DESIGN OF HIGH POWER AND EFFICIENT RF LDMOS PA FOR ISM APPLICATIONS

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Abstruct

Very high performance in power and efficiency radio frequency (RF) laterally diffused MOS (LDMOS) Class AB power amplifier (PA) designed, prototyped and tested for industrial, scientific, medical (ISM) applications at 2.4 GHz-2.5 GHz.

The design started with the load pull measurements. The impedances are chosen to be matched on the printed circuit board (PCB) by the best performance tradeoff.

The lumped element (LE) models are created for the input and output of the transistor to represent the source pull and load pull impedances to be matched on the PCB for the whole ISM band. In Advanced design system (ADS) from Agilent the LE passive networks represented onto source pull and load pull impedances over a large bandwidth and includes the internal resonance frequencies of the device. This fitting will diminish small discontinuities in the selected load pull points as the impedances represented by the models are smoothened representations and behave in a realistic physical way as compared to randomly picked points. These LE passive models are crucial for designing the PCB matching networks due to their large bandwidth and impedance coverage in between the selected load pull frequency points.

ADS used for LE matching networks optimization for the input and output matching circuits. Further optimization is done in the replacing the LE matching components to strip lines. The fine tuning of the RF LDMOS PA is done in 3D electromagnetic solver in ADS to achieve the desired performance.

The cost effective solution of ceramic package (SOT539A3) with internal low pass at the input and internal shunt inductor (Inshin) low pass at the output matching networks device has achieved 315.3 W powers and 57 % efficiency at 2.4 GHz which can be used to replace not only magnetrons used in microwave ovens for cooking, heating, drying, plasma generator for automotive application and medical developed various probes and ablation tools but also niche applications in ISM band.

Introduction

RF LDMOS PA is dominating as a cost effective technology for frequencies ranging from 1 MHz to greater than 3.5 GHz. The cellular infrastructure market has been benefited from it [1-7].

The performance achieved in this design clearly open the door for ISM band niche applications. In microwave oven RF LDMOS PAs not only replace the magnetrons used but also make different beams with phase shifters to cook different food gradient with the desired beams for each gradient. Different heating and drying applications can use this cost effective solution. In medical applications disposable probes and ablation tools can be possible with this low cost solution.

Inshin with low pass configuration was selected due to friendly impedances to match at the printed circuit board (PCB) for the internal matching at the output and low pass for the internal matching at the input. PCB matching network designed from the load pull data in 3D electromagnetic solver facility in advanced design system (ADS) from Agilent. Measurement results shows ultra high performance achieved which is required for niche applications in ISM band.

Inshin low pass variant and load pull data

Figure 1 show different internal matching topologies, improved Inshin, Inshin with back bond and Inshin with low pass variants considered for the output. Inshin with low pass configuration used in the device BLF2425M7L(S)250P for internal matching at the output due to its high performance and more friendly impedances to match on the PCB as shown in the Table 1.

TABLE I. OPTIMUM LOAD PULL DATA

Freq (GHz)	Zsource	Zload	Gain (dB)	Eff (%)
2.4	2.2-5.9j	3.2-2.6j	16.8	55.6
2.45	2.9-6.1j	3.8-2.4j	16.9	54.4
2.5	3.7-6.3j	3.2-2.9j	17.0	54.4

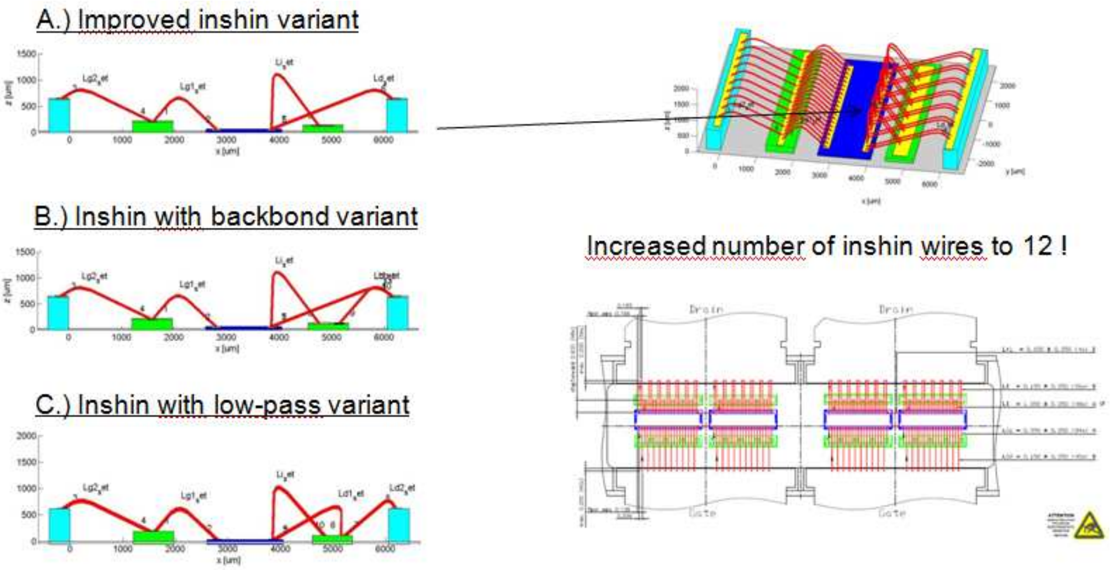


Figure 1. Different configurations considered for internal matching of BLF2425M7L(S)250P.

