTorr showing the insulator to metal transition at 68°C .

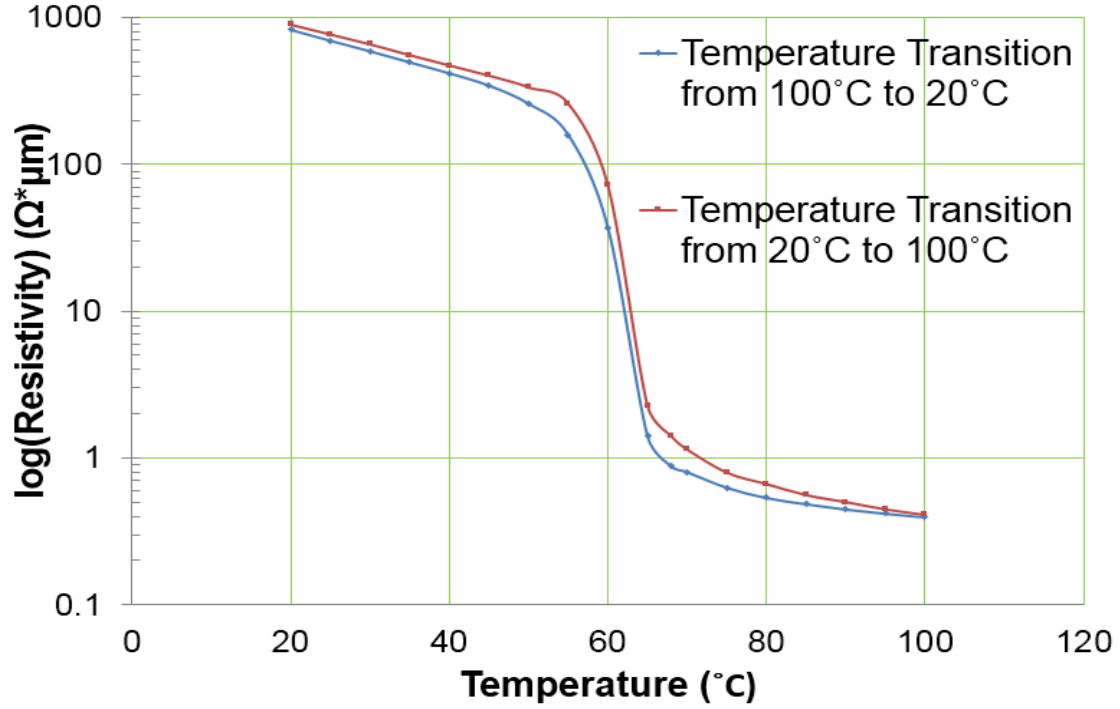


Figure 7: Properties of vanadium oxide thin-film on glass substrate [27].

It is also possible to lower the transition temperature of Vanadium oxide by mixing dopants such as tungsten. Mixing also helps the electrons to carry heat more efficiently in metallic phase and thus can be manipulated for different applications.

The unique properties described above motivated us to choose a VO_2 based switch along with a BST-based varactor for designing the reconfigurable PA. A few figures presented below show the electrical model of VO_2 –based switch in the ON- and OFF-states.

In Figs. 8 and 9, the parallel resistor (R1), represents the resistance of VO_2 thin film varistor. The capacitor C1 in Fig. 8 represents the capacitance of the switch when VO_2 is in the non-conducting phase. In this case, vanadium dioxide can be considered as dielectric material sandwiched between transmission lines. The capacitors (C2 & C3) and the resistors (R2

&R3) represent the capacitance and resistance between the signal line and the ground plane of the CPW line [27].

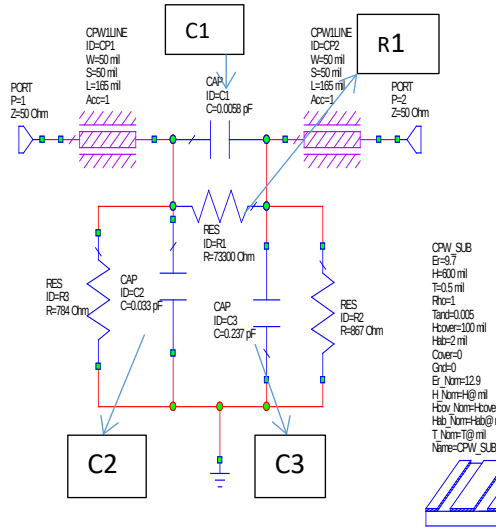


Figure 8: OFF-state of VO_2 based switch (electrical model) [27].

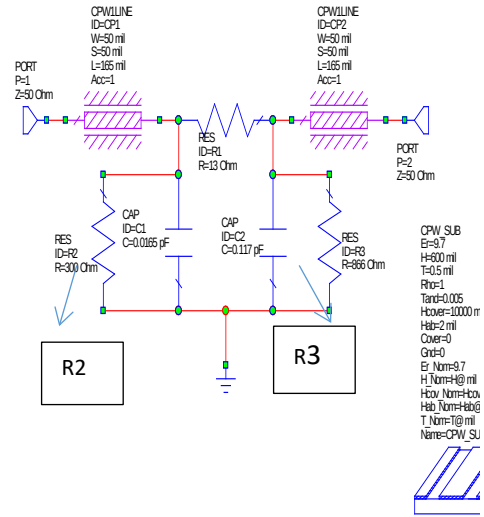


Figure 9: ON-state of VO_2 based switch (electrical model) [27].

Compared to the OFF-state model, there's no capacitance between the transmission lines in the ON state. The reason is VO_2 starts conducting as the temperature rises and transmission lines get connected by VO_2 .

The next section discusses the reconfigurable PA basic design concepts. Table 7 shows the performance comparison for various reconfigurable PAs where the reconfigurability was achieved mostly using BST varactors but this effort presents an unique design where one of the bands from the concurrent dual bands could be selected based on the bias voltage of the varactors. Vanadium dioxide-based switches are mostly used for phase shifters and antennas. Reconfigurable PA designs based on both BST-based varactors and VO_2 -based

switch have been presented. To the best of my knowledge, this effort first utilized the unique properties of vanadium dioxide-based switch for reconfigurable PA design.

2.6: Reconfigurable PA design

There are several ways to achieve multi-band amplifiers. Some of the configurations are shown in the following figure. Fig 10(a) is a unit-selection type amplifier. This type consists of a set of amplifier units and each of the amplifier units corresponds to a different frequency band. A specific amplifier can be selected by means of single-pole-n-throw (SPnT) switch. Very high efficiency can be achieved from this configuration and the design is simple since each unit is the same as that of a single band PA. The disadvantage of this type is that the circuit size increases in proportion to the required frequency bands. The second configuration in Fig 10(b) is composed of a single amplifying device and variable matching networks. In this configuration, high efficiency and high power can be achieved even if the required number of bands increases. With this type of configuration, smaller circuit size is attained than the unit selection type [28]. The literature review of reconfigurable PA circuits has been presented in Table 7. It can again be said from the Table 7 that this research presented the best efficiency and output power for the telemetry band. It is also an unique design which starts with the dual-band and is switchable to one of the single bands from the concurrent dual telemetry band. First the detailed design criteria starting from the transistor selection had been presented in chapter 3 followed by various reconfigurable PA design using BST varactors, tunable CHIPCAPS, and vanadium dioxide based switches are discussed .

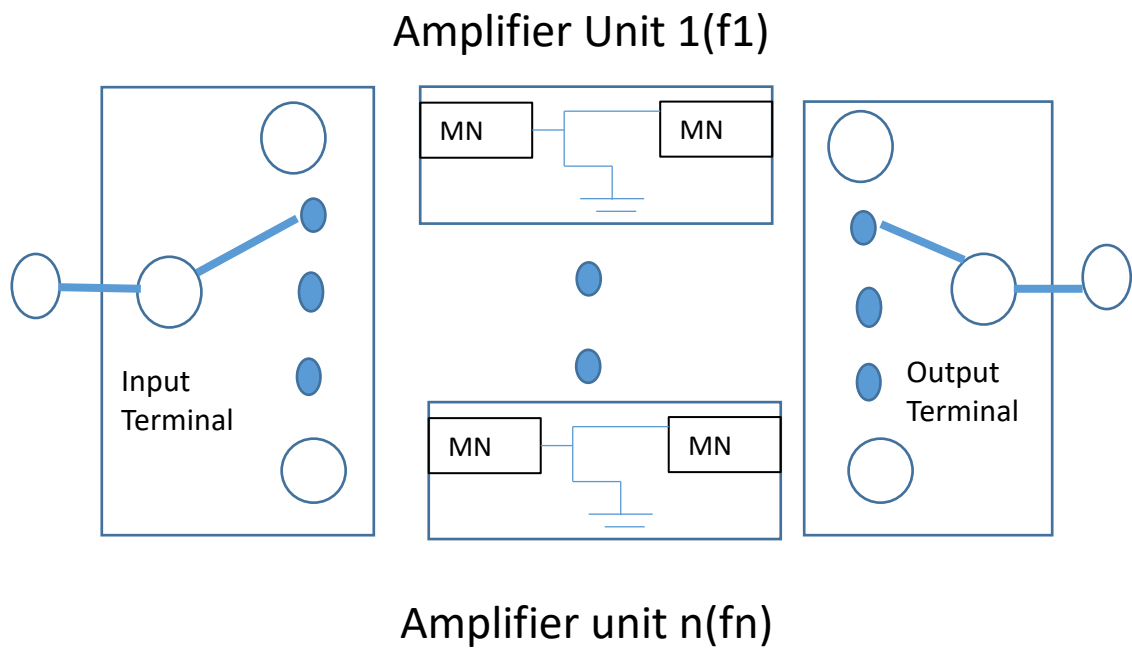


Fig a: Unit selection Type

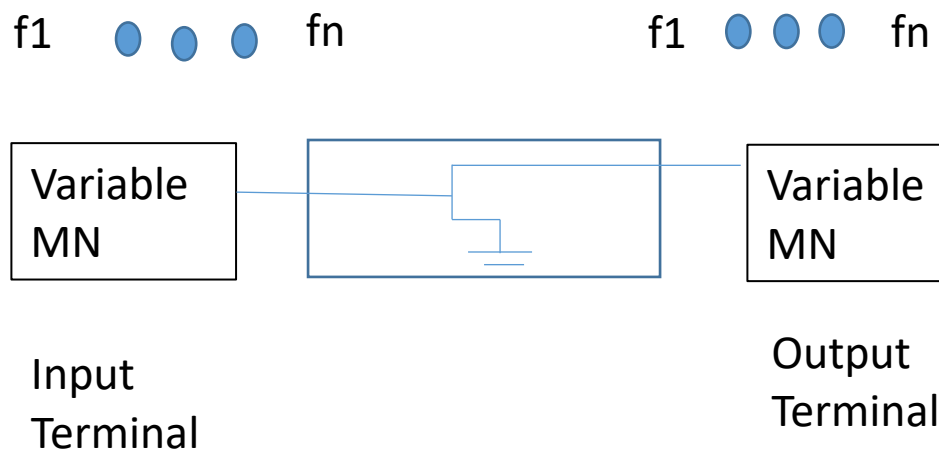


Fig b: Tunable MN Type

Figure 10: Typical multi-band power amplifier configuration[29].

Table 7: Literature review on reconfigurable PA

Ref No	Paper Title	Performance	Stage, switching technique
29	A Single Chain Multiband Reconfigurable Linear Power Amplifier in SOI CMOS	Pout: 28.5dBm, PAE: 40.7% and 46% for high and low frequency band group 3G/4G Bands (Band 112/4/5/8)	2 CMOS switch
30	Band Reconfigurable high-efficiency power amplifier using MEMS switches	Pout 30dBm, PAE:60% Frequency Band: 900, 1500, 2000MHz	1 MEMS switch
31	Broad-band power amplifier with a novel tunable output matching network	Pout: 30dBm, PAE:40% Frequency Band: .85-.95GHz and 1.71-1.95GHz	3 P-I-N diode
32	Tunable Power Amplifier using thin-film BST Capacitors	Pout:28dBm ACPR1: -40dBc Frequency: 1.85-1.91GHz	2 Thin film BST Capacitor
33	Adaptive Multi-band Multi-Mode Power Amplifier Using Integrated Varactor-Based Tunable Matching Networks	Pout: 27-28dBm, PAE:30-55% Frequency: 900, 1800, 1900, 2100MHz	1 High Q Varactor Diode
34	Frequency-agile and Power Scalable Power Amplifier for Multi-band Telemetry Applications	Pout: 29.7 dBm (L band), 29.8dBm(S Band) PAE: 44.8% peak (L Band), 55% peak (S Band)	1 GaN RF Switches
35	Widely Tunable High Efficiency Power Amplifier with Ultra Narrow Instantaneous Bandwidth	Pout:36dBm, PAE: 50-60% Frequency Band: 2.1-3.1GHz	1 Integrated Piezo-electric Actuator
36	A Novel Compact Reconfigurable Quad-band Power Amplifier Employing RF MEMS Switches	Pout: 30dBm, PAE: 45% Frequency: .9, 1.5,1.9, 2.5GHz	1 RF MEMS Switches
37	Design and Analysis of Frequency-Tunable Amplifiers using Varactor Diode Topologies	PAE: 42% Frequency Band: 1.74-2.14GHz	1 Varactor Diode
	Reconfigurable part of this Research	Pout: > 34 dBm PAE: >50% Frequency Band: Dual Band, L Band & C Band	1 BST Varactor

CHAPTER III

CONCURRENT DUAL-BAND AND RECONFIGURABLE

POWER AMPLIFIER DESIGN

The design of power amplifier is a complicated procedure which involves the simultaneous consideration of accurate active device modeling, good impedance matching, stability in operation, technical requirements, operating conditions, and also the realization of practical implementation [38]. The transmission lines are sometimes preferred over lumped elements at microwave frequencies due to the convenience of practical implementation, reduced effect of parasitics, lower insertion loss, and more predictable performance[14].

3.1: Design and simulation results of concurrent dual-band PA

For this effort, microstrip lines are used because of some of the problems associated with lumped elements. The lumped element design generally works well at low frequencies but there are some problems that arise at microwave and millimeter wave frequencies. First of all, inductors and capacitors are generally available only for a limited range of microwave and higher frequencies, where the distance between circuit components are not negligible. Based on Richard's transformation, a shunt inductor can be replaced with a short circuited stub and a shunt capacitor with an open-circuited stub[9]. Also, a series capacitor or inductor can be transformed to a shunt one using a transmission line[9].

A basic amplifier configuration has three major components: an input matching network, an active device, and an output matching network. A transistor amplifier operation requires that the transistor be biased and the input and output matching network be able to provide good power transfer at the input and output of the transistor stages [9]. The first step in the design process is to select the transistor based on the need and the design specifications.

3.1.1: Transistor selection

Design steps for the dual band PA are illustrated in detail first. A discrete 1.25 mm GaN on SiC High Electron Mobility Transistor (HEMT) has been chosen for this design. Figure 11 shows the configuration of the transistor TGF2023, the device parameters and the recommended operating conditions.

The dual-band PA is a single stage amplifier implemented using Rogers-TMM4 substrate material with a substrate thickness of 15 mils, dielectric constant of 4.5, and copper metal thickness of 0.7 mils. The first step in the design process is transistor selection based on the required output power (5W) and the frequency of operation (up to C-band). Toward that end, 0.25 μm GaN on silicon carbide (SiC) transistor is selected. The device size is 10-fingers with a 125 μm unit gate width, totaling 1.25 mm of gate periphery [40]. The dual-band PA is designed using NI/AWR Microwave Office and is implemented in a hybrid configuration. Simulated DC characteristics of the transistor (I–V) curves are shown in Figs. 12 and 13. The I–V characteristics has been plotted for gate bias voltage variations of 0 to (-5)V and drain bias of 0 to 50V variation. The DC characterization facilitated finding the proper bias conditions and as well as useful information about the expected current for a specific gate and drain bias conditions.

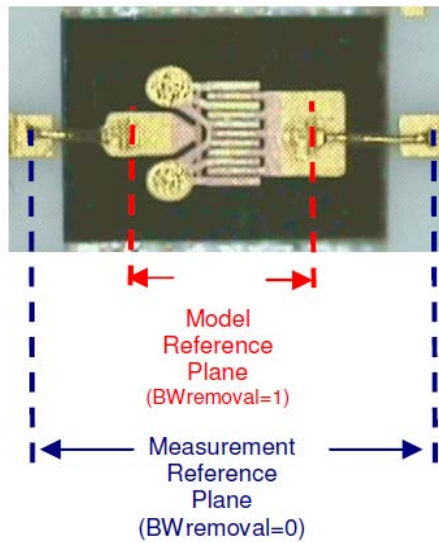


Figure 11 : TGF2023 operating conditions[18]

Parameter	Value
Breakdown Voltage	100V
Drain Voltage	40V
Gate Voltage Range	-50 to 0V
Drain Current	1.25A
Storage Temperature	-65 to 150 ⁰ C

Recommended Operating Conditions

Parameter	Value
Drain Voltage Range	28-32 V
Drain Quiescent Current	125mA
Drain Current Under RF Drive	400mA (Typ)
Gate Voltage	-3.0V (Typ)
Channel Temperature	225 ⁰ C

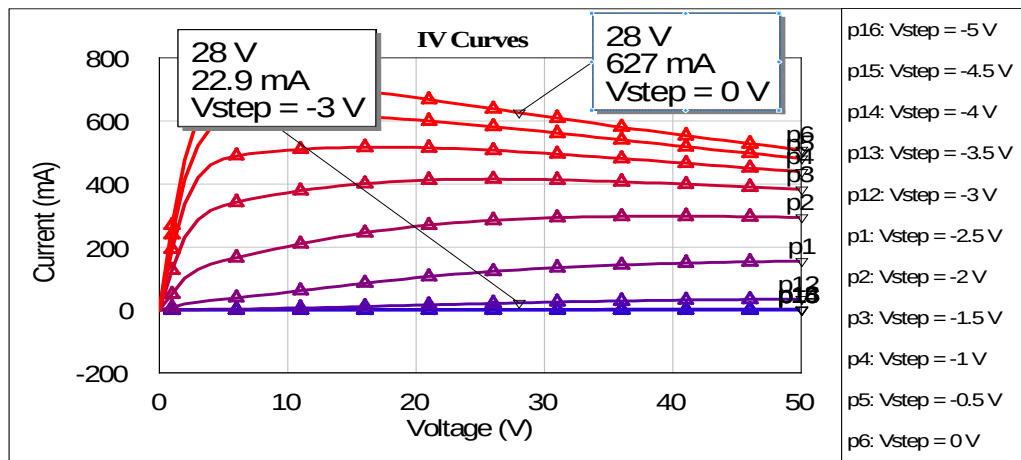


Figure 12: I-V characteristics (considering self-heating factor=1).

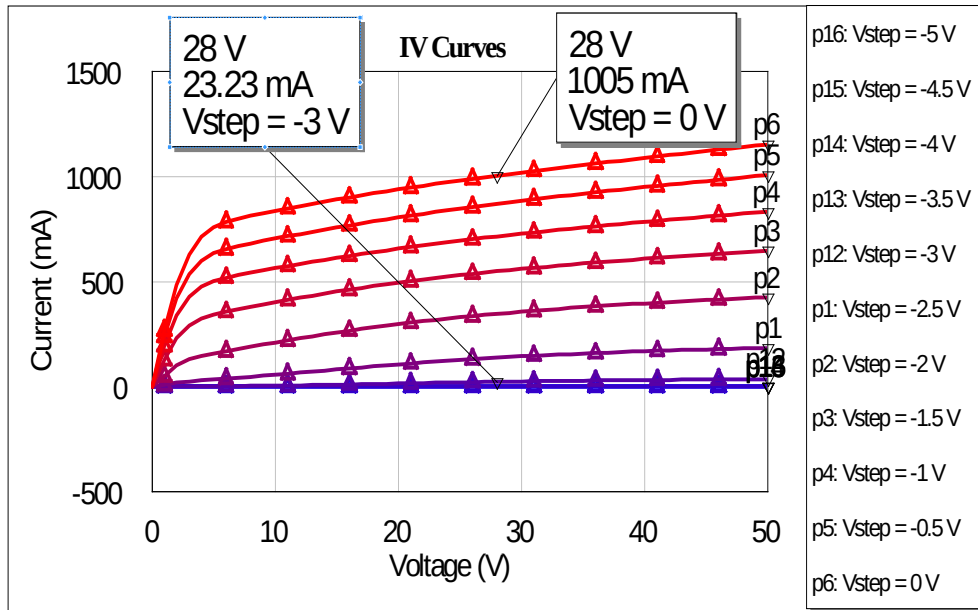


Figure 13: I-V characteristics (considering self- heating factor=0).

The simulation set up for measuring the I-V charactreistic of the bare-die transistor is shown below:

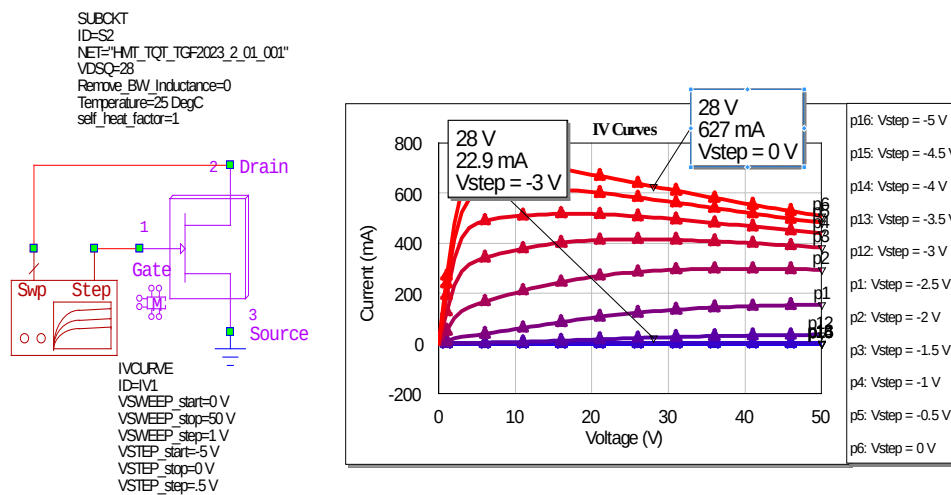


Figure 14: Simulation setup for measuring I-V characteristics.

From the I–V curve, we see a negative slope when the self-heating factor is 1 in Fig. 12. Figure 13 on the other hand, shows a positive slope. This is due to the self-heating of the transistor. As the transistor heats up, the drain current decreases.

3.1.2: Load Pull

In generic term, load pull refers specifically applying a priori impedance to a DUT in a precisely controlled fashion to extract the optimal performance from the DUT[23,39]. In load pull measurements, optimal performance is found by varying terminal impedances, frequency and bias to accurately establish conditions under which optimal performance from the target DUT can be measured. For the linear condition of power amplifiers, the optimal loading conditions can be directly identified from the S parameters[41,42]. The nonlinear conditions are significantly different from the linear conditions in that the impedance tuner physically changes the load reflection coefficient for the extraction of the desired design parameters[42]. The load pull is an iterative process and needs multiple iteration for achieving a realizable matching network circuit. Also, load pull must happen at each frequency or at least at the band of frequency of interest. The input and output matching circuits are designed based on the input and output reflection coefficient data from the load pull iterations. The load pull setup and the results are shown in the following Figs. 15–18. Then the Maximum efficiency points and the maximum power points have been extracted both for 1.75 GHz and 5GHz frequency points from the load-pull analysis that helped in designing the PA circuit according to the design requirements.

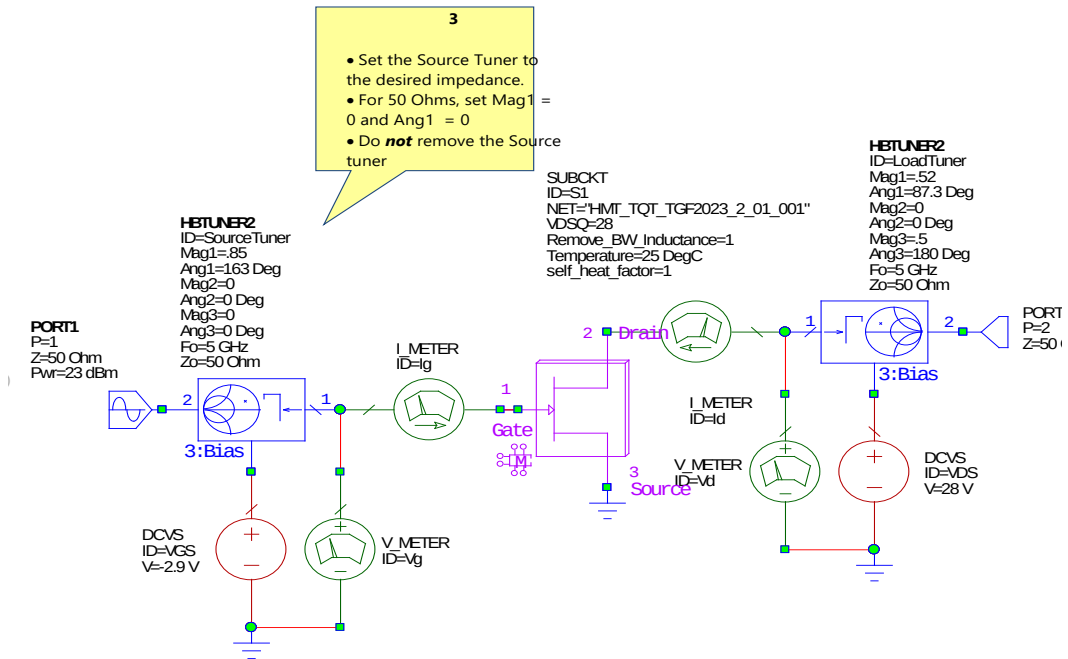


Figure 15: Load pull setup.

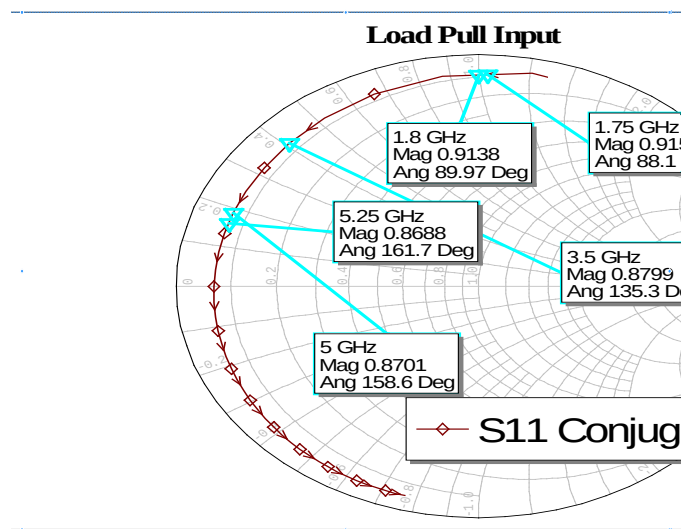


Figure 16: (Load pull input) [showing the points for the frequency band of interest].

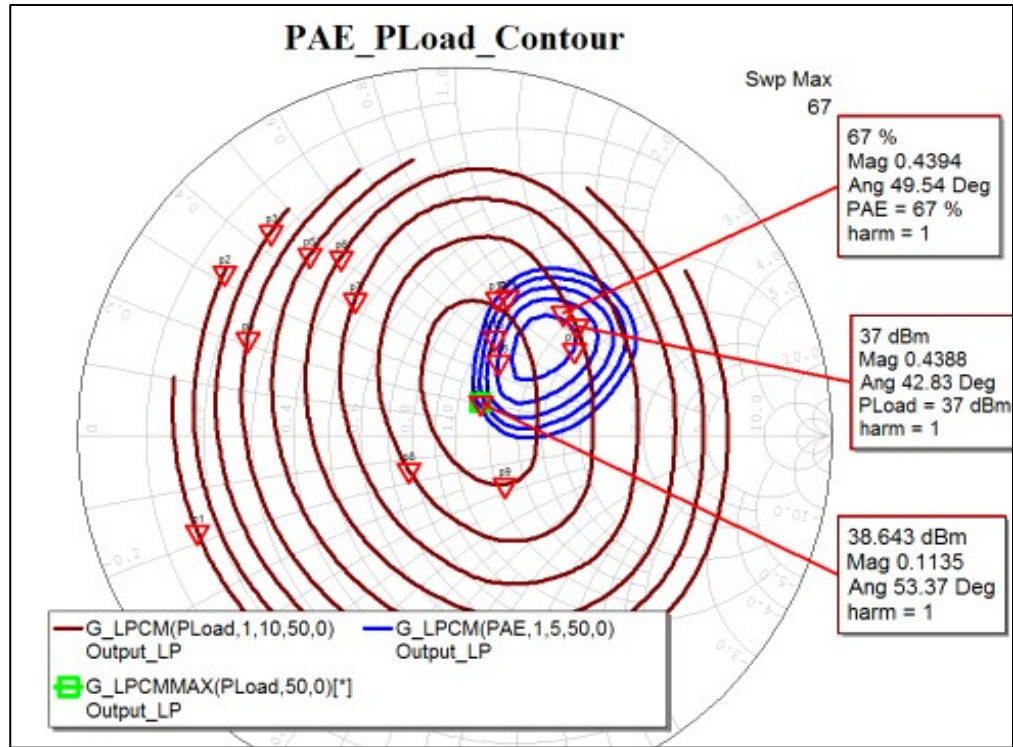


Figure 17: Load-pull contours at 1.75 GHz, blue circles: PAE, brown: power, Pmax: green.

Initially, load-pull analysis is employed to determine optimal power and efficiency performance of the 1.25 mm GaN device. The foundry model is used to ascertain the optimal loading condition (Γ_L) for maximum PAE and the corresponding output power (P_{out}) at L- and C-bands. For the analysis, the source impedance is set to S11 conjugate. Figures 17 and 18 are the plots of simulated PAE and P_{out} contours at 1.75 GHz and 5 GHz, respectively for $V_{DS}=28$ V and $V_{GS}=-3$ V, where blue contours represent PAE and brown contours represent P_{out} . For optimal efficiency operation, the plot in Fig. 17 illustrates the load reflection coefficient (Γ_L) is $0.43 \angle 49.5^\circ$ resulting in PAE=67% and an associated $P_{out}=37$ dBm at 1.75 GHz.

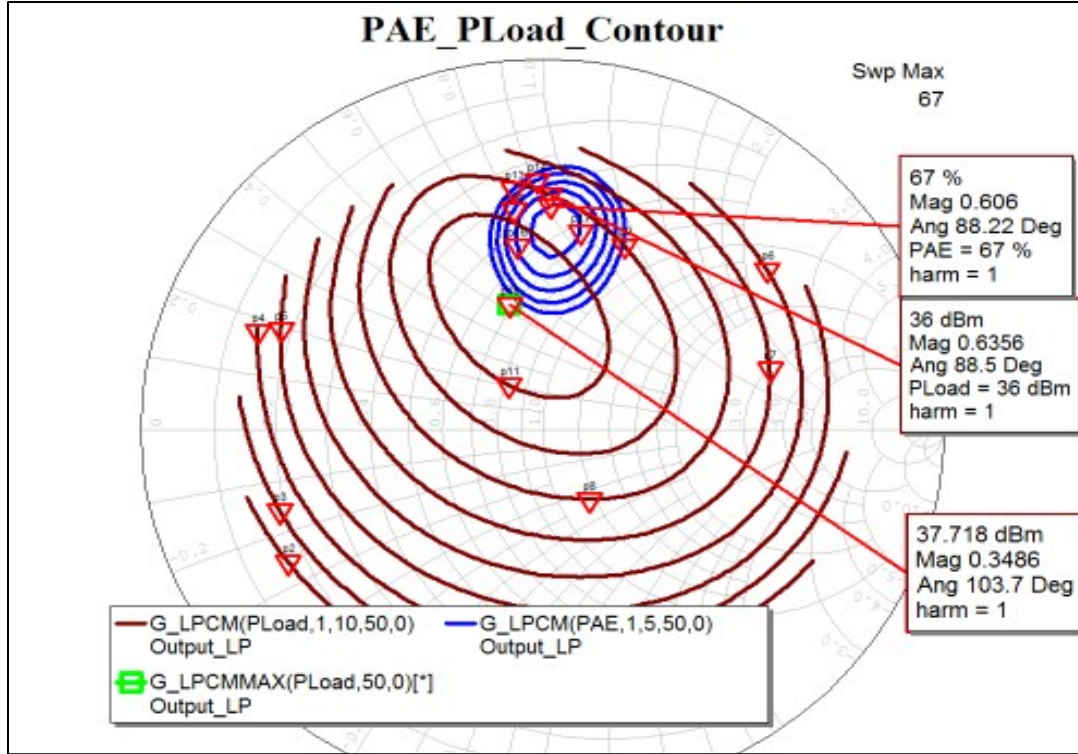


Figure 18: Load-pull contours for the 1.25 mm GaN transistor at 5 GHz. [blue circles representing efficiency and brown circles for power] { Pmax: green}.

Similarly, load-pull analysis of the device at 5 GHz yields $\Gamma_L = 0.606 \angle 88.2^\circ$ resulting in PAE=67% and an associated $P_{out}=36$ dBm as shown in Fig 18. However, $0.11 \angle 53.37^\circ$ results in maximum output power (38.64 dBm) for L-band and $0.34 \angle 103.7^\circ$ results in maximum output power of 37.71 dBm for C band. The Γ_L information is used as the initial starting point to design the dual-band PA output matching network with the goal of maximizing efficiency performance.

3.1.3: Bias circuit topology

The next design step is to choose a biasing configuration. The biasing network generally consists of drain and gate RF chokes, bypass capacitors, DC blocking capacitors in addition to the drain and gate bias voltages[18]. For this work, shunt short circuited quarter wave

stub was used as it presents a low admittance at the fundamental. Bypass capacitors are also used near the dc feed point to filter out any additional low frequency content.

3.1.4: Cut-off frequency

The figure below shows the cut-off frequency of the chosen transistor to verify that the frequency bands of interest are not outside the cut-off frequency range.

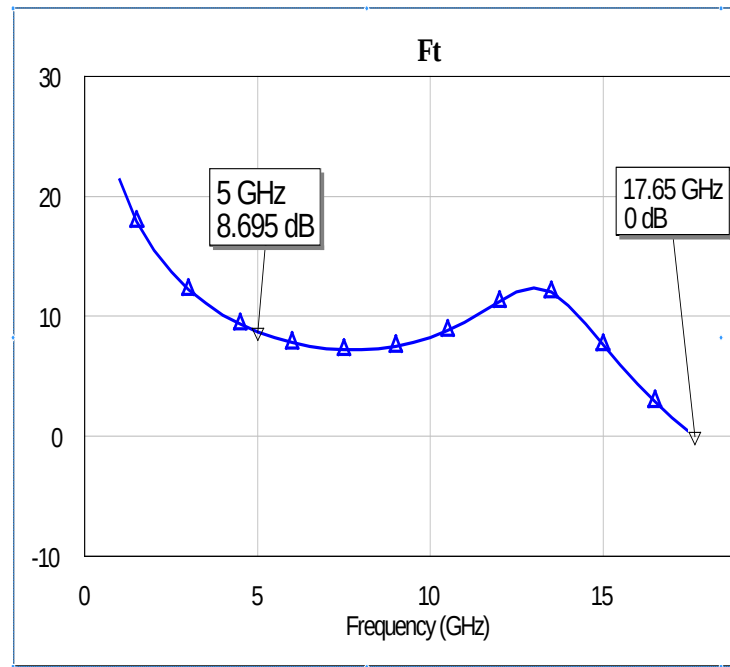


Figure 19: Finding f_t (the frequency points of interest are well within the cut-off frequencies) as the figure shows that the cut-off frequency is at 17.65 GHz.

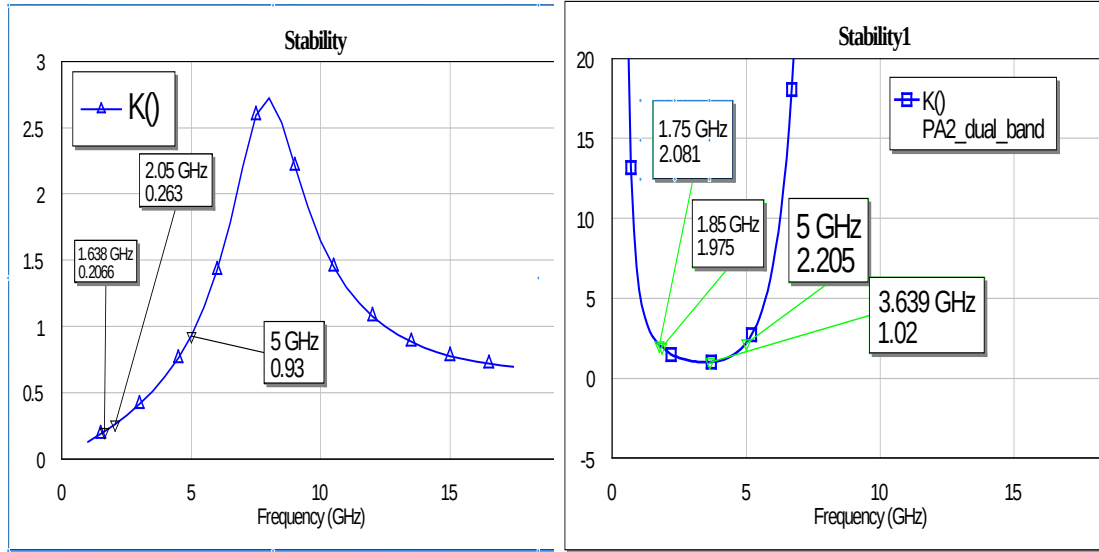


Figure 20: Finding stability of the transistor. Figure 21: Stability of PA after adding the stability circuit.

3.1.5: Stability circuit

All the RF and microwave circuits can have instabilities. Due to large signal, sometimes, the time varying nonlinear elements exhibit negative resistance and instability. These parametric instabilities tend to occur more often in the switch mode circuits because of their large input drive level required for saturated region of operation[43]. From the simulation results of the chosen transistor shown in Fig 20, it has been observed that the transistor is not unconditionally stable between the frequency range of interest. So a stability circuit had been designed to ensure unconditional stability. Generally, depending on the application and amplifier type, a stability network is composed of series or parallel loading with RC-RL circuits or series and parallel feedback at the input or output of the active device. A resistive stability network at the input might cause Noise Figure reduction for LNA, but a resistive stability network can be used for PA[44]. Sometimes, to get the

desired result, a combination of these networks is required[45]. For this design of the stability circuit, a combination of shunt and series resistor and capacitors are used.

It has been noticed from Fig 20 and Fig 21 that the transistor was not unconditionally stable at the frequency point of interest but after adding the stability networks, the entire PA circuit became unconditionally stable , i.e, $k \geq 1$.

3.1.6: Input and output matching network

The general concept in designing the input and output matching network is to use the small signal analysis to optimize the gain and return loss by tuning the circuit. For this work, at first the matching circuits were designed with the help of load pull simulations. Then the small signal analysis was done using Microwave office software to optimize the gain and reflection coefficient values. The large signal analysis was performed next on the circuit for output power and efficiency optimization. In this design, each matching network is made up of stubs resonant at the second and third harmonic in a series-shunt lowpass microstrip line configuration. Fig 22 shows the complete layout of the dual band design and figure 23 shows the fabricated board. The input matching network consists of two stubs to create proper matching conditions for this design, for L & C band. A stability network with a 68 Ohm shunt resistance is included to ensure unconditionally stable operation. The last component is a dc blocking capacitor at the RF input port. In a similar way, the output matching network consists of three shunt stubs to provide fundamental matching at both the frequency bands of interest. The harmonic terminations at higher frequencies has also been taken into consideration to ensure high efficiency.

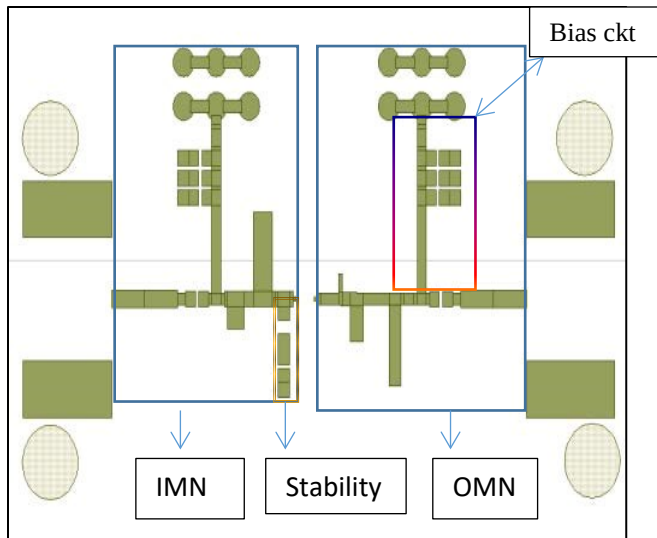


Figure 22: Layout of dual band circuit

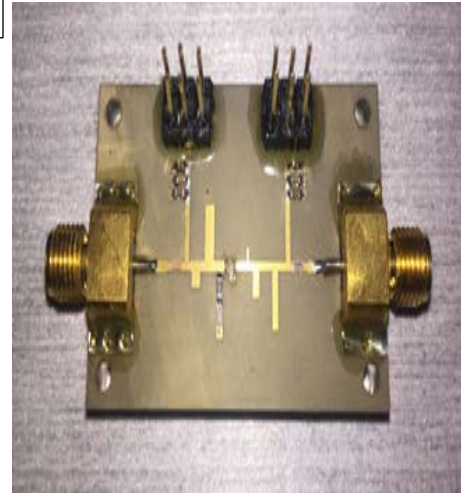


Figure 23: The fabricated board.

S11 of the output matching network along with the two maximum efficiency points found from load pull data have been presented in Figure 24. Thus with the help of load pull simulation results showing the maximum efficiency points near 1.75 GHz and 5GHz, stability circuit to ensure unconditional stability, two stubs in the input matching network and three stubs in the output matching circuit , a high efficiency dual band PA has been developed. Three stubs in the output matching network provided more control in achieving higher efficiency or in other way we can say that three stubs in the output matching side helped with getting well-defined dual band that presented very high efficiency. Several simulations were executed to verify the concept and also the designed circuit was optimized for best efficiencies with two stubs in the input matching circuit and three stubs in the output matching circuit. Small and large signal analysis of the designed circuit are shown in figure 25 and 26.

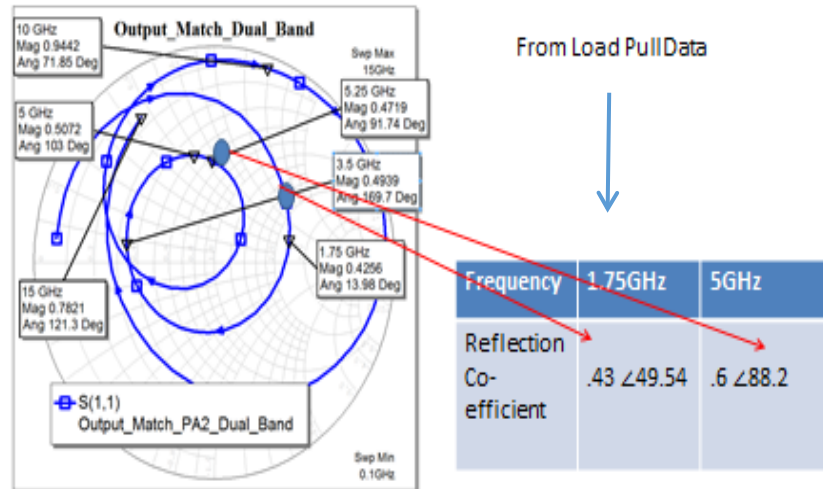


Figure 24: S_{11} of output matching network on Smith chart showing the values at the frequencies of interest.

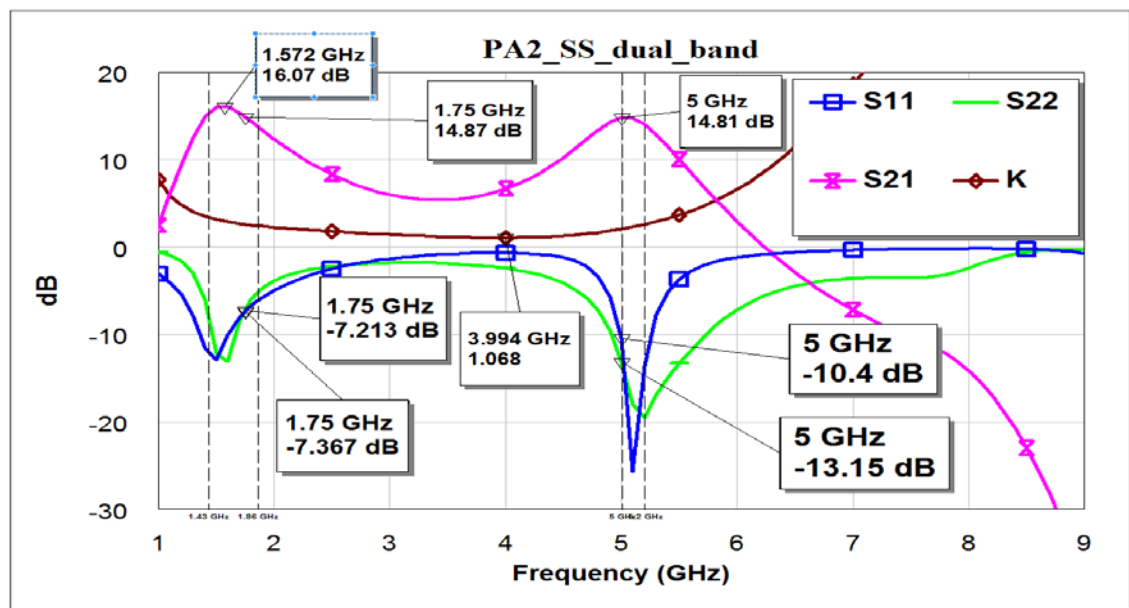


Figure 25: Small signal analysis of dual band design, S21 is shown in pink, S11 in blue, S22 in green and stability k in brown.

Small and large signal analysis of the PA are shown in the Figs. 25 and 26, respectively. In Fig 25, the gain is 14.8 dB at 1.75 GHz and 14.84 dB at 5GHz. Small signal input return loss is better than 7 dB at L-band and 10 dB at C-band. Output return loss is better than 7dB for L-band and better than 10 dB for C-band.

The net result is that the PA yielded excellent performance concurrently at both L- and C-bands. Figure 26, plots PAE (Blue), P_{out} (Magenta), and saturated gain (Brown) from 1-9 GHz. At Upper L-Band, this PA achieves PAE of 65 %, P_{out} of 35.4 dBm, and gain of 12.4 dB, while simultaneously achieving PAE of 61.7%, P_{out} of 36 dBm, and Gain of 13.6 dB at C-Band.

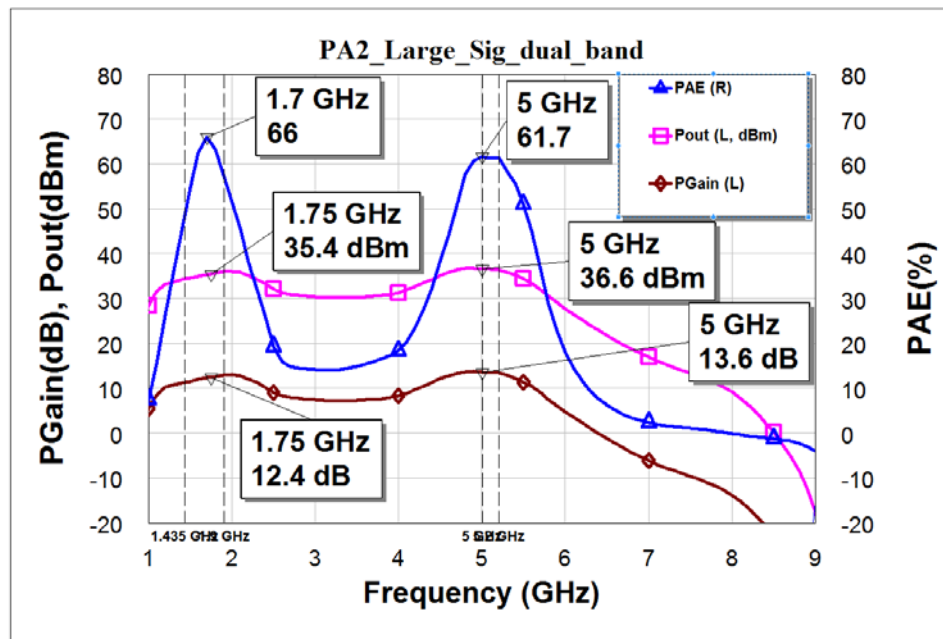


Figure 26: Large signal analysis (showing PAE, PGain and PComp)

The next section describes the reconfigurable PA design concepts.

3.2: Design and simulation results of reconfigurable PA

Designed circuits, layouts and simulation results of reconfigurable power amplifiers using different technologies have been presented here.

3.2.1: Reconfigurable PA using BST varactor

The basic design concept:

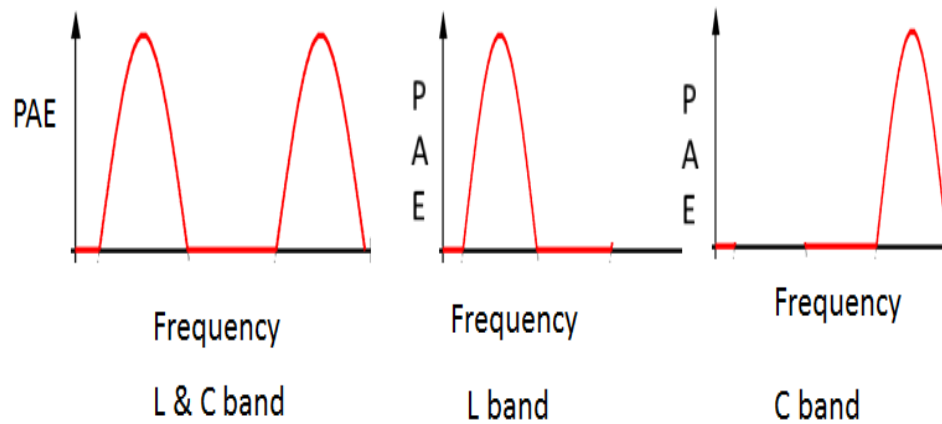


Figure 27: Dual band (L & C) to single band (L or C) selection.

The figure above (fig 27) shows the basic design concept. The idea was to develop a design that can select/switch from telemetry concurrent L & C band to one of the band L or C. Here, in this work, two BST based varactors have been used to create a tunable band/reconfigurable PA which presents a rejection/notch at some frequencies depending on the capacitance values and is switchable from dual to one of the single bands (L or C band). Figure 28 shows the electrical model of BST thin-film varactor. Under fixed bias condition,

the varactor device can be modeled as a conventional parallel plate capacitor using lumped elements. Here, the parallel capacitor C1 represents the BST capacitor and the parallel resistor represents the dielectric loss of the ferroelectric material. The series resistance represents the parasitic presented by the shunt line in the varactor. The series inductor represents the parasitic conductor inductance. Figure 30 shows the entire schematic of the reconfigurable dual band PA with the designed/ proposed input & output matching network for the reconfigurable PA using BST varactor.

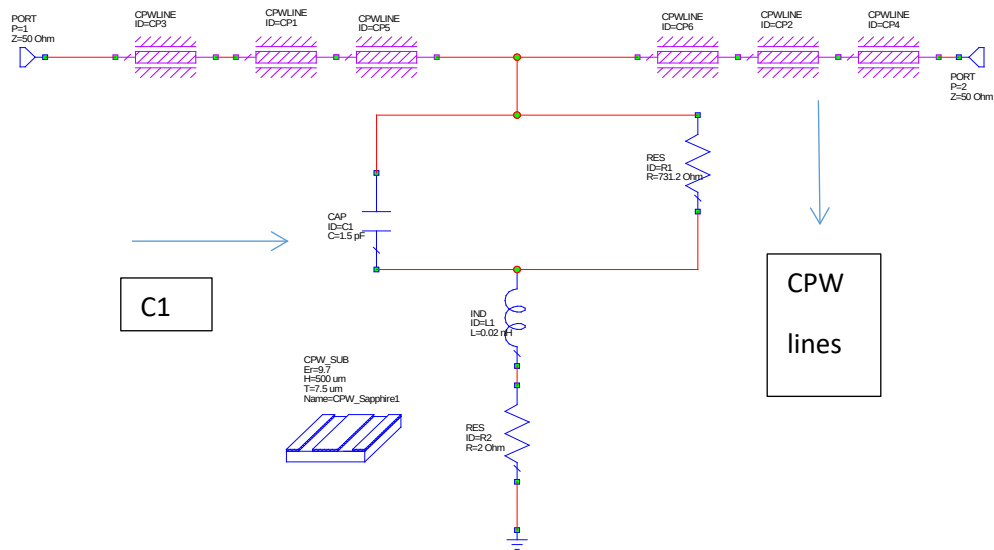


Figure 28: Electrical model of the varactor.

This design is unique because both of the varactors have been placed on the input side. It helped getting very good efficiency at the desired band of interest. Figure 29 & 30 are showing how and where the varactors are used. The selection of one of the bands from concurrent dual band has been done by either applying bias to the varactors, basically to lower the capacitances, or by using the varactors without biasing. The design can also be used as concurrent dual band (L & C) PA.

Figure 29: Zoomed view of the location of the BST varactor.

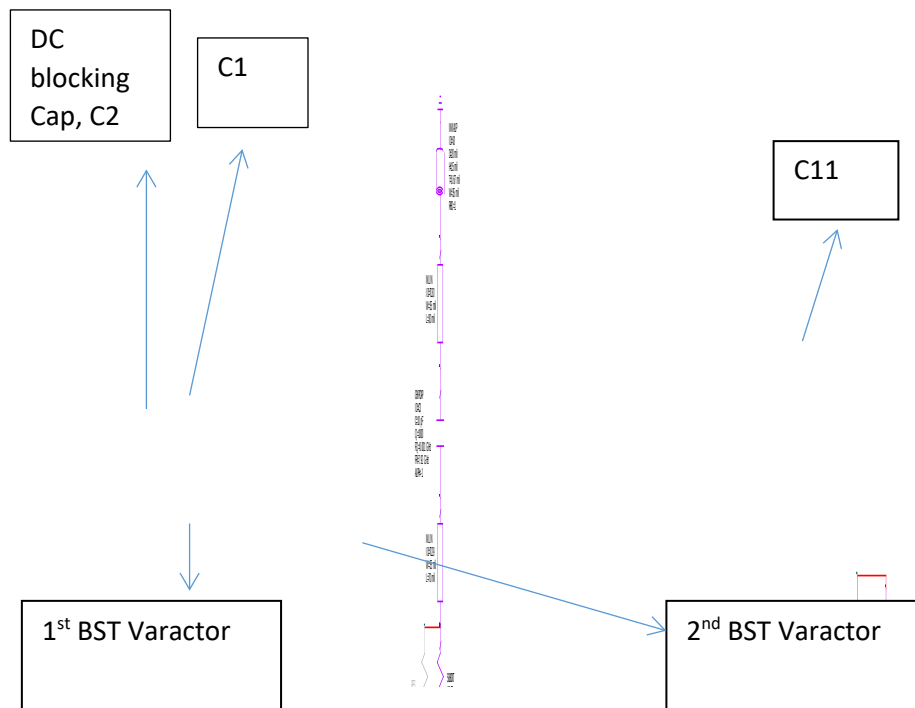


Figure 30: The entire schematic of reconfigurable PA (initial design).

The next couple of figures (31-33) describe the simulation results with bias and /or no bias condition. These are the results of the initial design concepts.

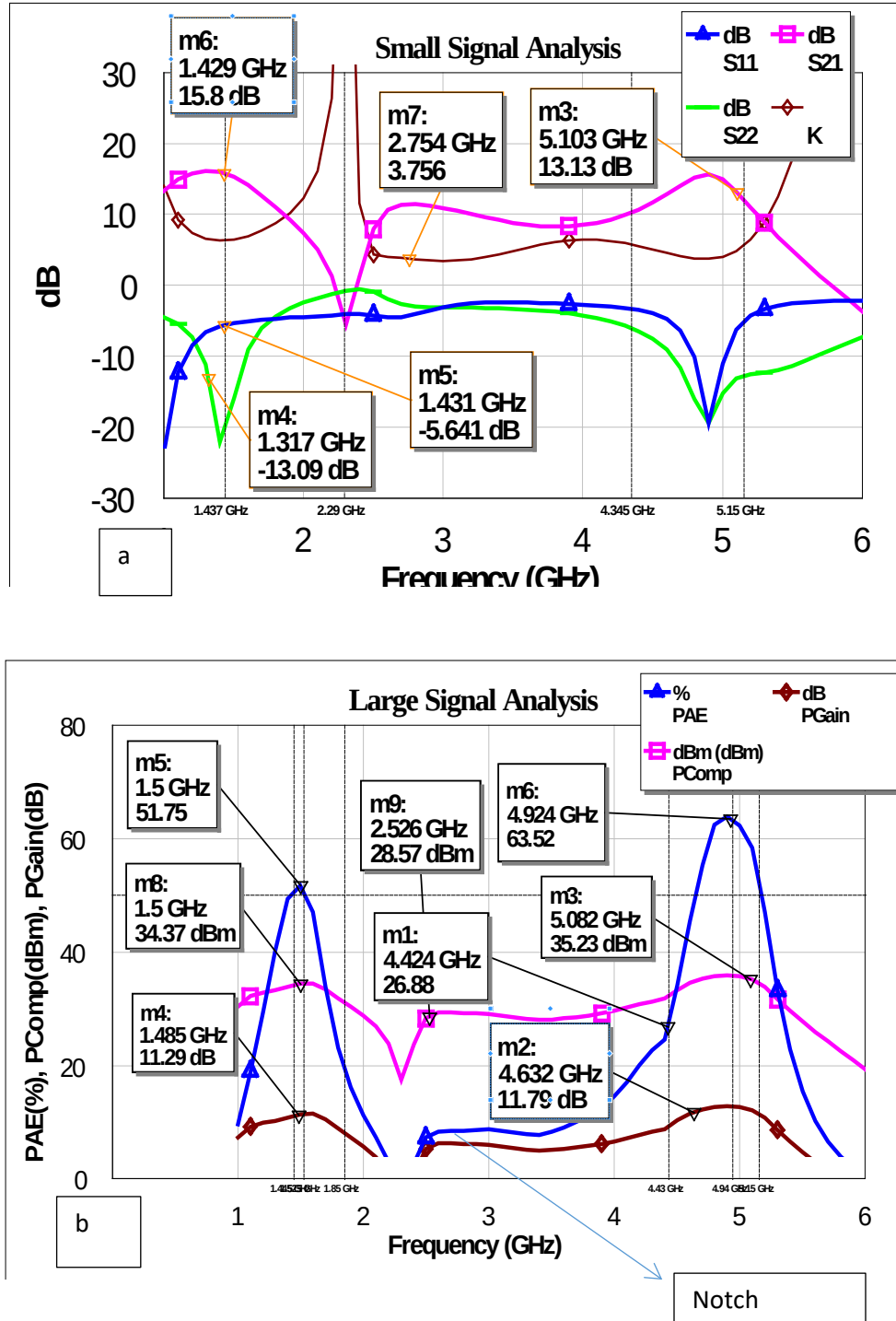


Figure 31: Dual band, (a) Small & (b) Large signal (first varactor, no-bias, 4pF, second one with bias, .8pF, C11: .4pF, C1: .5pF, C2: 5pF).

The figures (31-33) shows the small & large signal simulation results of the selection of one of the single band (either L or C) from dual bands (L & C) just by either biasing the varactor or using it without any bias. For the dual band design, maximum gain of 15.8 dB at L band and 13.3 dB at C band was achieved. S11 and S22 are also better than -6dB. Maximum efficiency at Lower L band is approximately 51.75% and is above 60 % in the Middle C band. In the single C band selection simulation result, maximum efficiency is above 60% and for single L band selection result it is 51.5%. Figure 32(a) presents the gain of 17.4 dB at C band, S11 better than -7dB and S22 better than -9dB. Figure 32(b) shows greater than 60% PAE, output power and ac gain of 36.4 dBm and 13.45 dB gain respectively. Figure 33(a) presented 18dB gain , S11 and S22 better than -9dB, PAE of 51%, output power 34dBm and gain 11.7 dB are presented in figure 33(b) for C band.

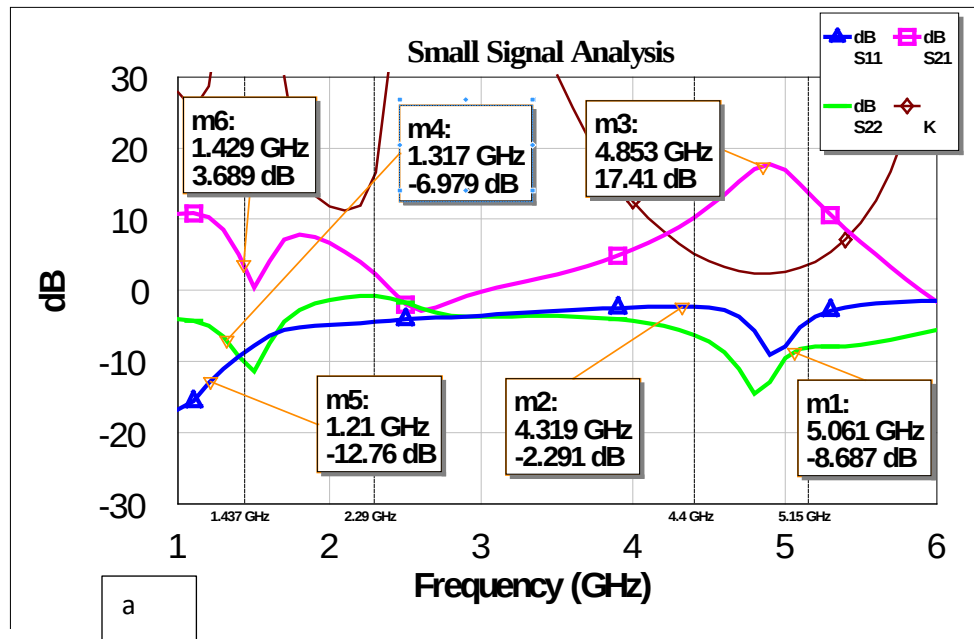


Figure 32(a): Small signal response showing single (C band) band selection conditions (Both BST varactor, 0V, 4pF, C11, .4pF, C2: 5pF, C1:.5pF).

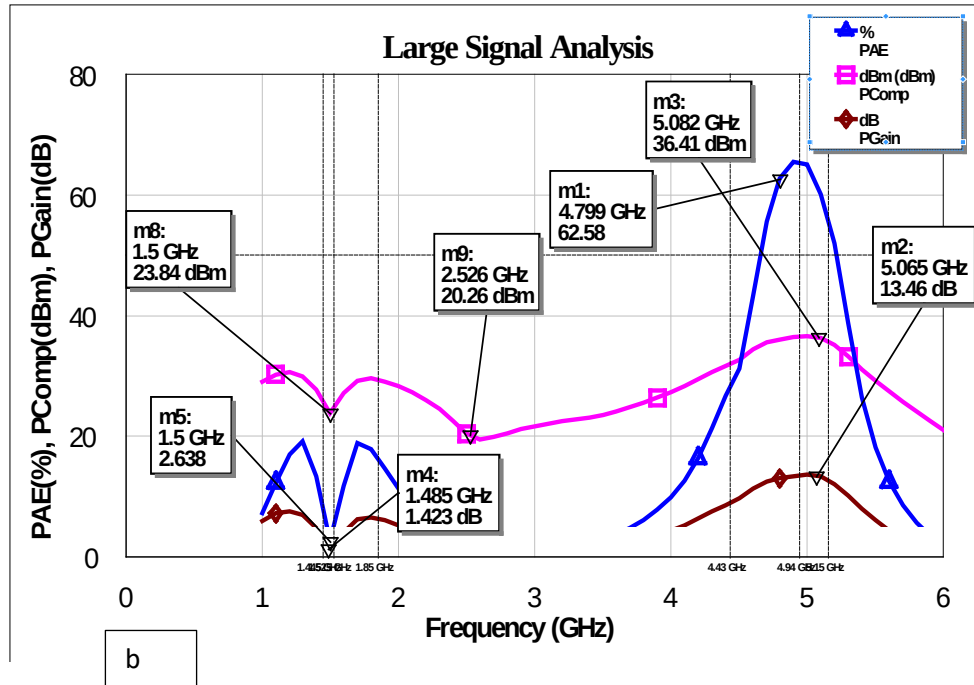


Figure 32(b): Large signal response showing single (C band) band selection conditions (Both BST varactor, 0V, 4pF, C11, .4pF, C2: 5pF, C1:.5pF).

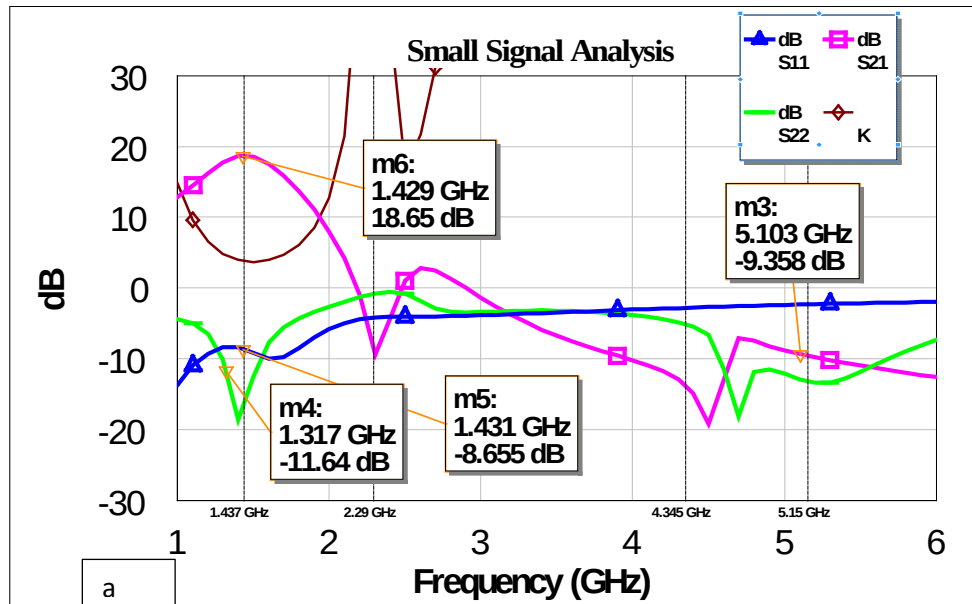


Figure 33 (a): Small signal response showing single (L band) band selection (Both BST varactor, 8V, .8pF, C11, .4pF).

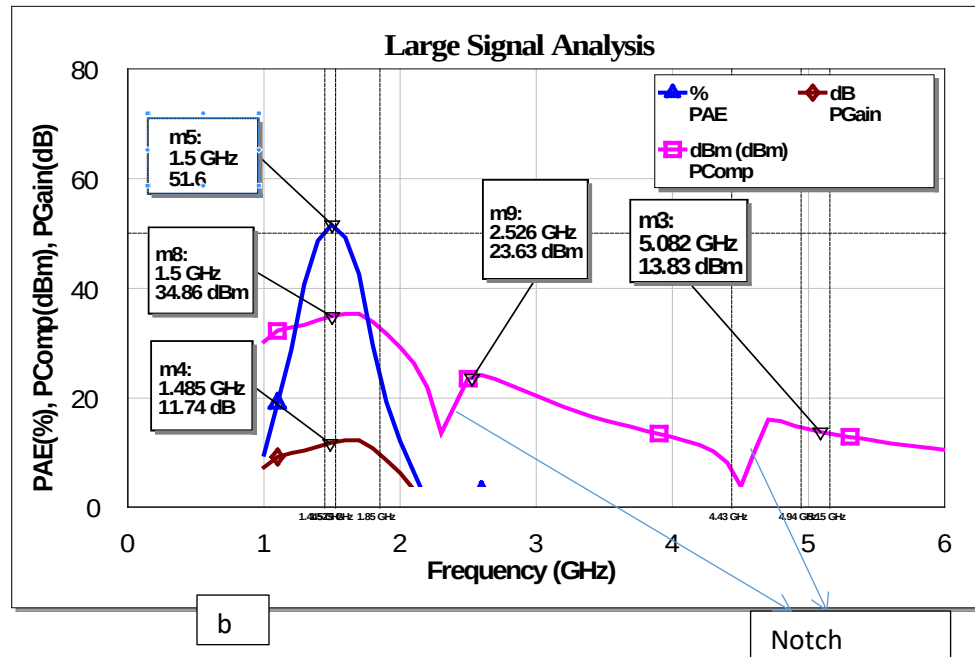


Figure 33(b): Large signal response showing single (L band) band selection (Both BST varactor, 8V, .8pF, C11, .4pF).

Final layout design & simulation results

The previous design/ layout has been modified slightly before the fabrication to ensure that the transistor is not affected by the varactor biasing. For that purpose, two dc blocking capacitors of 10pF has been added to isolate the transistor from varactor bias voltage influence. The EM model of the varactors has also been used here. With these additions and modifications, there has been slight change in the simulation results. Figure (34-37) shows the modified layout, schematic & the simulation results of the design that has been used for fabrication. Figures 36(a, b) shows the small and large simulation results of the dual band design. To get the dual band, both of the varactors needed to be biased so that the capacitance value is 0.8pF. The gain is 14.13 dB at 1.4 GHz and 15.71 dB at 5GHz. Small signal input return loss is better than -7 dB at L-band and -10 dB at C-band. Output return loss is better than -6dB for both the bands.

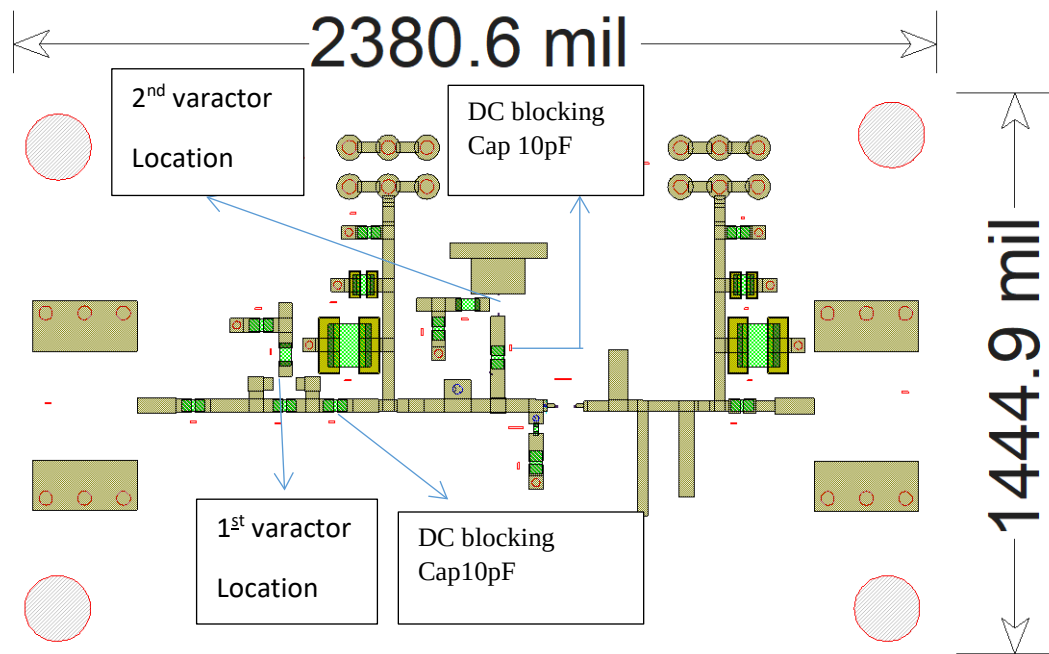


Figure 34: Layout for fabrication showing the locations of the dc blocking capacitors and the varactor location.

Here in this figure, the varactors are not shown as the s-parameter from the EM model has been used.

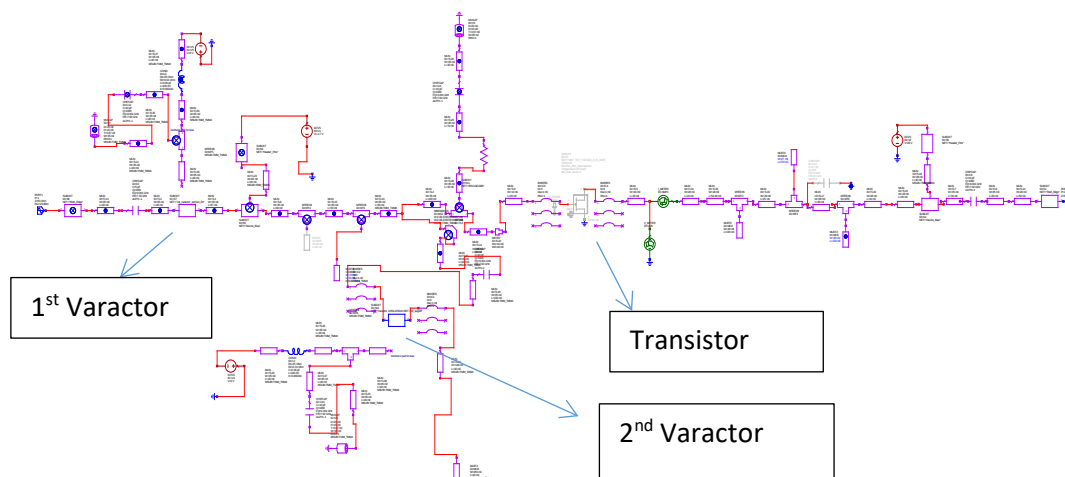
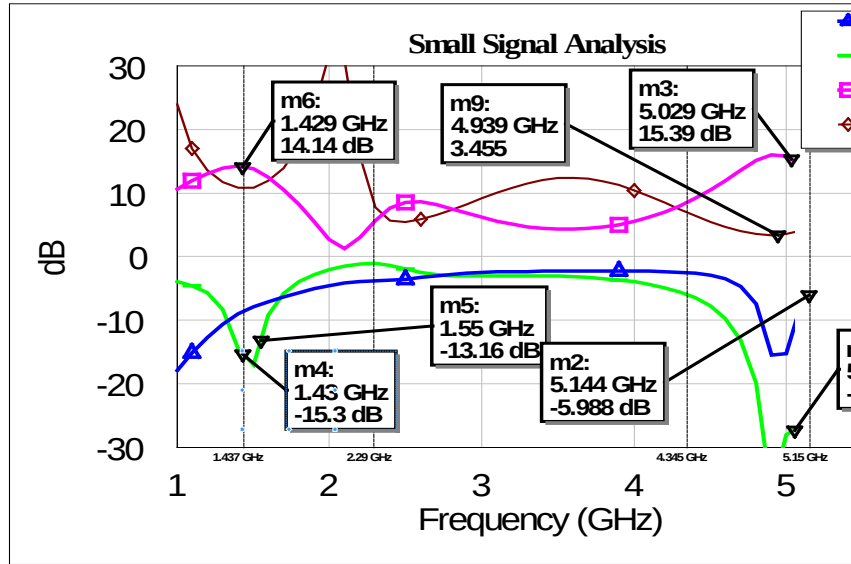
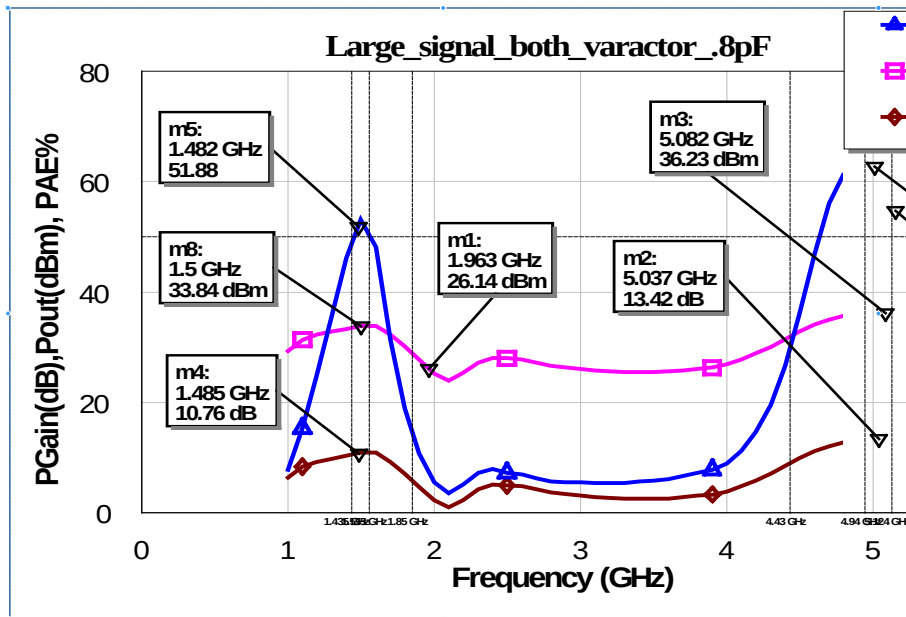


Figure 35: Entire schematic of the reconfigurable PA

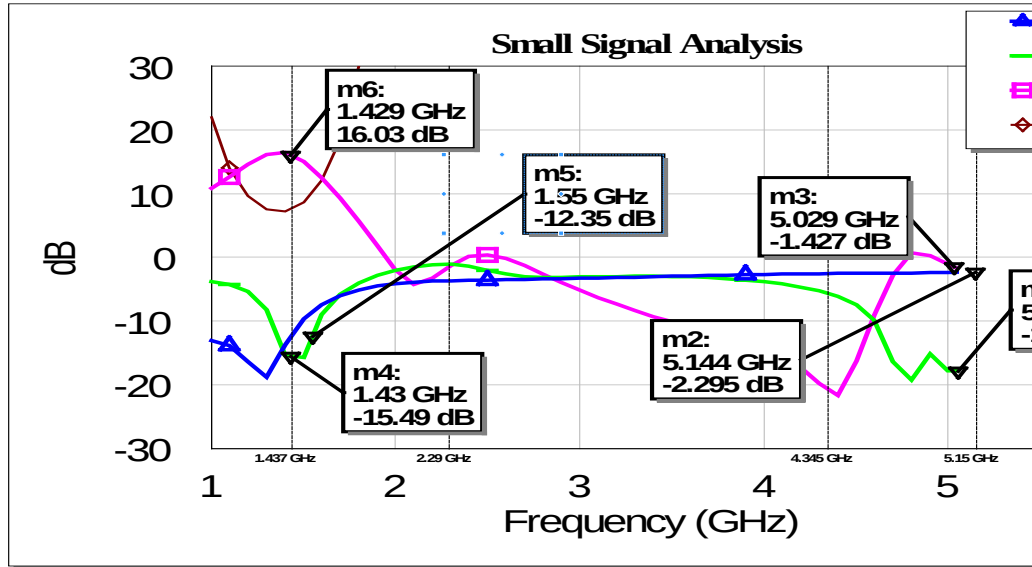


(a)

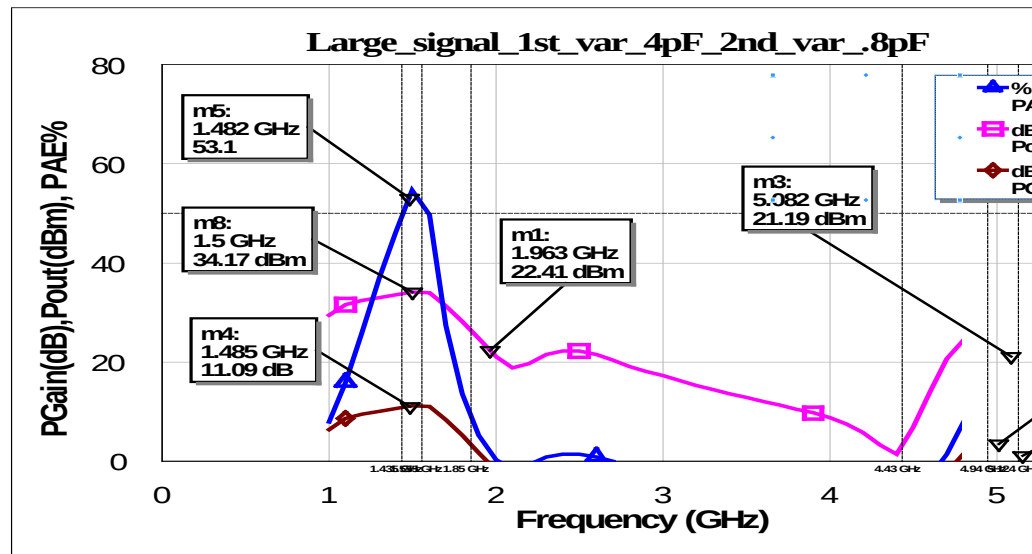


(b)

Figure 36: Small (a) & Large (b) signal analysis showing similar results after the modifications. PAE (power added efficiency) is better than 50% on the L band and better than 60% in the middle C band (dual band, L & C band)



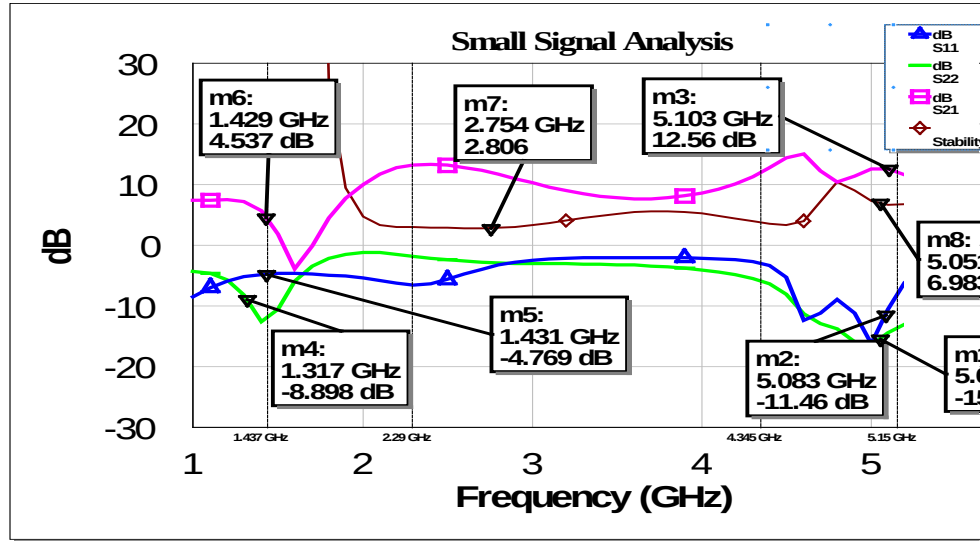
(a)



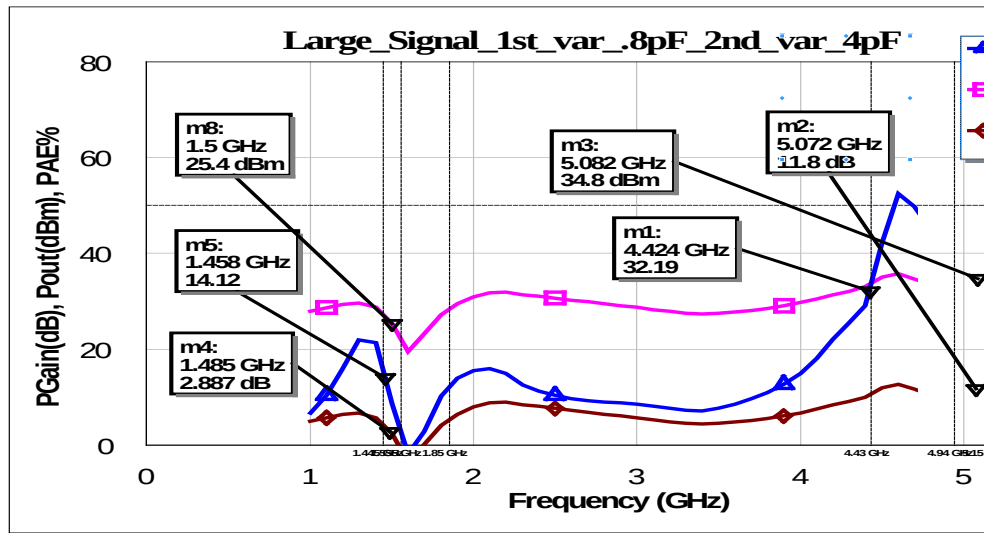
(b)

Figure 37: Small (a) & Large (b) signal analysis showing similar results after the modifications. PAE (Power added efficiency) is better than 50% on the L band. Complete rejection of C band has been achieved.

Figure 37 (a) shows $S_{21} > 15\text{dB}$ and S_{11} , S_{22} better than 12dB and figure 37(b) shows $\text{PAE} > 50\%$, $\text{Pout} > 34\text{dBm}$, $\text{PGain} > 11\text{dB}$.



(a)



(b)

Figure 38: Small (a) & (b) large signal analysis showing similar results after the modifications. PAE (Power added efficiency) is better than 50% on the C band. Complete rejection of L band has been achieved and output power and gain decreased significantly for the L band.

Figure 38 (a) shows $S_{21} > 10\text{ dB}$, S_{11} and S_{22} better than -9 dB and figure 38(b) shows $\text{PAE} > 50\%$, $\text{Pout} > 34\text{ dBm}$, $\text{PGain} > 11\text{ dB}$. Figure 39 shows the 3D view of the designed circuit.

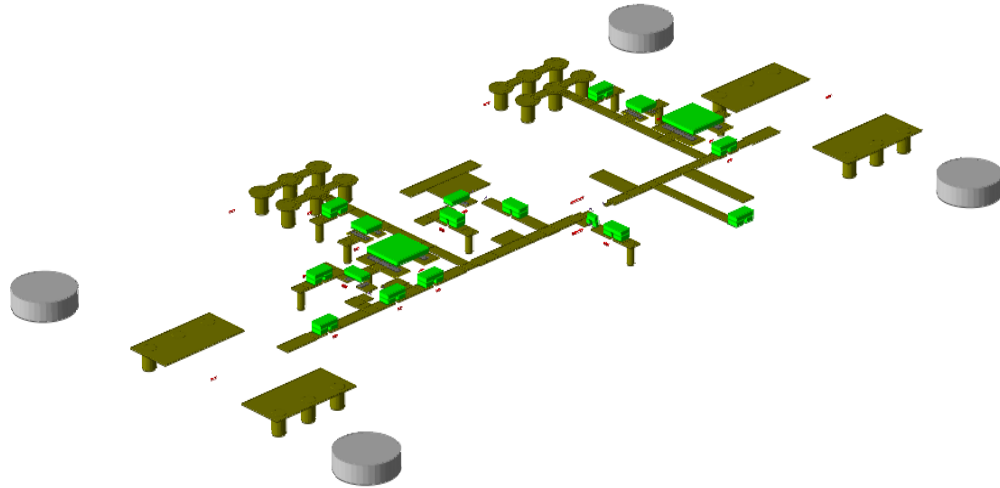


Figure 39: 3D view of the designed circuit

Next, some of the simulation results are presented to show that the three stub output matching circuit provided better efficiencies than the two stub design for the BST varactor based reconfigurable PA. The simulation data, plotted in figure 40, from 1 GHz to 20 GHz shows that there are no significant ac gain or output power peaks for frequencies above 5 GHz. The efficiency is 51.88% in L band and 62.76% in C band with no significant peaks at higher frequencies. Figure 41 presents the large signal data when the first stub from the transistor on the output side was disabled. This figure presents little bit higher efficiencies in the L band, 53% but C band efficiency is lower than the three stub design. A peak output power of 21.15 dBm is shown in the figure 41 at 11.64 GHz. This figure also shows that the output power does not drop abruptly at 5.2 GHz. Whereas in figure 40, there are no significant repeated peaks of ac gain or output power at harmonic frequencies above 5.4 GHz and output power dropped abruptly after 5.2 GHz. Figure 42 shows the large signal analysis when the middle stub from the transistor was disabled. It presented two peak output power at higher frequencies, one at 7.4GHz and another at 17.17 GHz with output

power of 7.92 dBm and 11.82 dBm respectively. Figure 43 presented large signal analysis when the 3rd stub from the transistor was disabled. This design showed 52.75 % in L band but C band efficiency is low, 27.63%. Figure 43 also presented a prominent peak at 7.34 GHz and at 17.94 GHz with peak output power value of 23.98 dBm and 11.38 dBm. After analyzing the simulated data of figures 40, 41, 42 and 43, it can be concluded that the three

stub design provided the best result eliminating the peaks at higher harmonics. Those were the reasons in choosing three stub design over two stub design.

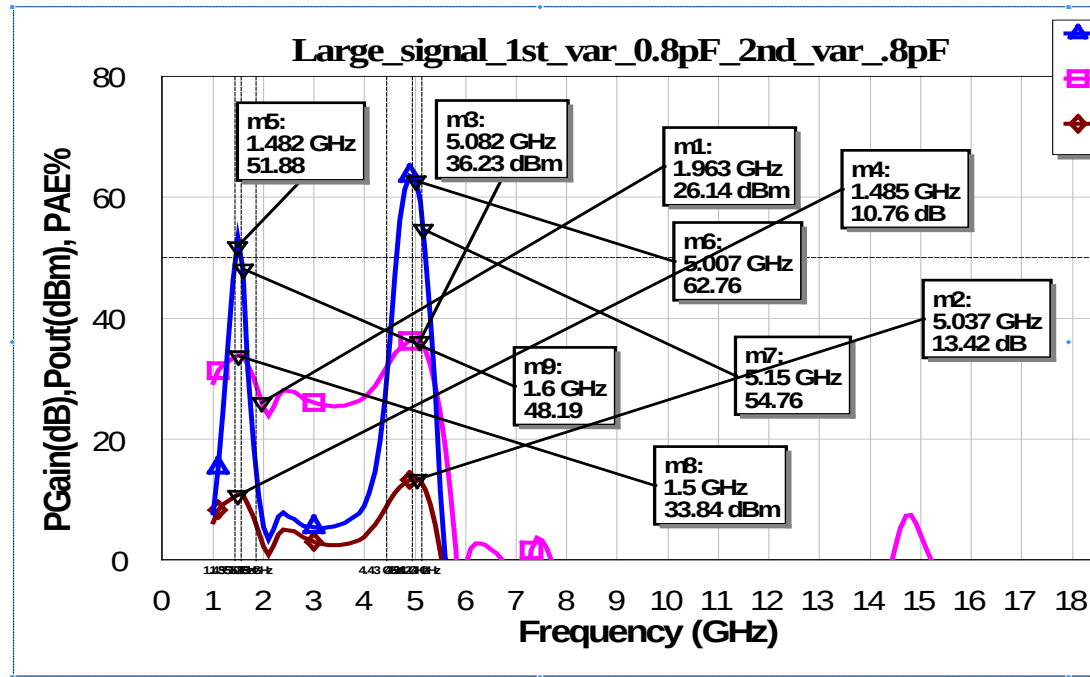


Figure 40: Large signal analysis with three stubs on the output side

In the figures (40 – 43), PAE is represented in blue, output power is shown in pink and brown is used for ac gain.

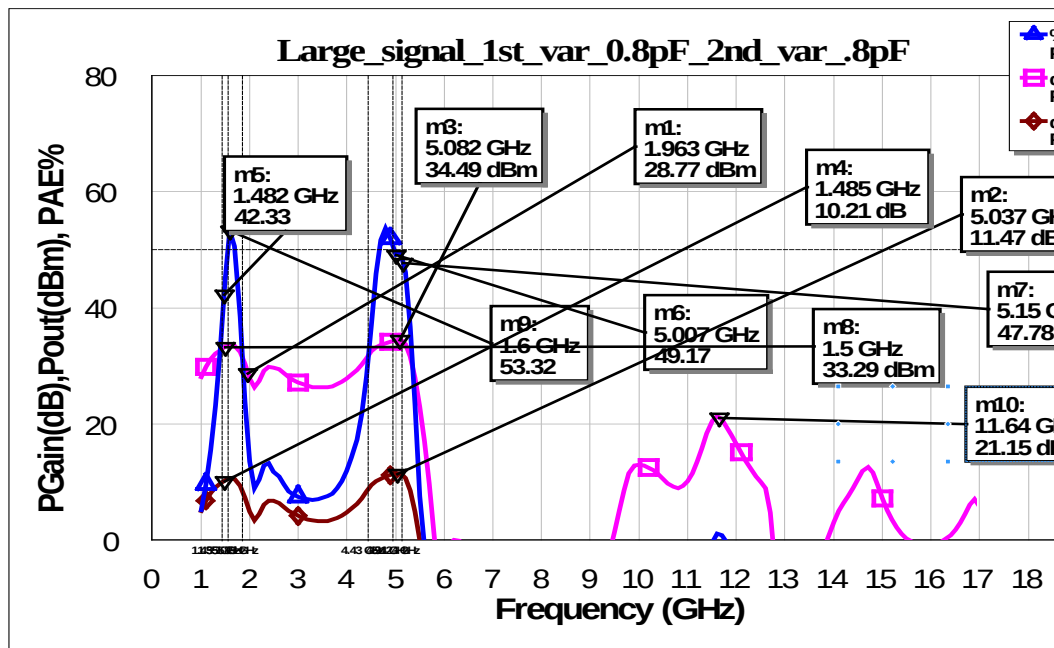


Figure 41: Large signal analysis with two stubs on the output side (with first stub from the transistor disabled)

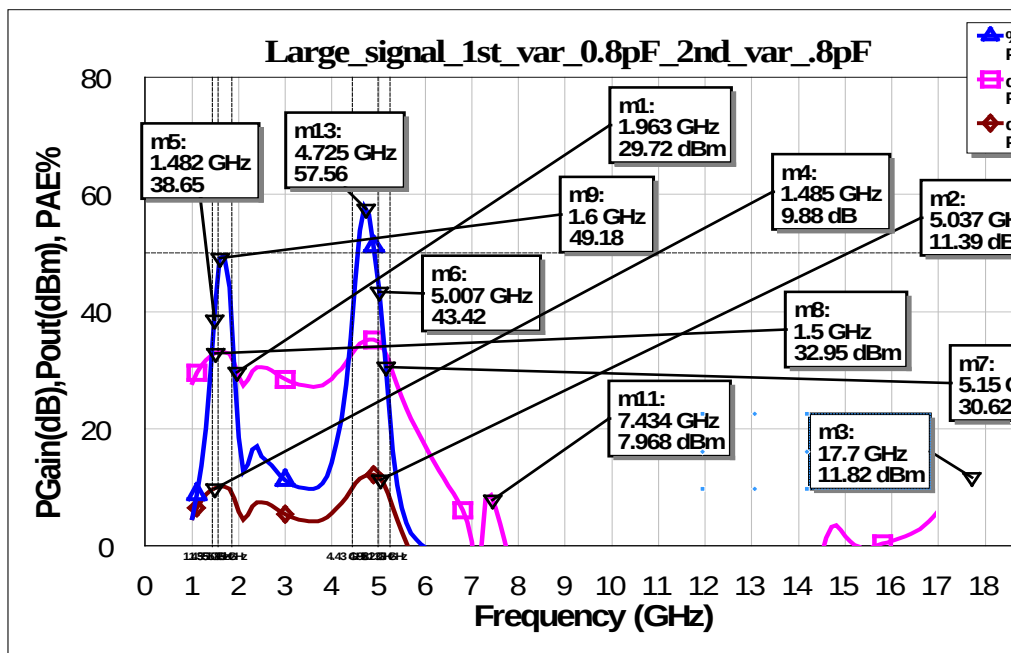


Figure 42: Large signal analysis with two stubs on the output side (with middle or 2nd stub from the transistor disabled)

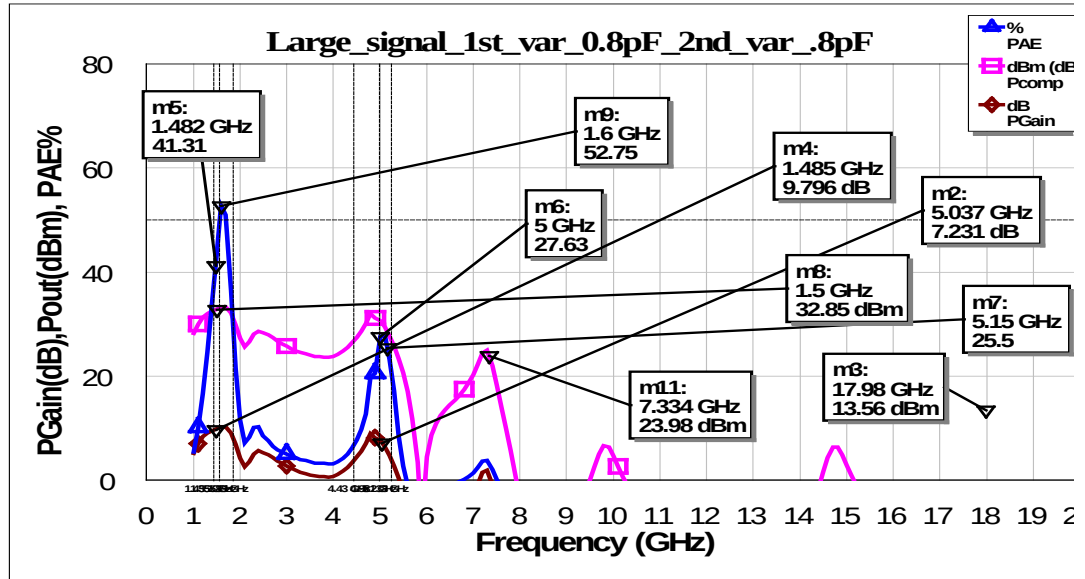


Figure 43: Large signal analysis with two stubs on the output side (with the last or 3rd stub from the transistor disabled).

3.2.2: First varactor section on the wafer design

Another design has been introduced where the entire 1st varactor section has been implemented on wafer. Figure 44 shows the 3D view of that design.

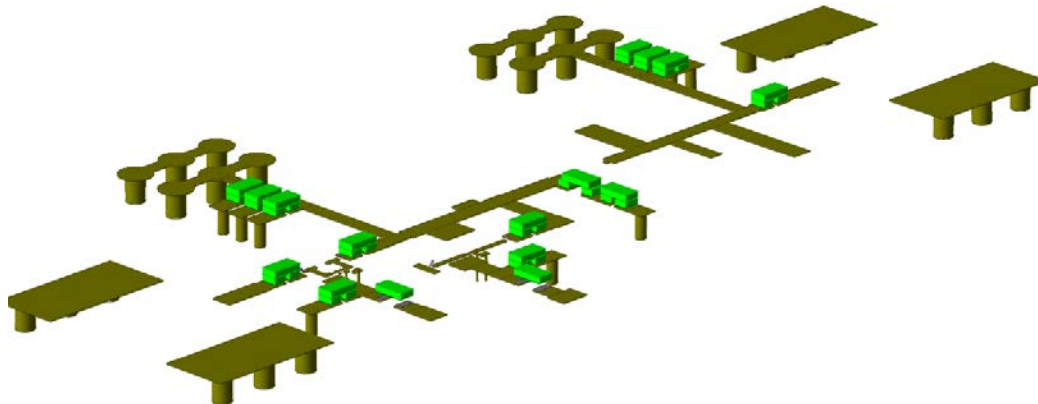


Figure 44: 3D view of the entire design with entire 1st varactor section on wafer.

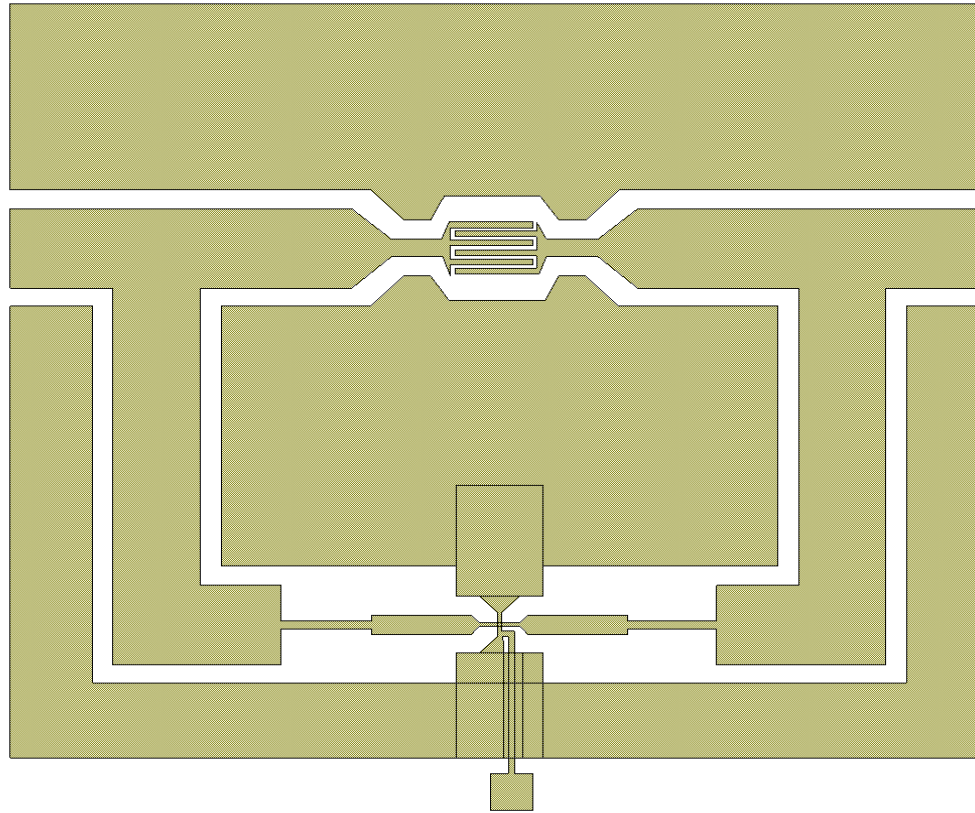


Figure 45: 1st varactor section (on-wafer design)

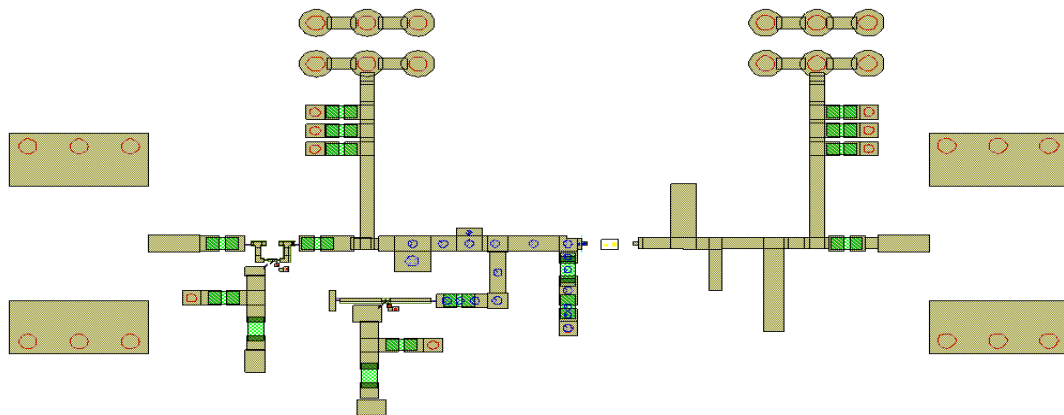
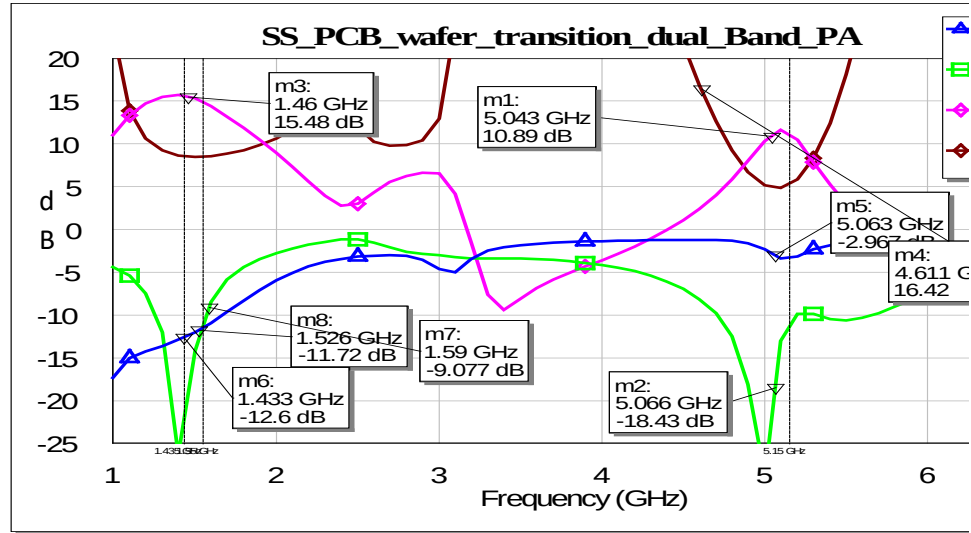
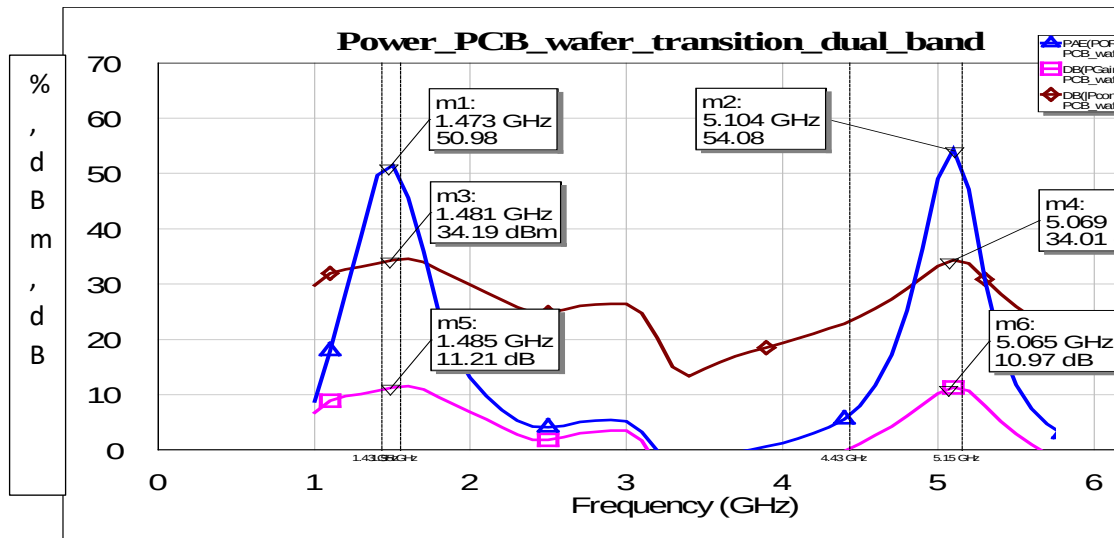


Figure 46: Entire layout with the varactor section on wafer design.



(a)

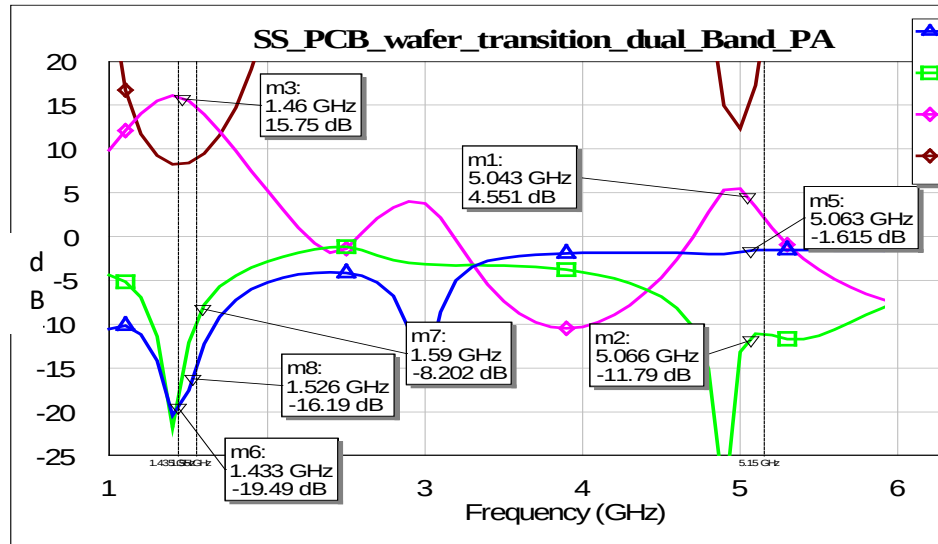


(b)

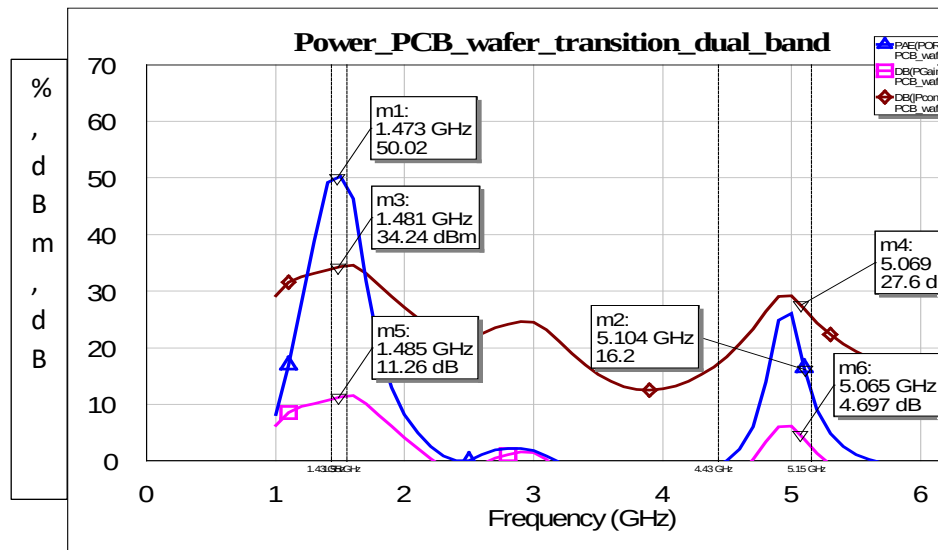
Figure 47: (a) Small signal & (b) Large signal. Dual band (L & C), both varactors on (.8pF capacitance). Efficiency is more than 50% on both the bands.

Here, as shown in figure 45 & 46, instead of using the varactor by itself as a separate component, a big section of the area surrounding the varactor has been placed on wafer.

The simulation results has been shown below in figures (47-49). It can be noted here that complete rejection of one of the bands from dual bands were not achieved.

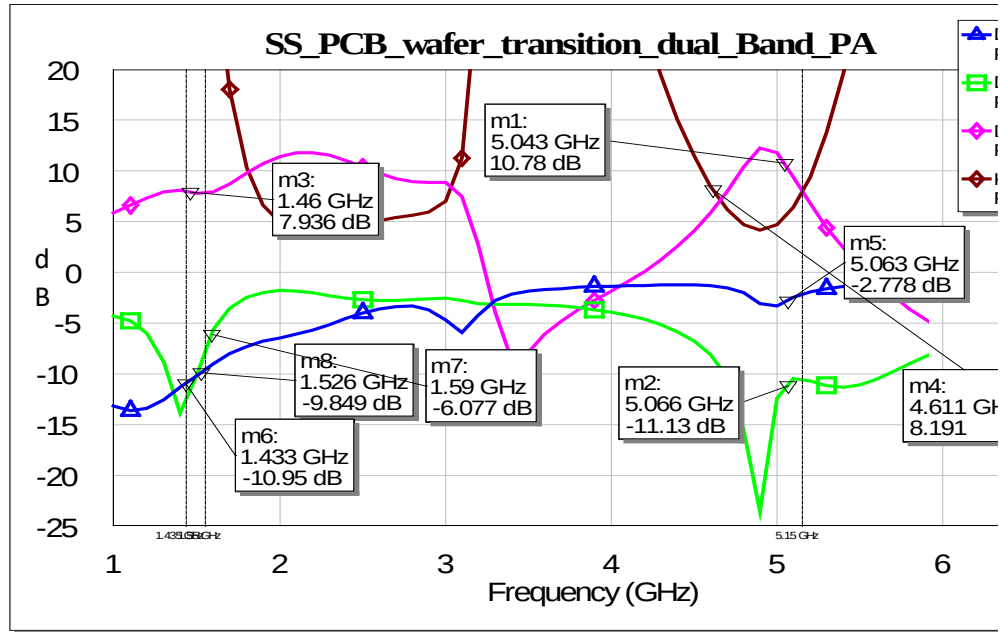


(a)

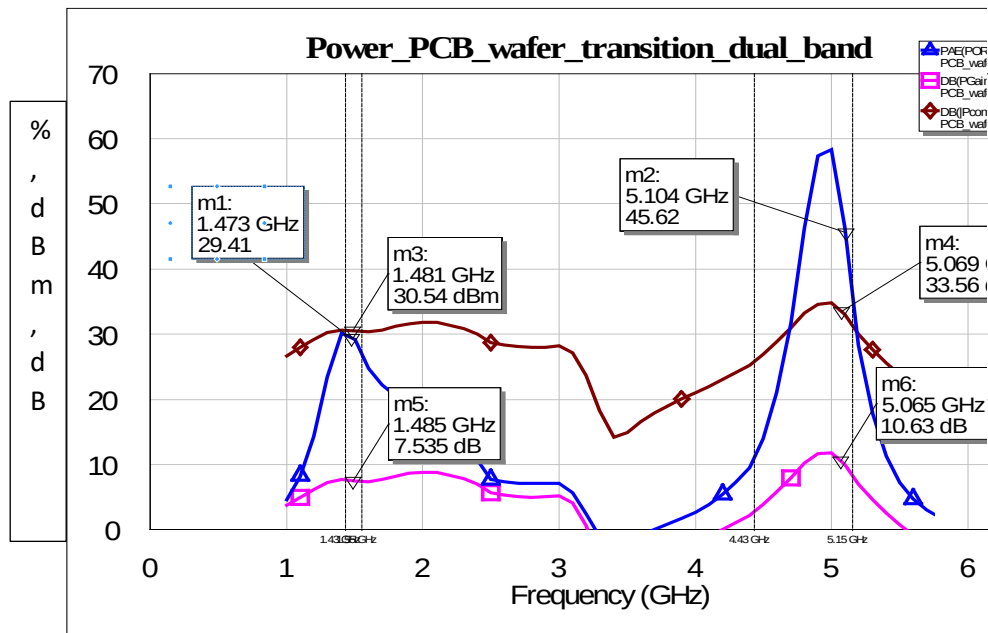


(b)

Figure 48: (a) Small signal & (b) Large signal. L band, first varactor off (4pF), 2nd varactor on(.8pF). Efficiency is more than 50% on the L bands.



(a)



(b)

Figure: 49: (a) Small signal & (b) Large signal. C band, first varactor on (.8pF), 2nd varactor off (4 pF). Efficiency is not more than 50% on the C bands.

3.2.3: One BST varactor, three tunable CHIPCAPS & one fixed CHIPCAP design

The following few figures are the simulation results from a different topology. Here only one BST and four CHIPCAPS (tunable) are used to achieve reconfigurability. Similar results are achieved like the simulation results of Fig 36-38, (using two BST varactors) except in this case, fine tuning (selecting between Upper L & Lower L) & (Lower C & Middle C) are also achieved. It is shown here that this simulation result covers more bands such as Upper L and also Mid C band. Also for fine tuning conditions, efficiency greater than 53% in Upper L band and above 65% in Lower C band was achieved. Only the large signal responses has been shown here for simplicity. Figure 57 is small signal response for dual band.

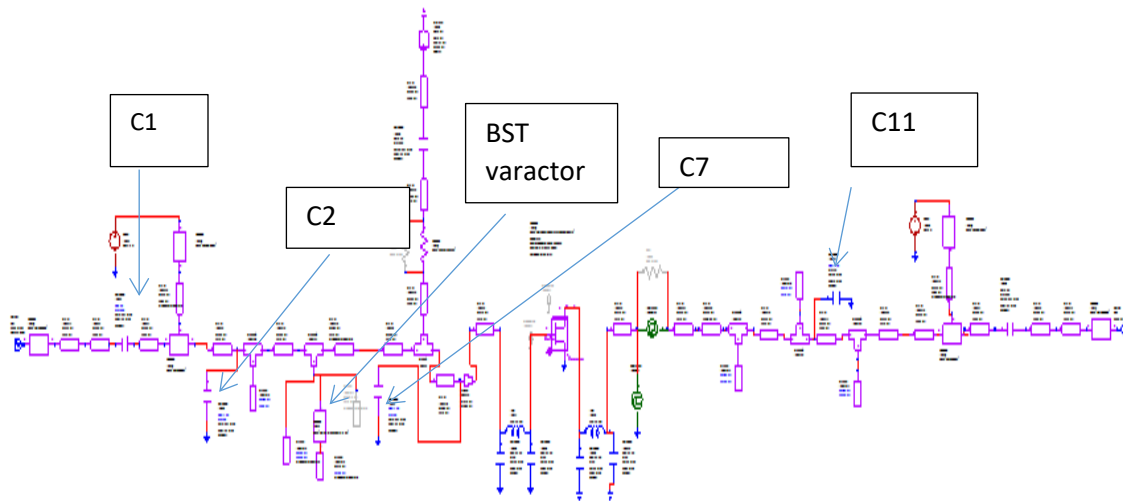


Figure 50: Entire circuit (different configuration) , one BST based varactor and four CHIPCAPs. C7 is fixed.

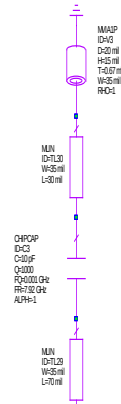


Figure 51: Zoomed view of different configuration (one BST varactor and four CHIPCAPS).

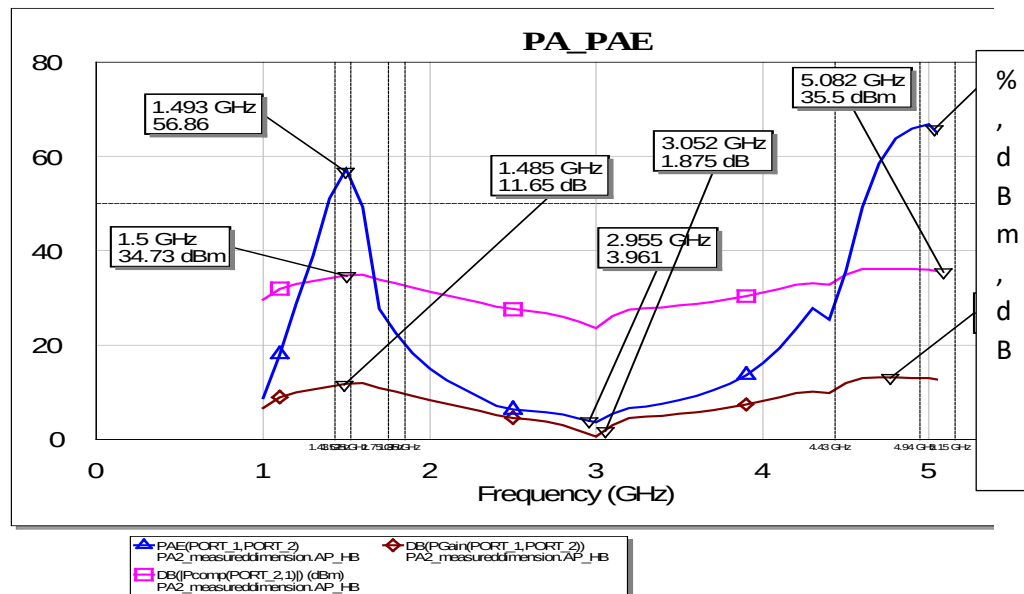


Figure 52: Dual band: lower L (1.43-1.525 GHz) & middle C (5-5.15GHz) band (C1:7 pF, C2:1pF, C7:1pF, C11:1.2pF).

Here for figures (48-52), PAE is shown in blue, output power in pink and gain is shown in brown. For figure 53, S21 is shown in pink, S11 in blue and S22 in green.

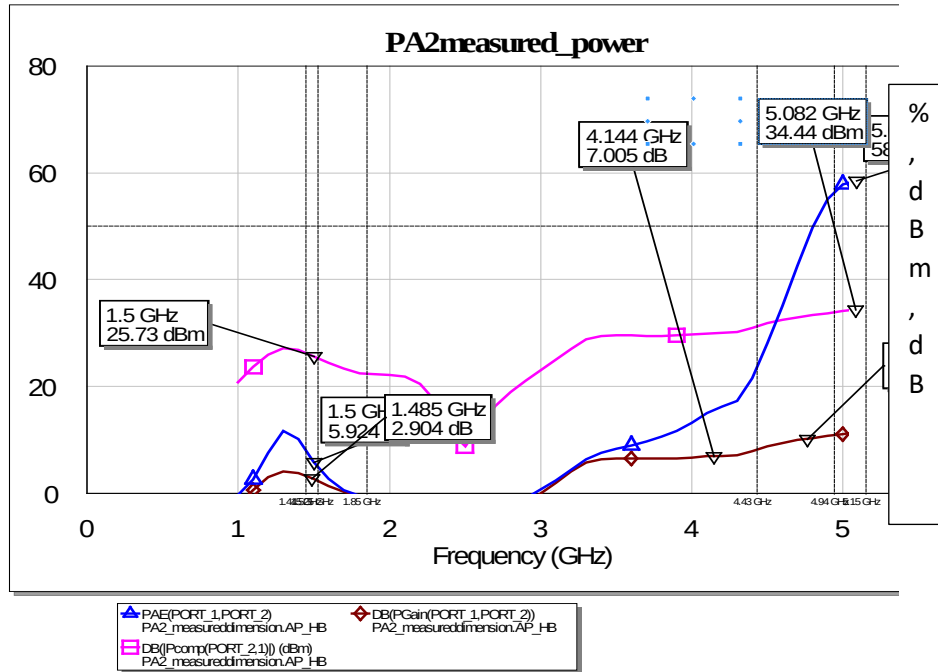


Figure 53: Tuning to single band (middle C band).

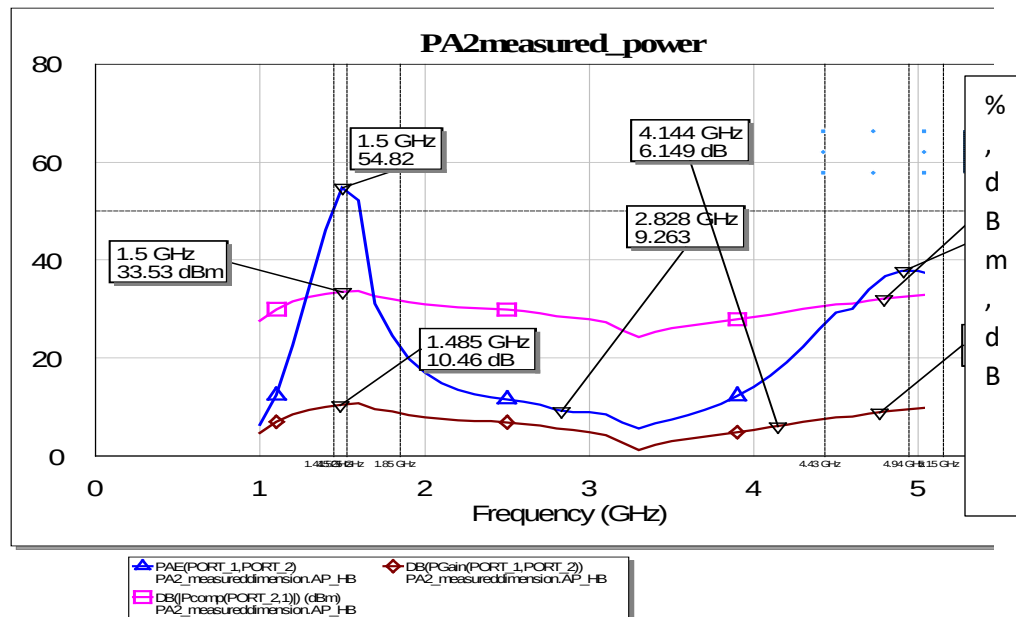


Figure 54: Tuning to single band (lower L band).

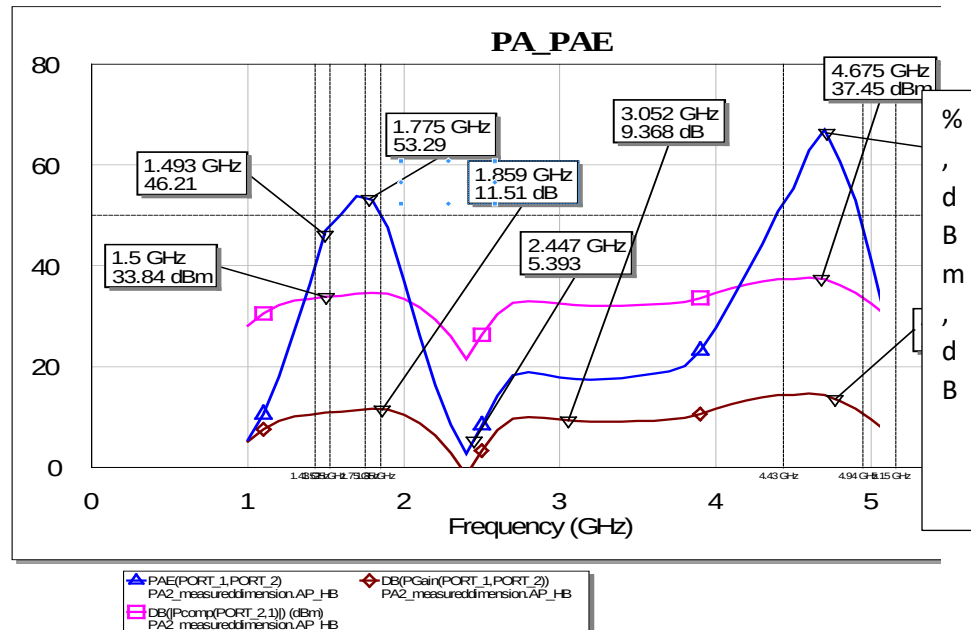


Figure 55: Use of C11 and state change of BST varactor to get upper L (1.75-1.85 GHz) & lower C (4.4-4.94GHz) band (C1:5 pF, C2::1pF, C7::1pF, C11::7pF).

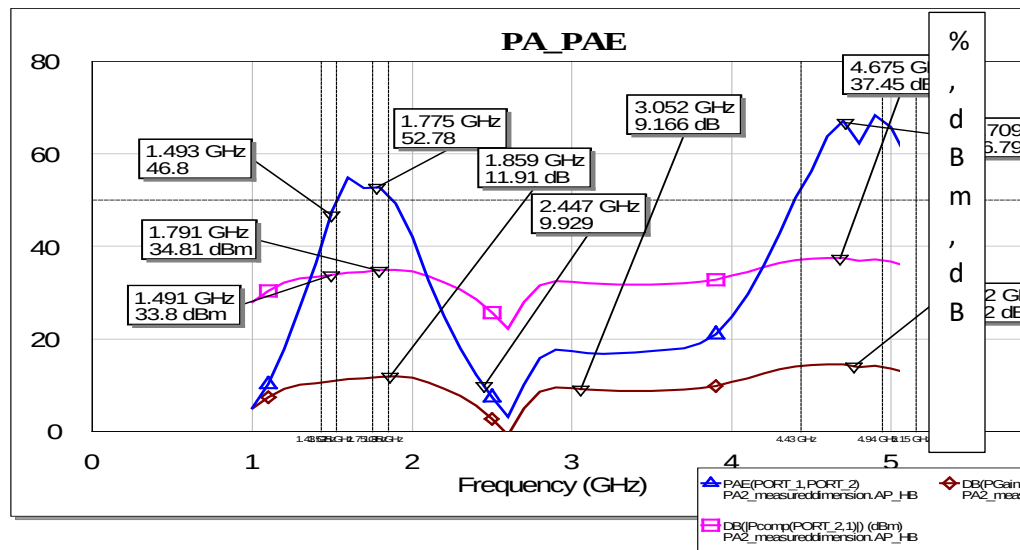


Figure 56: Large signal analysis, use of C11 and state change of BST varactor to achieve upper L (1.75-1.85 GHz) & lower to mid C (4.4-5.15GHz) band (C1:5 pF, C2::1pF, C7::1pF, C11::1pF).

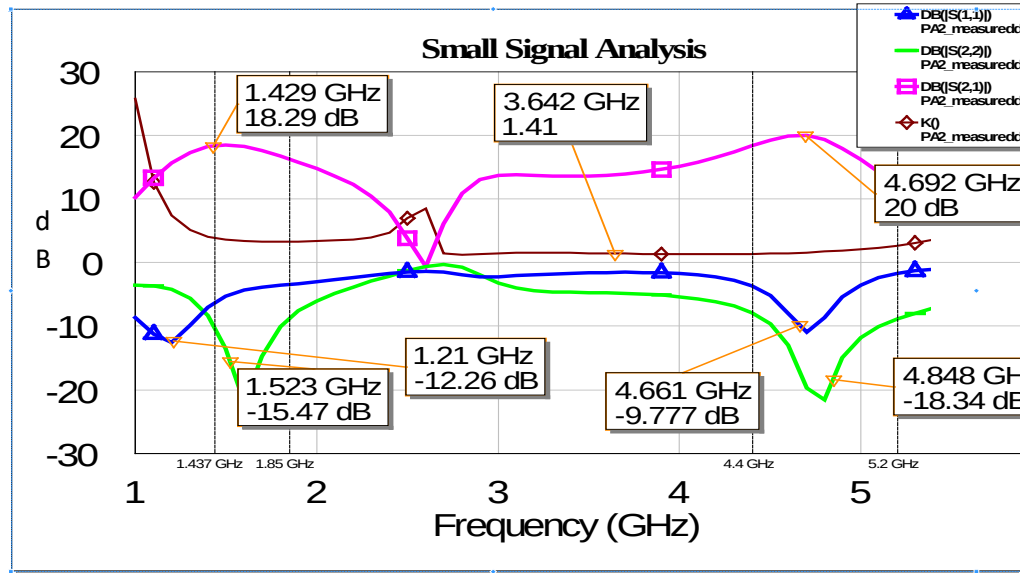


Figure 57: Small signal analysis of dual band.

3.2.4: Reconfigurable PA using three CHIPCAPS

To find out the required capacitance value for reconfigurable dual/single band PA with good PAE, several simulations results were analyzed. Here the sweep variables were used to vary the capacitances and PAE vs capacitance values has been plotted. Next small and large signal analysis has been shown by varying two of the capacitance values. Figure 58(a) showed the difference in the capacitor location (in the circuit) and the capacitors used for tuning to get results of figure 58(b) and 58(c). Figure 58 (b) shows the dependence of PAE on capacitor (C11) variation, keeping the other two fixed C1(1 pF) and C2 (.5pF) at 5GHz & 1.75GHz. Figure 59 shows the dependence of PAE on capacitor (C2) variation, keeping the other two fixed C11(.13pF) and C1 (1pF). Figure 60 shows the dependence of PAE on capacitor (C1) variation, keeping the other two fixed C11(.13pF) and C2 (.5pF). It can be concluded from the figures (58-60) that C1 (the series capacitor) has the most effect on PAE.

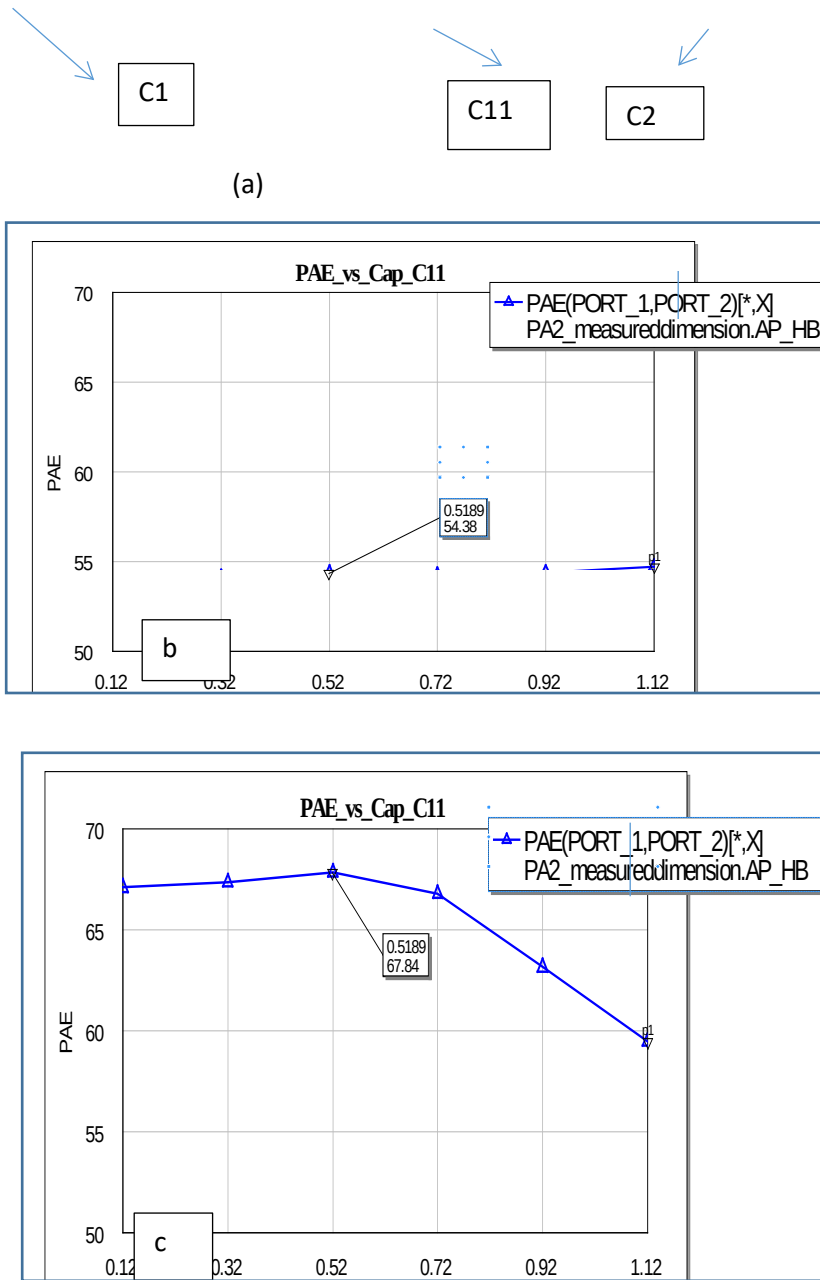


Figure:58: a) A zoomed view of the section (different from the previous circuit from figure 46 and 47), b) PAE vs capacitor C11 keeping C1(1pF) & C2 (.5pF) fixed at 1.75GHz, c) PAE vs capacitor C11 keeping C1(1pF) & C2 (.5pF) fixed at 5GHz.

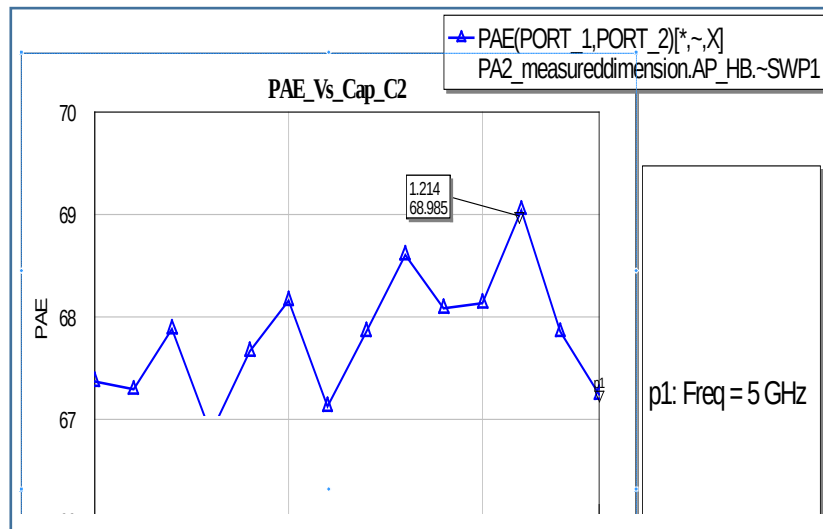


Figure 59: PAE vs capacitor C2 keeping C1 (1pF) & C11 (.13pF) fixed at 5GHz.

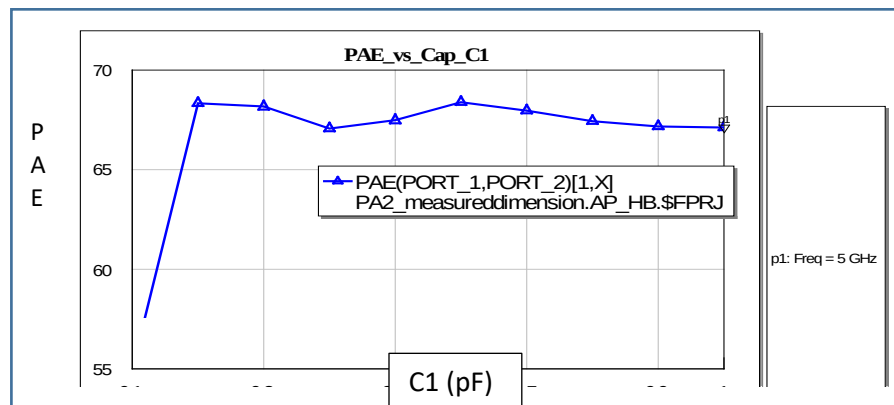
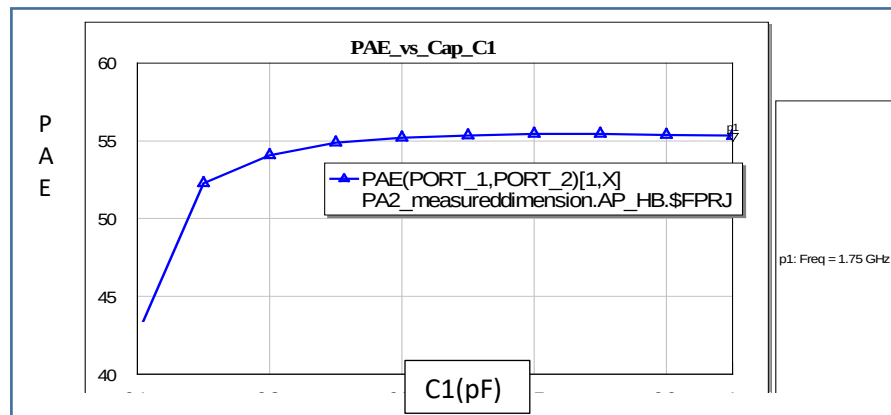


Figure 60: Variation of PAE vs capacitor C1 keeping C11(.13pF) & C2(.5pF) fixed (at 1.75GHz & 5GHz).

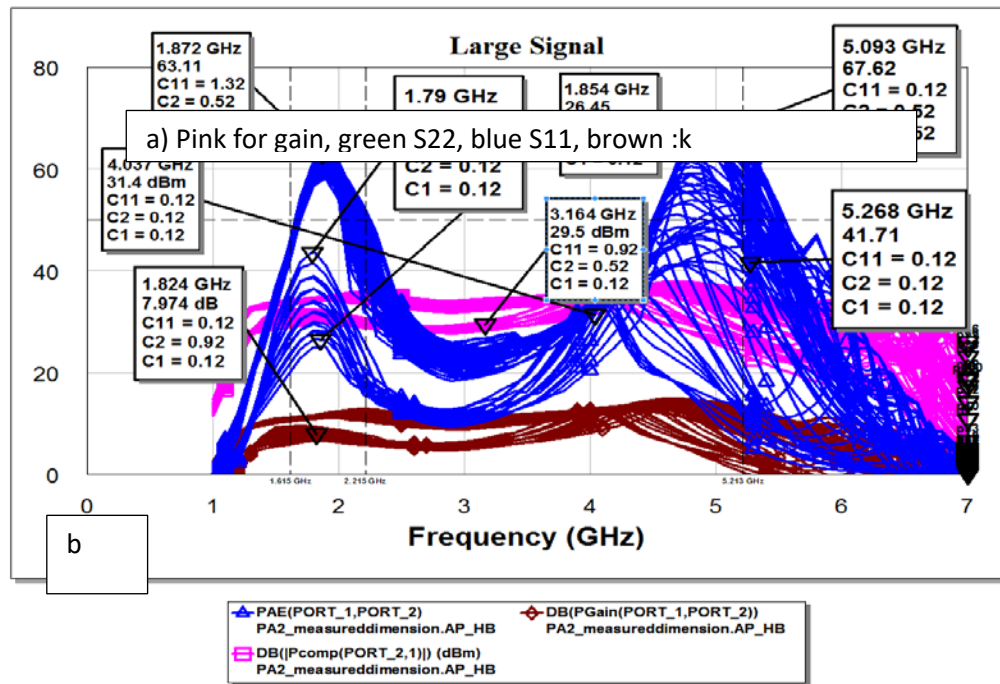
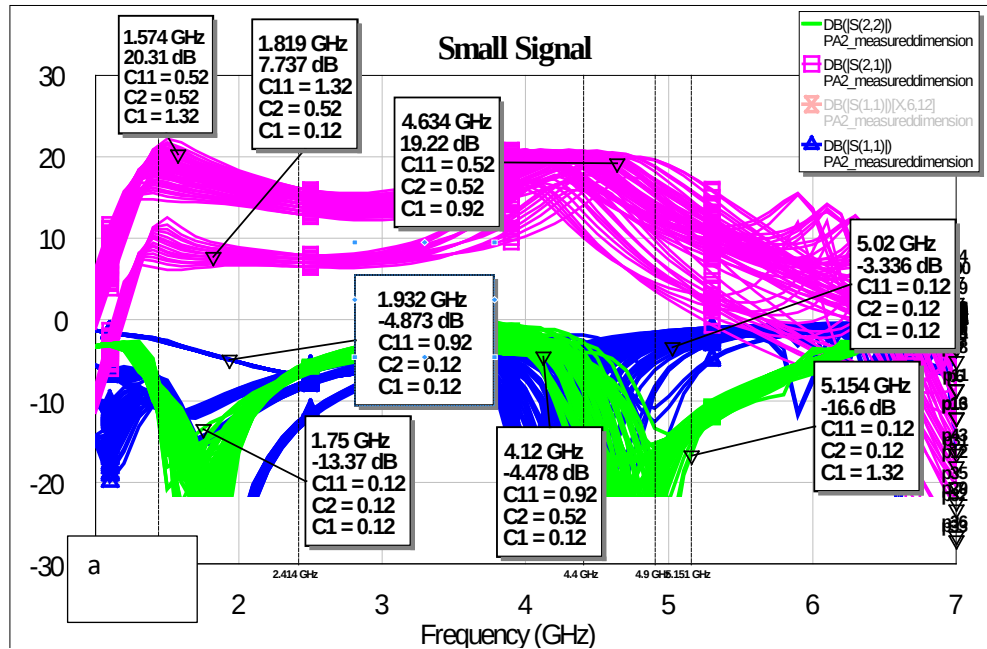


Figure 61: Small (a) and (b) Large signal response varying two capacitors (C11 & C2), blue showing efficiency, pink curve is for output power and brown is for gain in the second graph.

Figure 61 shows the small and large signal response when varying all three capacitors (C1, C11 & C2) values. It can be observed from here too that values of C1 had the most influence.

3.2.5: Reconfigurable PA using Vanadium Dioxide (VO_2) based switch

A reconfigurable PA design using VO_2 based switch has been presented in the next few figures. Figure 62 shows the entire designed circuit and the zoomed view of the section where the switch was used to achieve reconfigurability. When the switch is in the ON state (Figure 63), it provides very good efficiency(>60%) at Lower & Mid C band (for the design presented in figure 62). But complete rejection was not achieved in this design. From Figures 63 & 64, it is observed that when the switch is in the ON state, (by raising the temperature), it provides good efficiencies at the lower & middle C band but, the designed circuit will give good efficiencies for broader and more frequency bands (Upper L, Lower to Middle C Band) for the OFF state status.

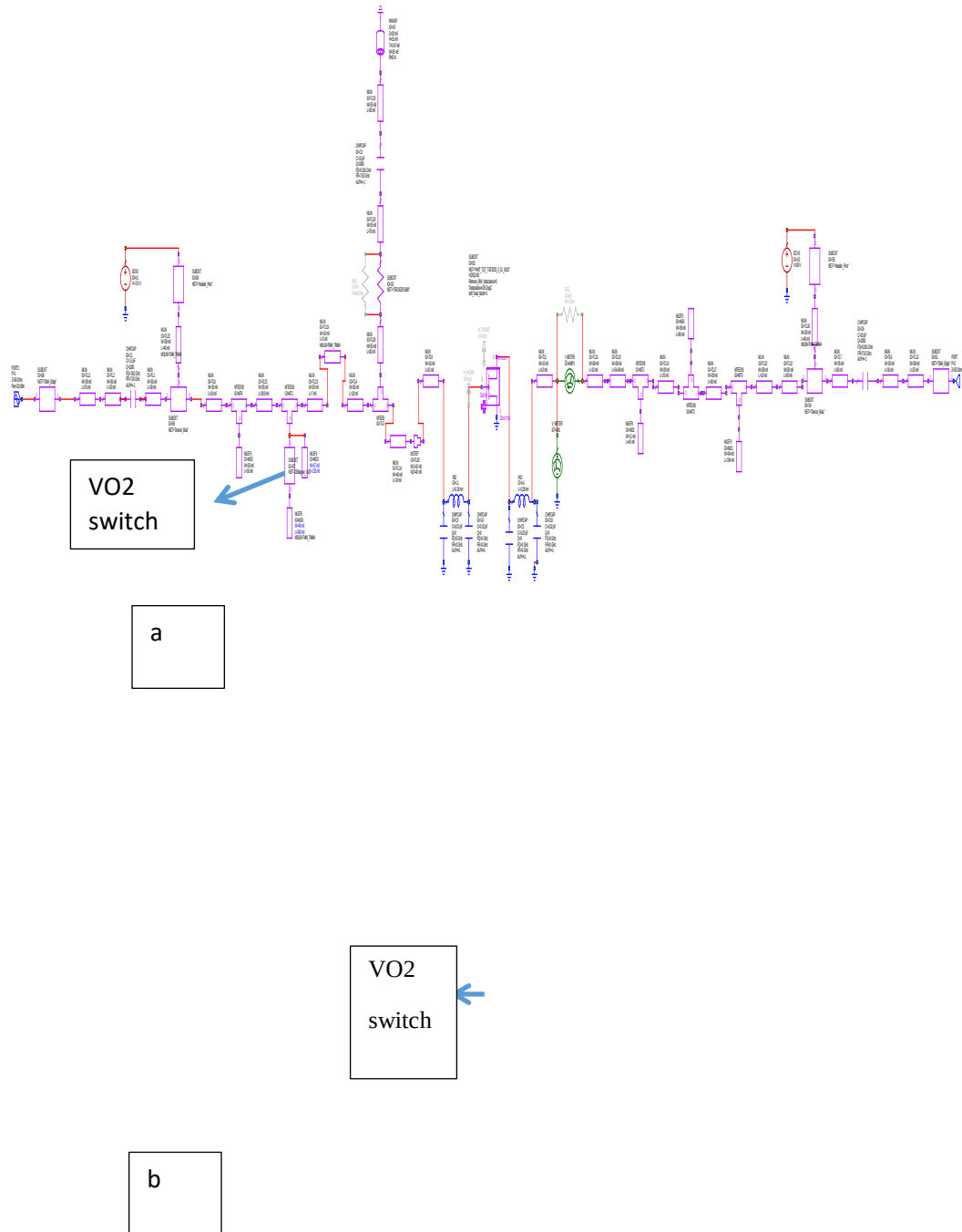


Figure 62: a) The entire schematic and b) The location of the VO_2 switch has been shown.

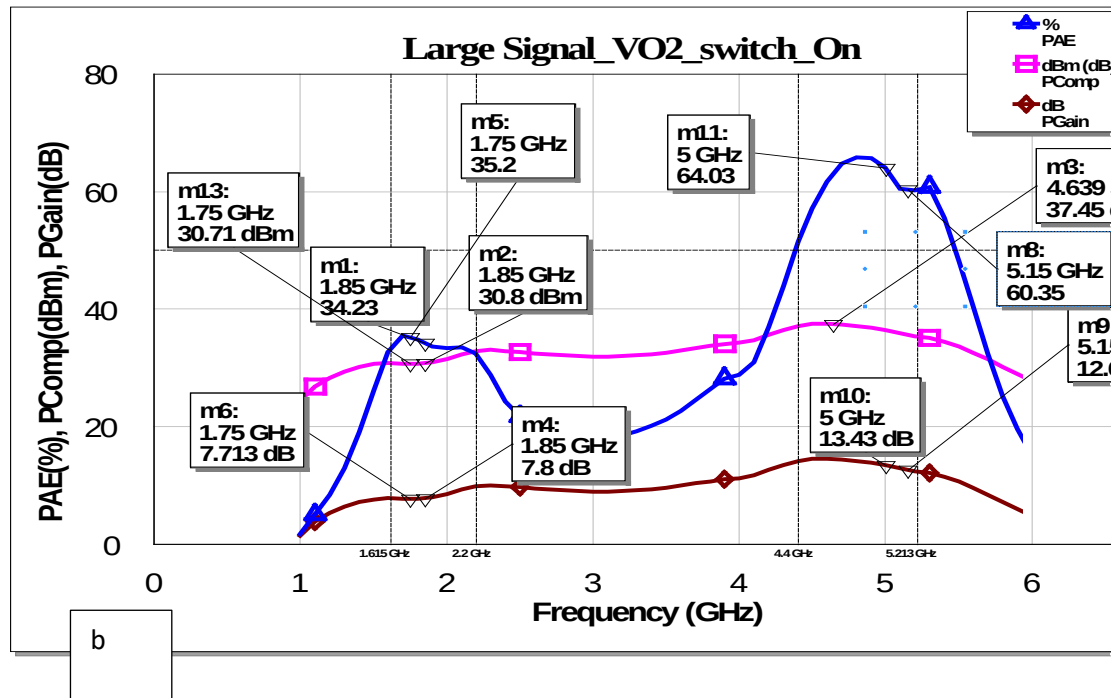
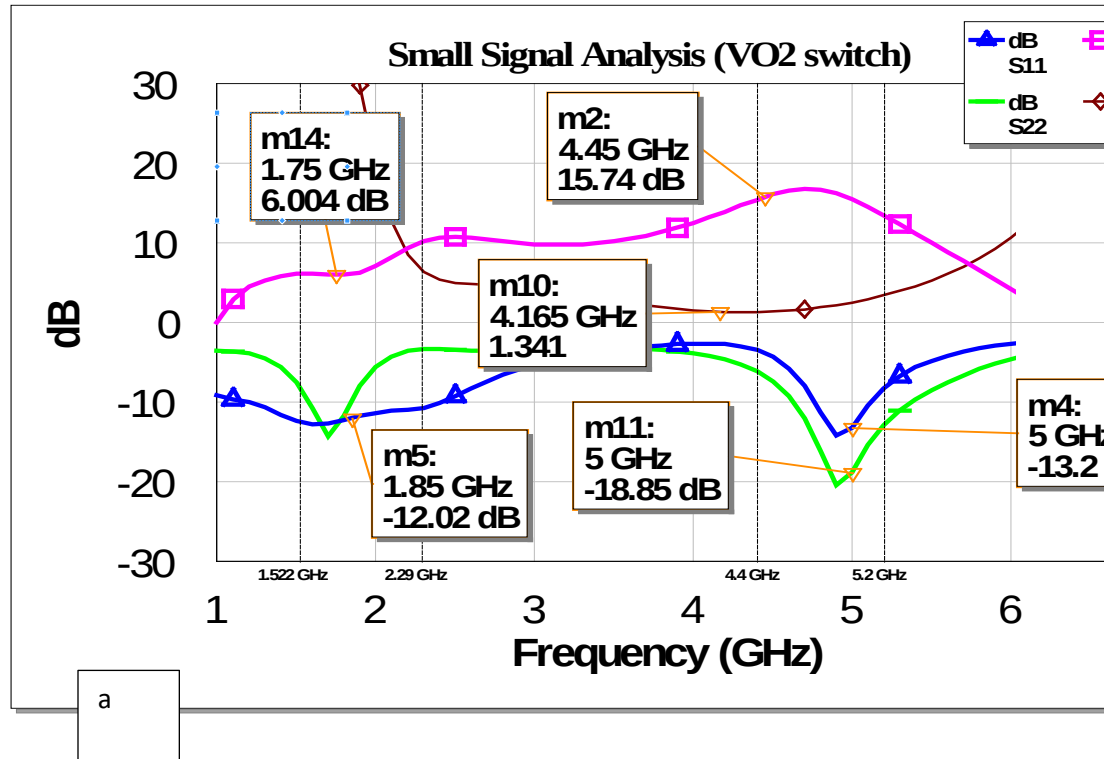


Figure 63: a) Small signal (pink:S21, green:S22, blue:S11, brown: K) b) Large signal (blue:PAE, pink:output power, brown:gain).

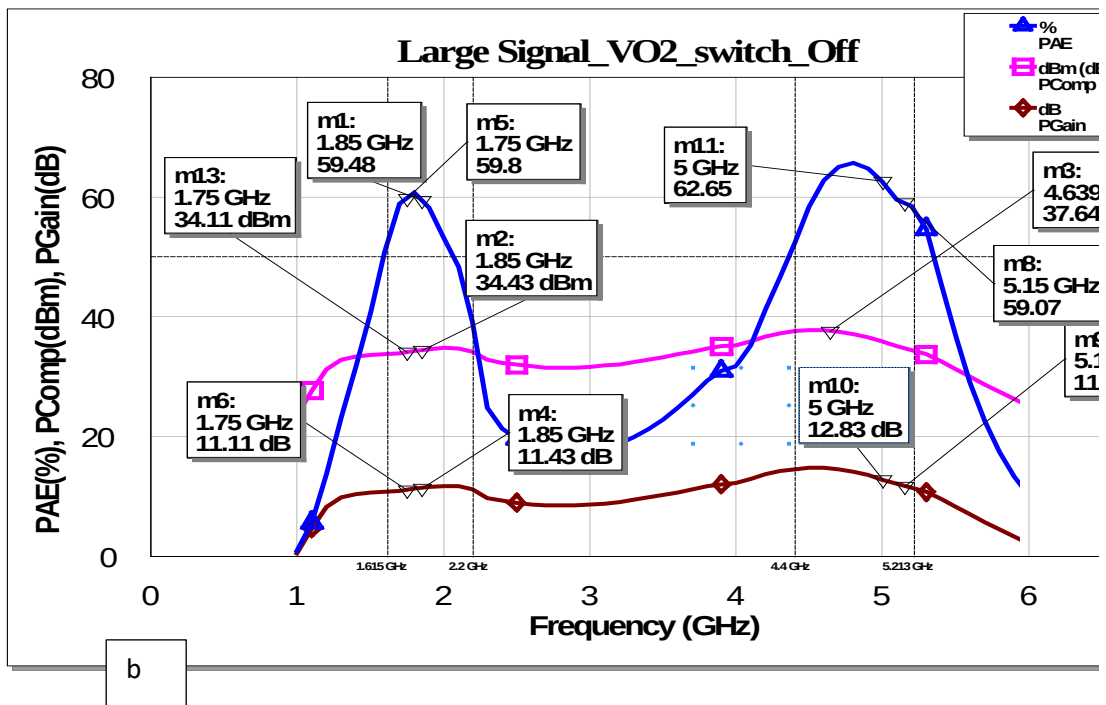
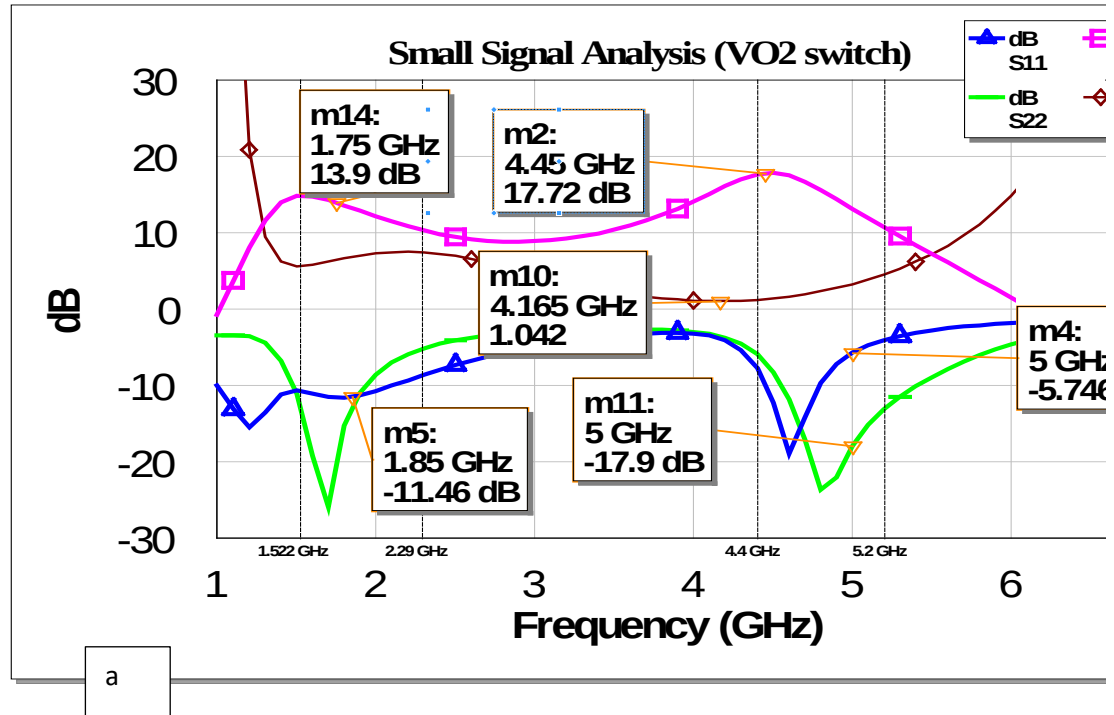


Figure 64: a) Small signal (pink:S21, green:S22, blue:S11, brown: K, b)Large signal(blue:PAE, pink:output power, brown:gain).

Slightly Different Design Simulation Result, ON State

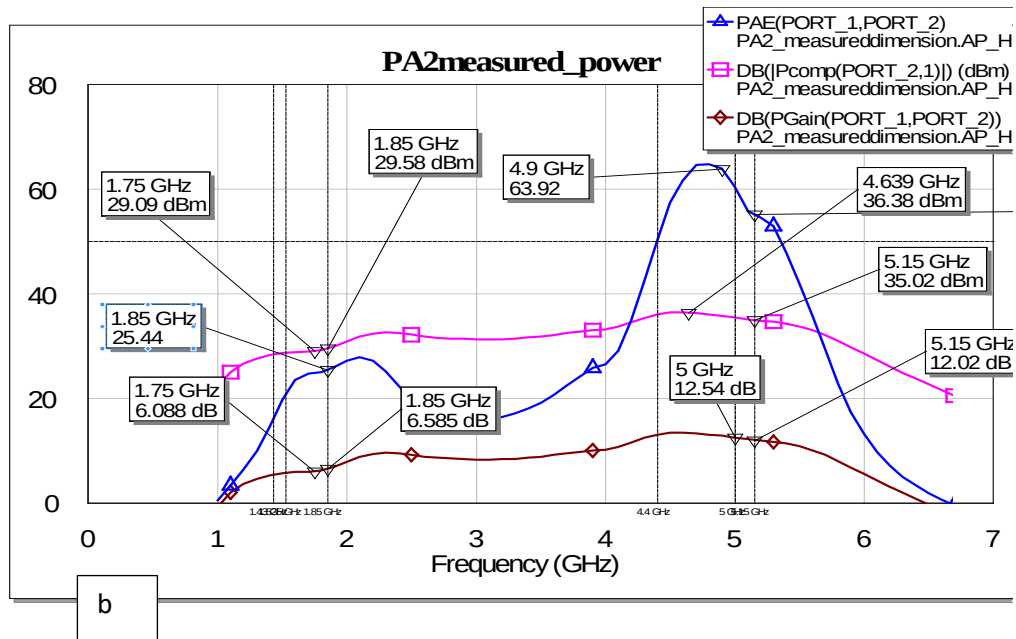
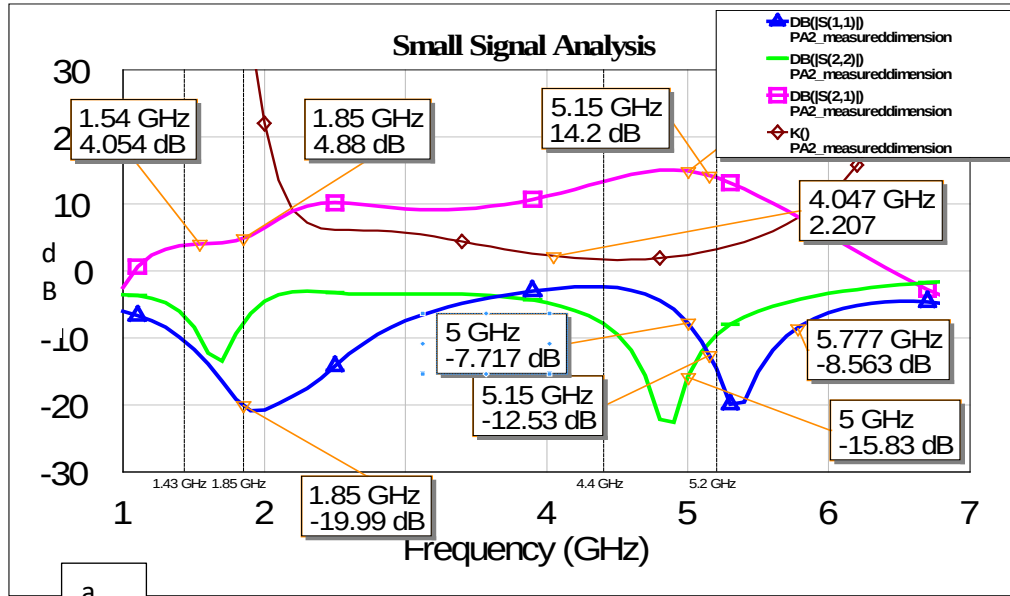


Figure 65: a) Small signal, b) Large signal. When the switch is in the ON state. It provides good efficiency (53%) & gain (14.2%) for lower and mid C band. L & S band are rejected. Better rejection is achieved.

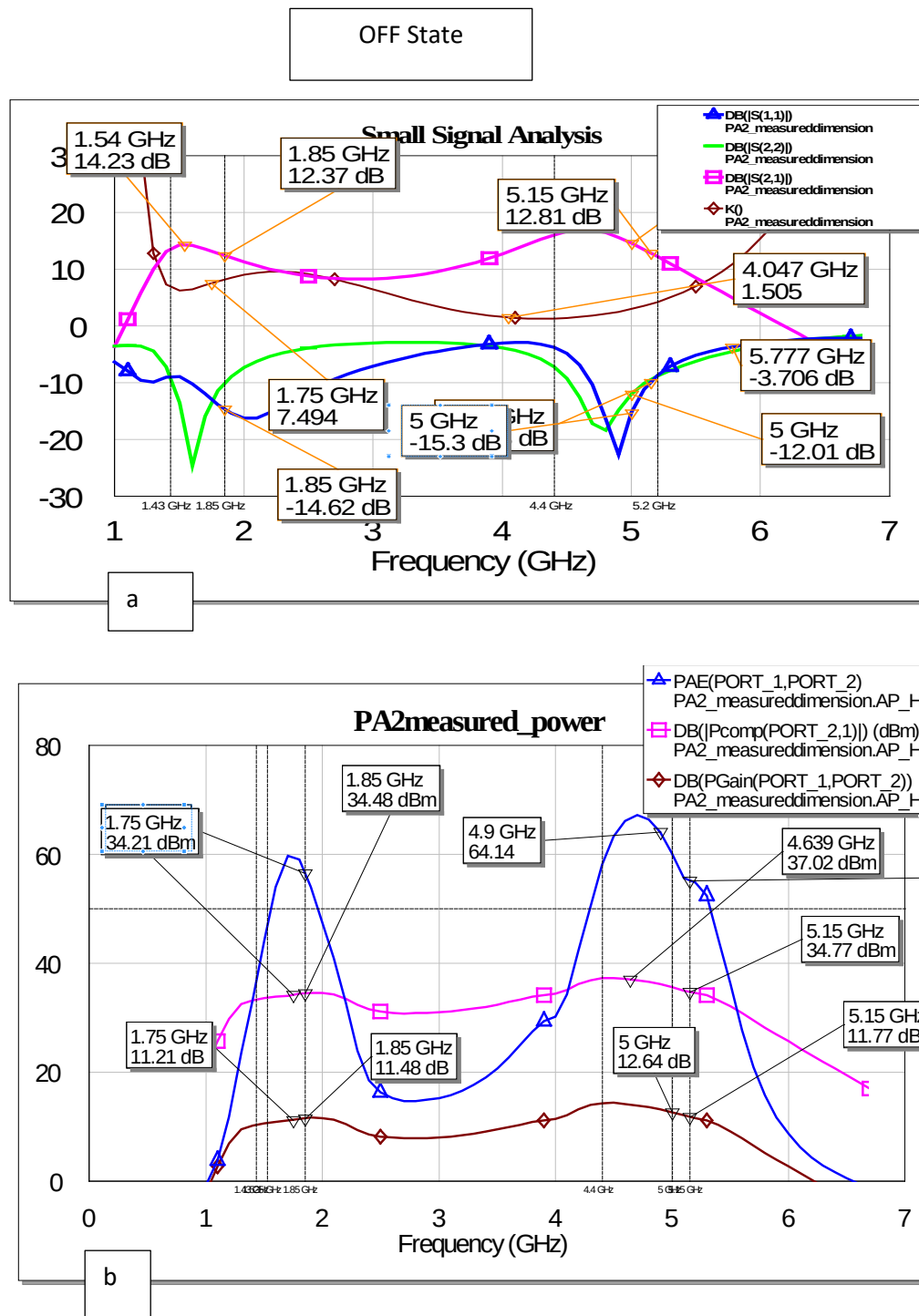


Fig 66: a) Small signal, b) Large signal. When the switch is in the OFF state. It provides very good efficiency(>55%) for multiple bands (lower L to lower S band and lower to mid C band).

Simulation results from a slightly different design have been presented in figures 65 & 66. Figures 65(a) and 65(b) presented better rejection when the switch was in the ON state than the results presented in figures 63 (a) and 63(b). It showed comparable good efficiencies in the Lower to Middle C band in the OFF state . The OFF state results are comparable but better rejection is achieved for this design presented in figure 65(a) and 65(b) for the ON state condition (raising the temperature of the switch to 80 degrees celsius.

The next chapter, chapter IV describes the experimental setup to test the fabricated circuits, test set-up pictures and measured data comparison plots with simulation data. .

CHAPTER IV

MEASUREMENT RESULTS, DISCUSSION AND EXPERIMENTAL SET-UP

The first step in characterizing an amplifier circuit is to measure the small-signal parameters or the S parameters. The main idea behind the scattering parameters is that they relate forward and backward travelling waves on a transmission line. Thus, the S parameters are related to the power flow and are very important to check the performance of the power amplifiers.

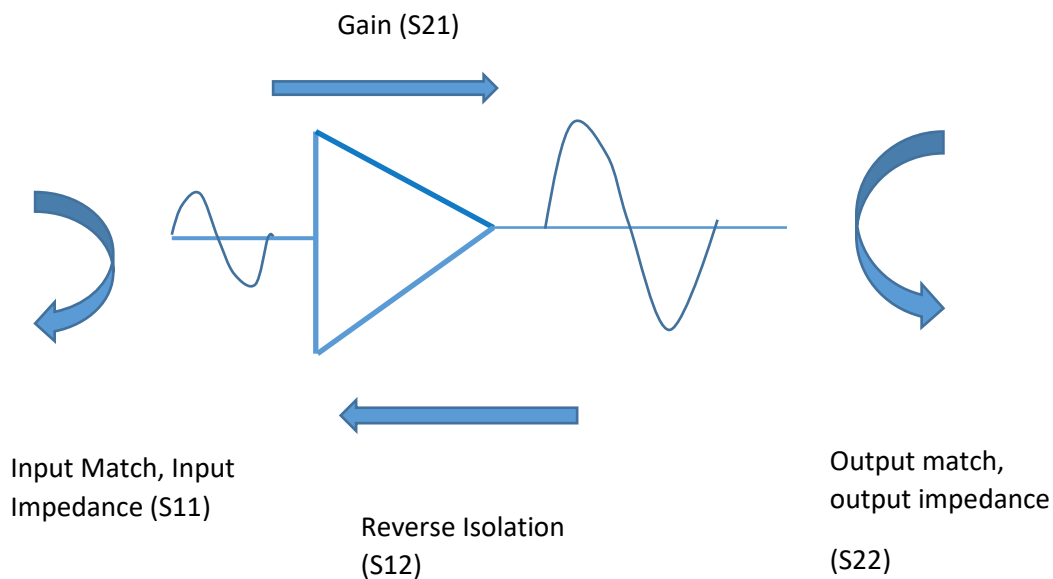


Figure 67: Amplifier S parameter significance (S_{11} , S_{21} , S_{12} , S_{22})

While the small-signal model considers that the signal is so small that the operating point does not change, a large signal, on the other hand, actually affects the operating point. This

type of analysis also considers non-linearity of the elements and can be limited by the power supply values. The test set-up photos and measurement data of fixed concurrent dual-band design and reconfigurable concurrent dual-band design, are presented below and the results from the measurement data are analyzed.

4.1: Measurement methodology & test set up

The vector network analyzer has been used to measure the S parameters. The stability factor k has also been measured to ensure the stability of the amplifier.

RF power meters are the essential instrument to measure the power as the output power level is the most critical factor in many RF applications. Different types of RF power meter and power heads are available. Power heads are basically a sensor that converts the RF signals to analog voltages which the power meter can read and later on displays in a readable format.

There are mostly three types of sensors used in power heads. The first one is based on thermistor sensor and is considered as old-fashioned. The second variation is thermocouple and the third one is diode detector. With the diode detector, very low power (-75dBm) could be measured.

There are two variations of power meter that are used in general. The first one is through-line RF power meter and the second one is absorptive RF power meter. Through-line power meters are used in live systems like radio transmitters to check the outgoing powers. This

type of power meters is frequency independent meaning they basically measure the total power entering into them irrespective of the frequency.

The other approach used in measuring power is utilizing absorption. The power sensor used in this type of meter generates a signal proportional to the power level entering the sensor. Measurements by this type of meter are also frequency independent. It is important to choose the right type of power sensor [46].

Spectrum analyzers can also be used for power measurements as they have power measurement capabilities within them but the issue with the spectrum analyzers are that they are able to measure the RF power level only at a particular frequency. They cannot measure the total power encompassing all frequencies. The power measurement with power meters are generally considered to be more accurate than the spectrum analyzers [46]. Power test bench set-up criteria has been presented in figure 68.

HP Power meter E4419b has been chosen along with Keysight /Agilent N5245A network analyzer for power measurement after analyzing all the factors and the small-signal analysis was performed with the network analyzer. The general block diagram for power measurement has been presented and then the photos of varactor test set up have been shown followed by fixed concurrent dual-band board and reconfigurable dual-band board.

Figure 69 is the varactor test set-up photo with network analyzer and Fig. 70 presents a close-up view of the UD BST wafer (148). Figure 71 shows the fixed concurrent dual-band board and the reconfigurable dual-band board is presented in Fig. 72. Two of the small signal test set-up photos of reconfigurable dual-band board has been presented in Figs. 73(a) and 73(b).

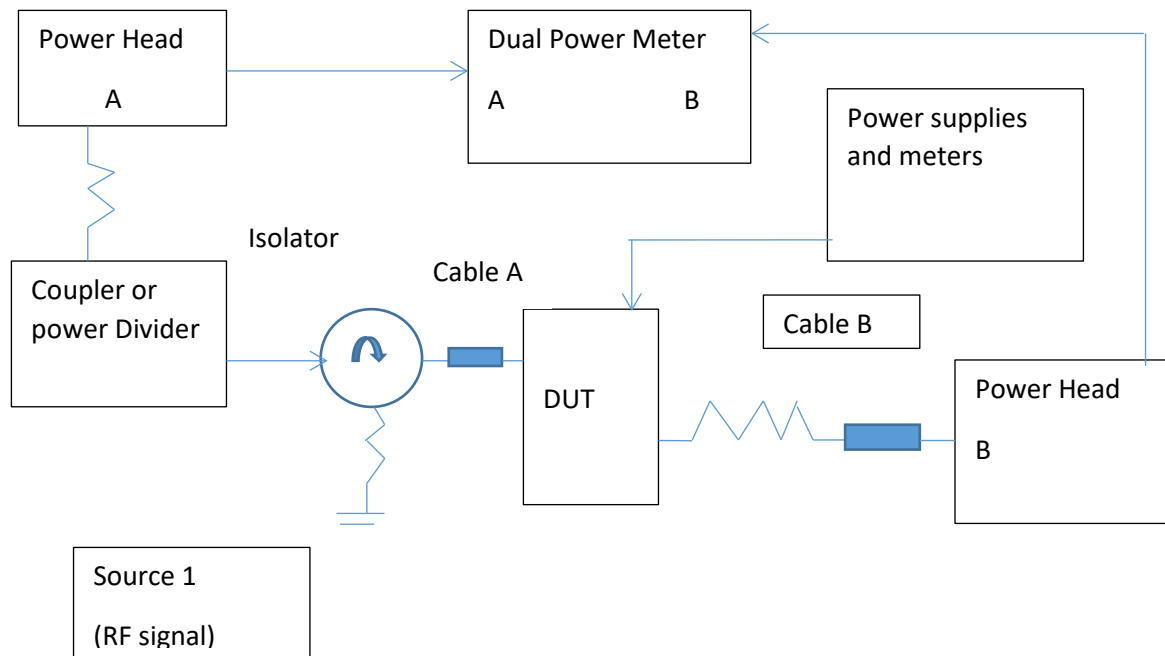


Figure 68: Power test bench.

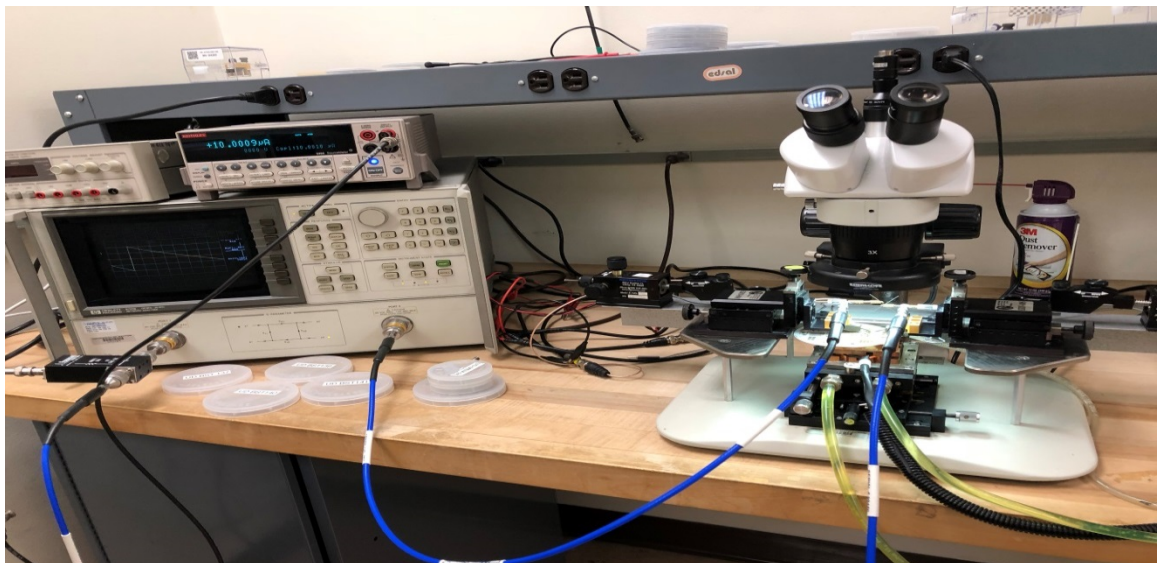


Figure 69: Varactor test set-up with network analyzer

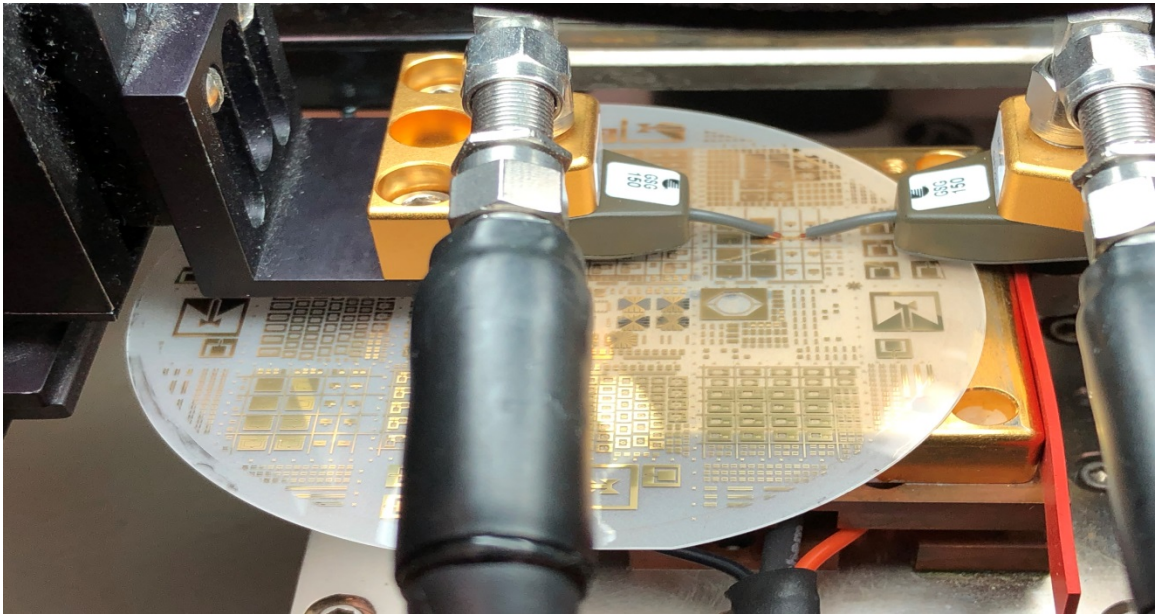


Figure 70: Varactor testing (UD BST 148 wafer)

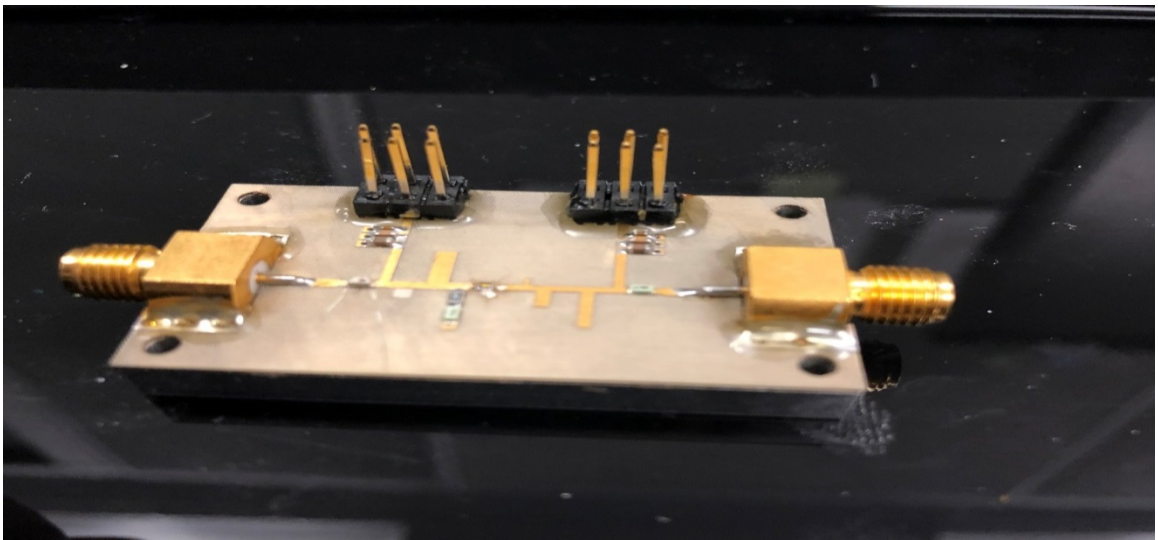


Figure 71: One of the DUT (fixed concurrent dual band board) (no varactors)

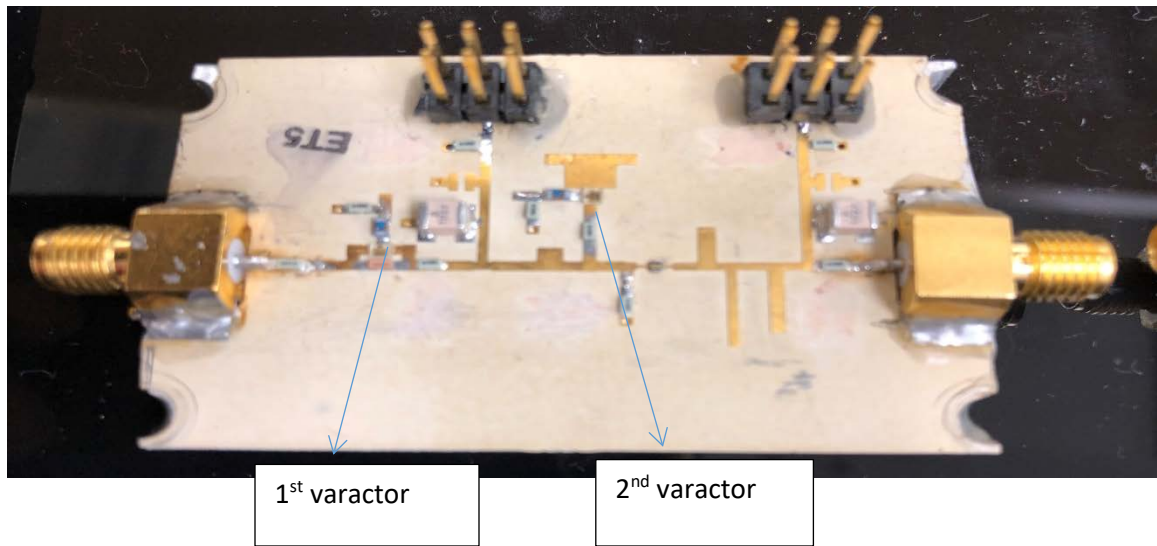
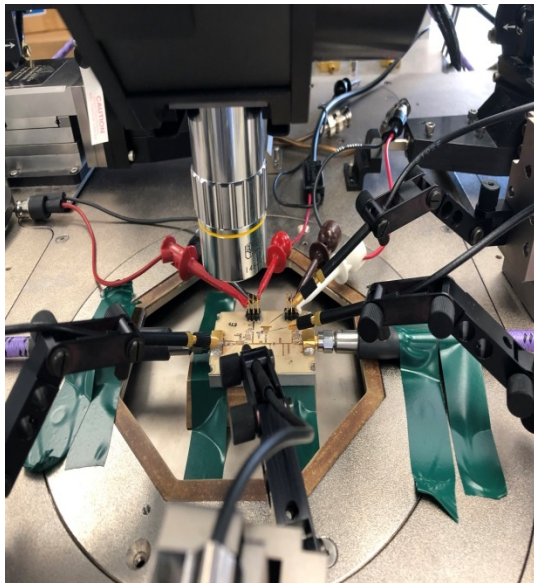
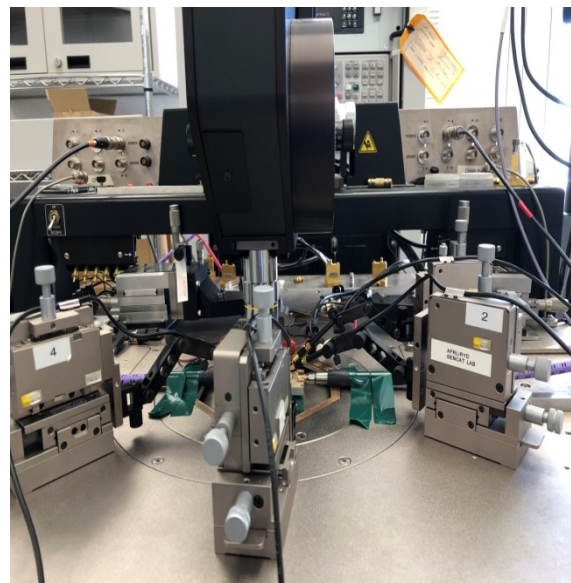


Figure 72: Reconfigurable PA board



a)



b)

Figure 73: a) Close-up view, b) Small signal analysis test set up photo for the reconfigurable board.

4.2: Measurement results and discussions

Small signal measurement data from the fixed concurrent dual-band design has been presented and compared with the simulated data for the input capacitance (input dc blocking capacitor) specification of (C1: 1.5pF, Q:30, FQ:1GHz & FR:16 GHz) and for gate bias voltage of -2.9 V and drain bias voltage of 28V.

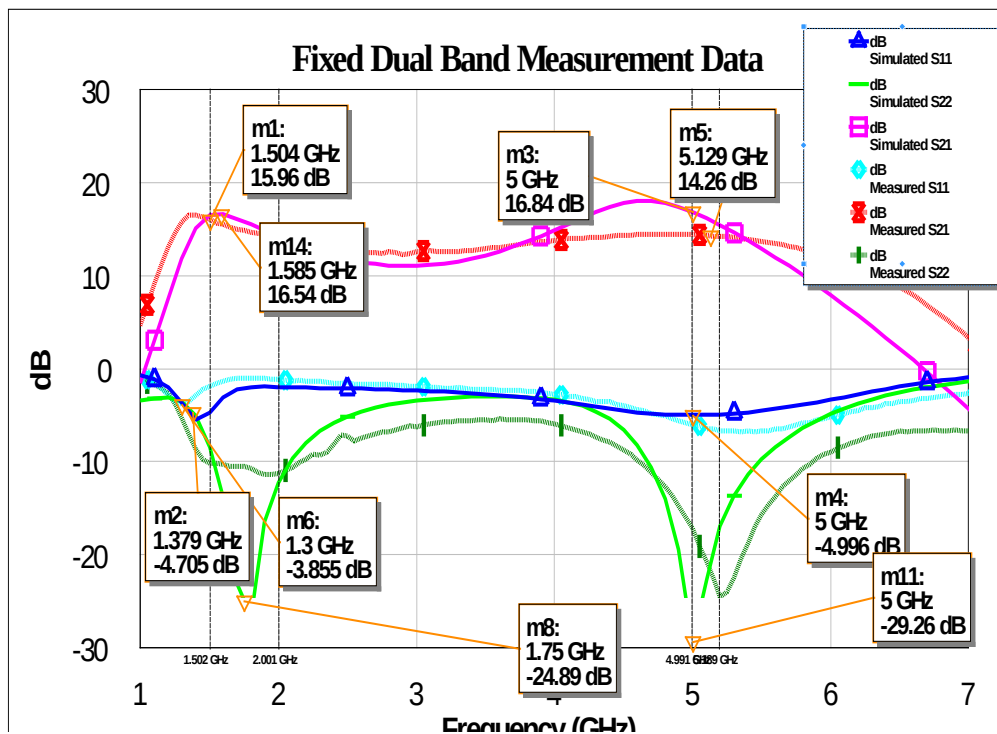


Figure 74: Small signal simulation and measured data comparison (concurrent dual-band)

In Fig. 74, the dotted red line represents measured S21, dotted cyan measured S11, and dotted dark green line measured S22. Whereas, pink represents simulated S21, blue S11 and green S22, respectively. Capacitance C1 and all the other capacitors used for the board

has different specifications than the ones used for original simulation. The original simulation specification of capacitor C1 is (C1:1.5pF Q:1000, FQ:.001GHz, FR:7.98GHz) and the one used for matching with the measured data has specification: (C1: 1.5pF, Q:30, FQ:1GHz & FR:16 GHz). The discrepancy between the simulated results and the measured data is due to the unavailability of the 500S millimeter wave capacitors used for the original simulations. With the use of just one capacitance (dc blocking capacitor at the input side, C1, shown in Fig. 75 of the above specified value, (C1: 1.5pF, Q:30, FQ:1GHz & FR:16 GHz), the simulated data was matched with the measured data. It can be concluded that use of the capacitors of different specifications caused the mismatch of S11. It can be noted from Figs. 74 & 76 that higher efficiency and output power can still be achieved from the fabricated board. Figure 74 presents high gain of 15.96 dB and 14.26 dB at L & C band, respectively; S22 values are better than -10dB at L band and better than -20dB at C band. But the S11 for the L band was -4.7dB and for C band it was better than -6dB. The power measurement data could not be presented as the board got damaged due to an accident but the simulation data for large signal based on the small- signal measurement data shows good efficiency, output power, and gain. For large-signal simulation, the small-signal

parameters and the values of the varactors that displayed better matching with the small signal measured data were used.

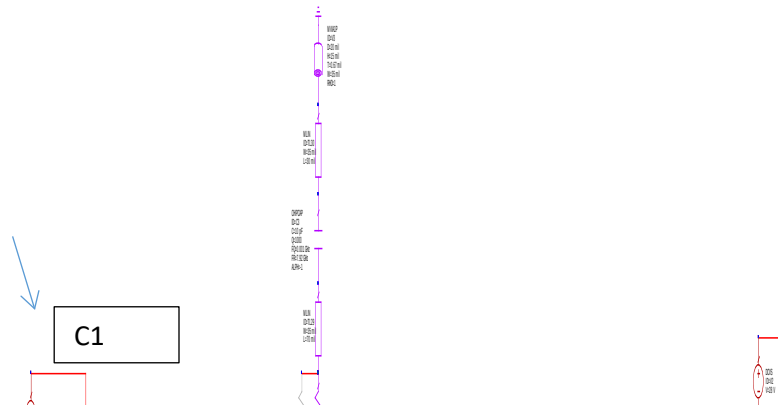


Figure 75: Entire dual band PA circuit showing the location of C1

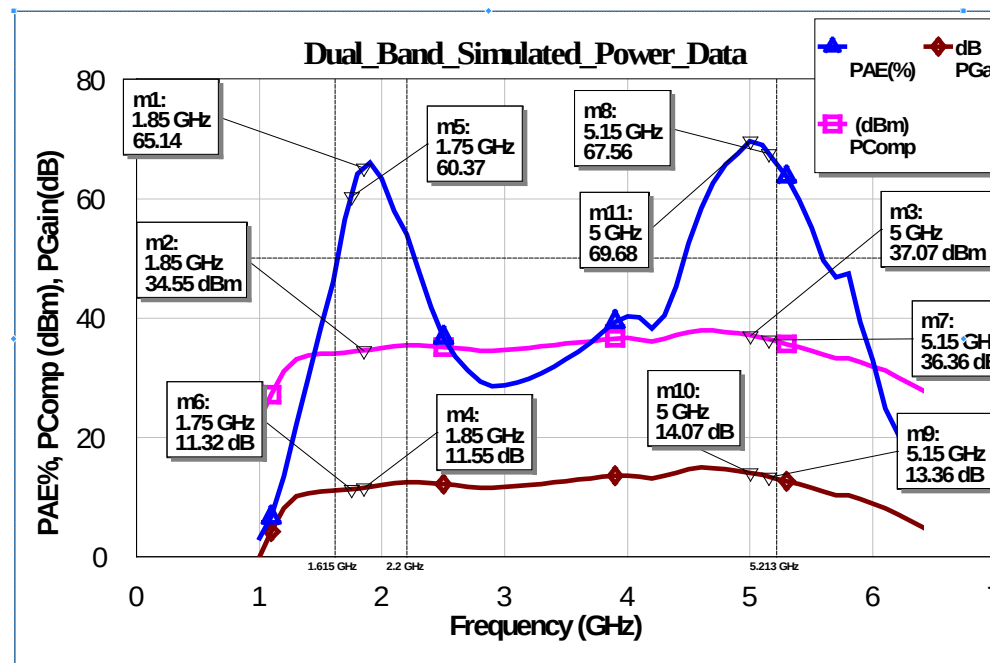


Figure 76: Large signal analysis, PAE in blue, AC gain is in pink and output power in brown.

Figure 76 shows PAE of 65.14%, output power of 34.55dBm and 11.32 dB gain in L band and 67.56% PAE, output power 36.36dBm and 14.07dB gain in C band. Measured and

simulated data of BST varactor used for the reconfigurable board, with zero bias voltage and 6 V bias voltage has been compared in Figs. 77 and 78.

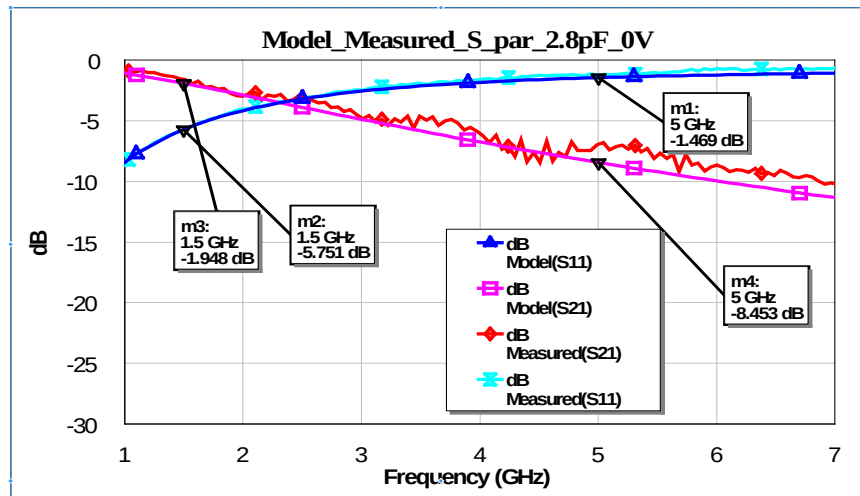


Figure 77: Varactors with 0V bias voltage, measured (S11 in cyan and S21 in red, simulated S21 in pink and S11 in blue) resembles capacitance of value 2.8pF.

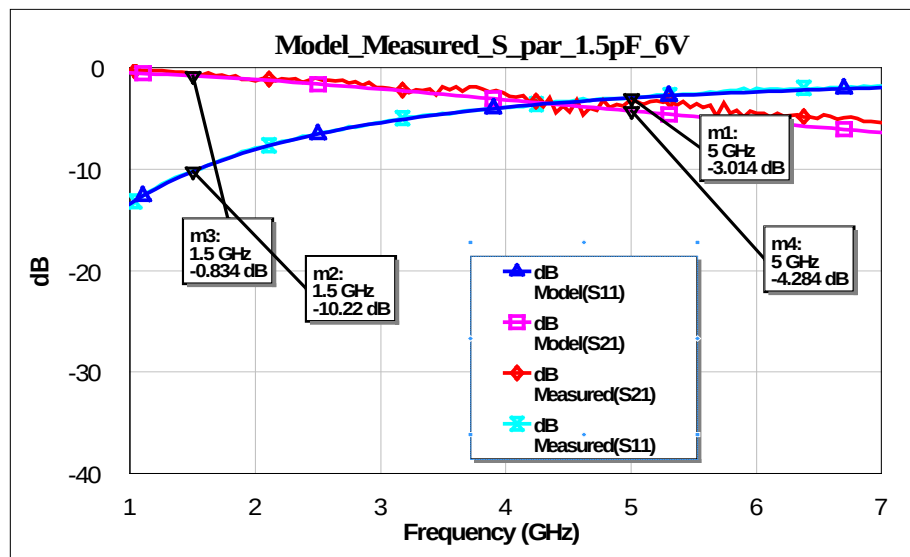


Figure 78: Varactors with 6 V bias voltage, measured (S11 in cyan and S21 in red, simulated S21 in pink and S11 in blue) resembles capacitance of value 1.5 pF.

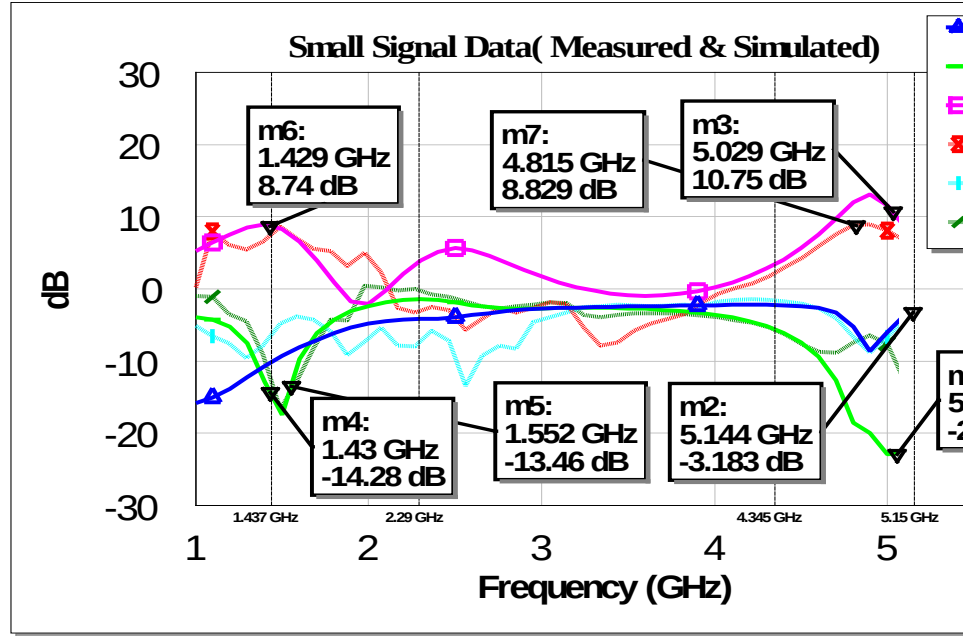


Figure 80: Measured and simulated small signal data comparison for 0v bias.

Two of these varactor devices were used for the reconfigurable PA board. Small-signal measured data from the reconfigurable board is presented in Fig. 80, which matched with simulation data for capacitance value of 1.5pF for both varactors for 0v bias voltage. In Fig. 80, red dotted lines represent measured S21, pink: simulated S21, cyan: measured S11, blue simulated S11. Dotted green is for measured S22 and the solid green is for simulated S22. It is observed that the measured data matched well with the simulation data for capacitance value of 1.5 pF. Figure 81 shows the corresponding efficiency, output power, and ac gain that matched the small-signal simulated data with the measurement data. PAE of 47.4%, gain 7.6dB, and output power of 30 dBm at L band and PAE of 62.75%, gain 10 dB, and output power of 32 dBm was observed in Fig. 81. The measured capacitance value from the varactor wafer (as shown in Figs 77 and 78) are 2.8pF and 1.5pF for 0V and 6V, respectively, resulting in a tuning ratio of less than 2:1.

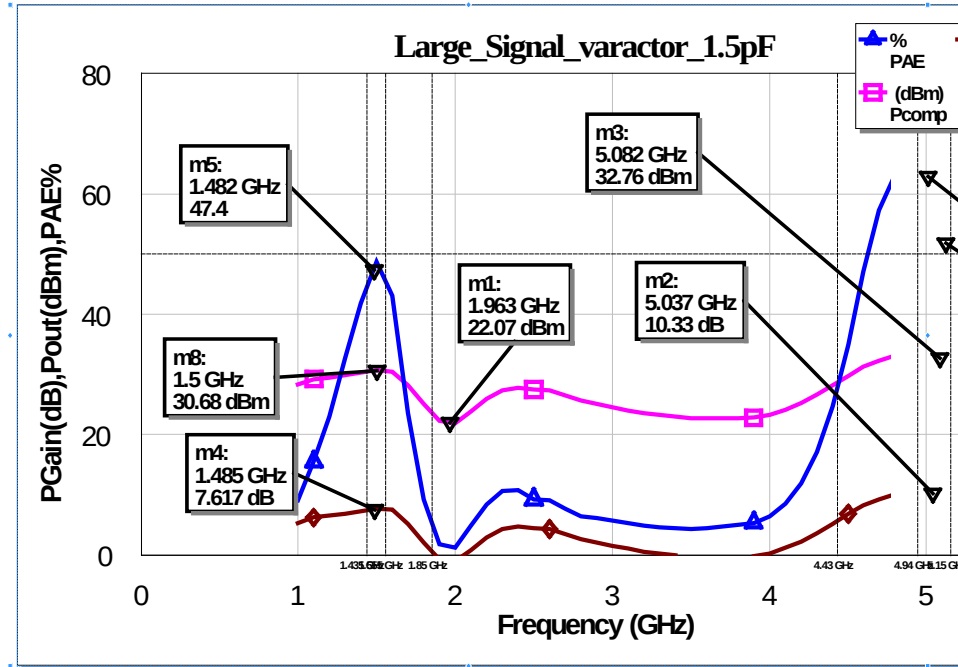


Figure 81: Large signal response for the specifications that matched the small signal measured data (considering both varactor capacitance value 1.5pF).

To achieve better results from reconfigurable dual band board, a new wafer has been fabricated with BST thickness of 500 nm. Higher thickness of BST layer helped in achieving better tunability. The measured data from new varactors showed better tuning (4:1), capacitance variation from (2.0 pF: 0.5pF). The measured S11 data has been presented in figure 82 and S21 data in figure 83 below and compared with the simulated value of 2.0 pF. The board will be tested in near future with these newly developed varactors replacing the older ones.

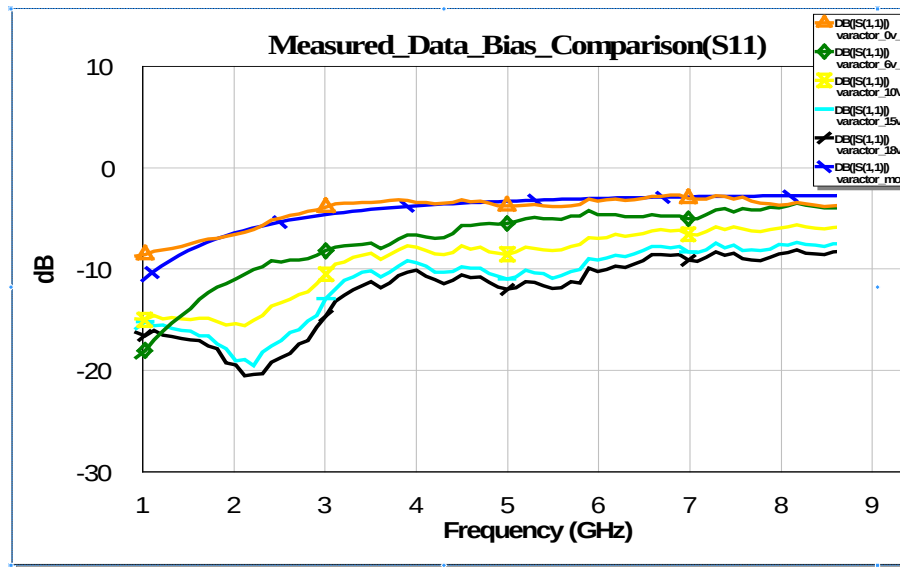


Figure 82: S11 variation with bias voltage (0v to 18v) (UD BST 144)

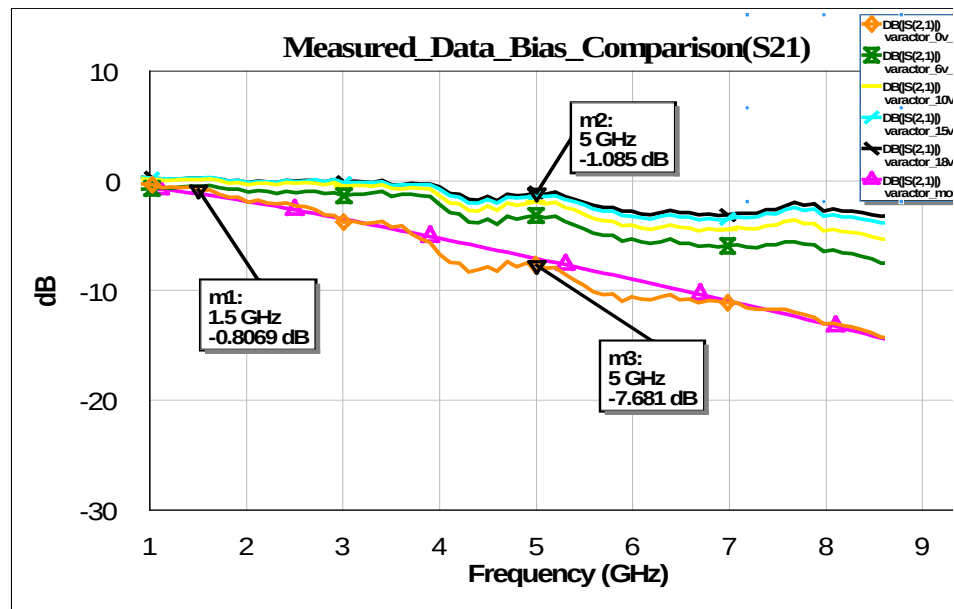


Figure 83: S21 variation with bias voltage (0v to 18v) (UD BST 144)

The value used for simulation is 2.0 pF and the figures 82 and 83 proved that the measured S11 and S21 matched well with the simulated results. The next chapter summarizes the

results from all the designs presented in this research and the scope of the future research work has also been presented.

CHAPTER V

CONCLUSIONS

5.1: Conclusions

The Power Amplifier (PA) is an essential component of many microwave and millimeter wave systems. An issue that arises when working with frequency ranges over an octave bandwidth is that the harmonic frequencies of the lower band begin to overlap with the fundamental frequencies of the higher band. In this research effort, the input and output matching network has been optimized to achieve maximum efficiency for the concurrent dual-band and reconfigurable dual-band amplifiers. Efforts have been made only to match the fundamental frequency in L-band where performance can be sacrificed and to facilitate fundamental and harmonic matching for C-band where high performance efficiency is necessary. A GaN on SiC HEMT transistor amplifier by Qurvo had been characterized and the design steps of a concurrent dual-band power amplifier operating at L- and C- bands has been presented employing 0.25 μ m GaN technology. Analysis of the device characteristics shows that this transistor is capable of delivering up to 6W output power with efficiency greater than 50%. The design of the PA focuses on optimizing the output matching network to achieve excellent power performance at L- and C- bands with $P_{out} > 35\text{dBm}$. Simulated results on various technologies (BST-based varactor, tunable capacitors,

and VO_2 -based switch), for designing reconfigurable power amplifiers based on the concurrent dual-band architecture has been presented. Complete rejection of one of the bands from concurrent dual-band is obtained with BST-based varactor either by applying small amount of bias voltage or without any bias. BST-based varactor also facilitated the fine tuning of the bands allowing the selection of Upper L /Lower L and Lower C/Mid C band in one of the designs. In order to obtain proper BST capacitor values, simulation has been performed by tuning the value of CHIPCAP capacitors and evaluating the relationship between PAE vs capacitance ratios. A detailed analysis has been presented for choosing the correct location and values of the capacitors (varactors) either to select or eliminate one of the bands. VO_2 -based switch was also used in the concurrent dual-band PA architecture and, selection of multiple bands (Lower L to Lower S band, Lower C to Mid C) was obtained by relying on the state of the switch. Rejection of L–S band was achieved by turning the switch on. Measured small-signal data from the fixed concurrent dual-band board, reconfigurable dual-band board, and BST varactor from UD BST 148 have been included in this dissertation and matched with the results from numerical simulation. Measured small-signal results have been presented for both fixed and reconfigurable dual-band board. For plotting PAE, output power, and ac gain, matched values from small signal measured data were used. Efficiency above 50% for the fixed concurrent dual-band board and above 45% for the reconfigurable board has been observed. The electrical model of the BST varactor has been also extracted from the measured data and it showed the capacitance variation of 2.8pF to 1.5pF (approximately 2:1 ratio) for bias voltage of 0v and 6v, respectively. But for the reconfigurable board, the measured data resembled varactor value of 1.5 pF for 0v bias condition.

For the fixed dual-band board, the measured data was matched with the simulated data using a dc blocking capacitor of lower Q value. For the original simulation result, all the millimeter-wave capacitors had higher Q values. Work is underway in testing a set of new varactors with higher tunability.

5.2: Future work

Power measurement will be completed soon to verify how closely the simulation results match with the measured data as shown in Fig. 71. Varactors from various wafers with thicker BST layer for providing better tunability will also be used replacing the current varactors on the reconfigurable board and measurement data will be compared. Further research will be performed to test their ability to reject one of the bands as well as their shifting capacity. Both BST-based varactor and VO_2 -based switch will be used to improve the efficiency and output power of the amplifier. The reconfigurable PA with the designs concepts discussed here will be fabricated in the near future and the performance will be compared with the result of simulation. The impact of the resulting work will be significant because of the limited nature of published work in the reconfigurable concurrent dual-band area of the telemetry band that employs BST-based varactor and/or VO_2 -based switches.

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