PCB design from load pull data

Load pull data is used to design the PCB matching network on RO4350B, 0.762 mm. The resistive impedance of the LDMOS devices is inversely proportional to the output power. The impedance matching network losses increase exponentially as the resistive impedance decreased. Due to this effect the multi order matching network require for high performance over the broad band.

Load pull and source pull impedances are represented by the LE passive network which covers the whole band of interest including the internal resonance frequencies of the device. Input matching network need to cover the whole band which can be limited by the high internal gate capacitance and very low gate resistance. Output matching network require minimizing the losses as they degrade the overall performance.

Figure 2 shows the schematic used for extracting the LE replacement model from the input circuitry of the RF LDMOS transistor. The input resonance frequency is measured in small signal measurements for pre-matched devices at 100-300 MHz above the band of interest due to high capacitance comparing with large signal to avoid the resonance within ISM band. Low pass topology is used to ensure the physical behavior of the model is the same as the actual transistor with the correct parasitics like Cpackage (Capacitance of an empty package.), Cprematch (Capacitance value of the pre-match capacitor. Multiply the capacitance by the number of input capacitor dies included in the package) and Cgs (The input capacitance of the active die. Multiply the capacitance by the number of dies used.).

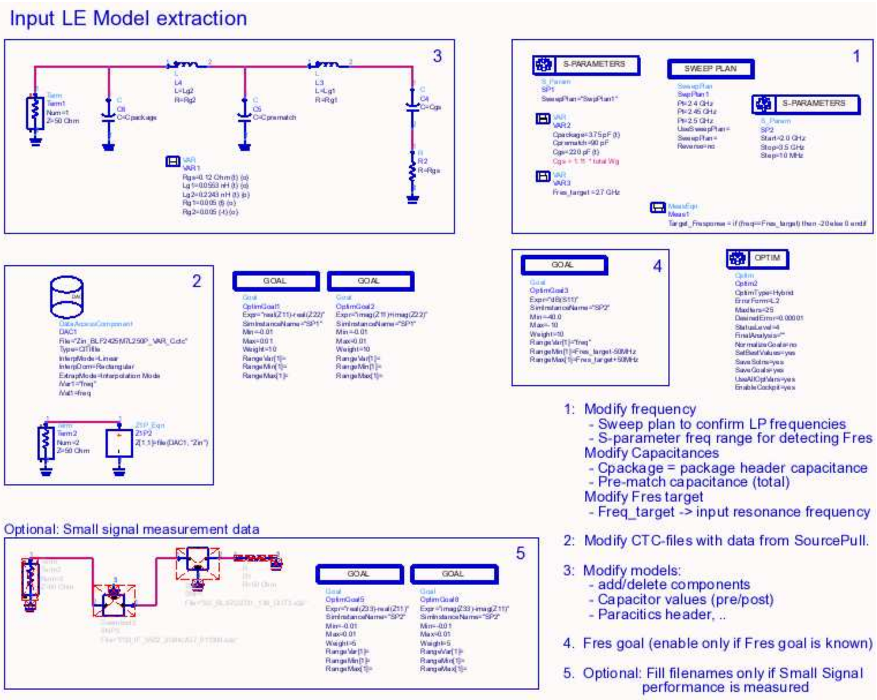
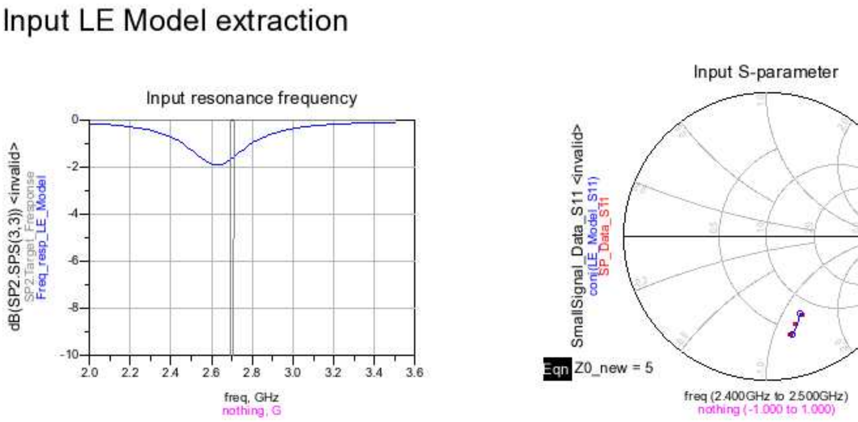


Figure 2. Input LE model extraction schematic with low pass topology.

Figure 3 shows the extracted passive LE model for the input nicely fitted in the resonance frequency and the source pull data on the Smith chart.



Input Impedances Model vs measured device

freq	LE_Model_Zin	SP_Data_Zin	..al_Data_Zin <invalid>
2.40 GHz	2.14 + j5.98	2.20 - j5.90	
2.45 GHz	2.83 + j6.17	2.90 - j6.10	
2.50 GHz	3.72 + j6.13	3.70 - j6.30	

Formulas

Eqn LE_Model_S11 = stos(SP1.SP.S(1,1),50,Z0_new)
Eqn SP_Data_S11 = stos(SP1.SP.S(2,2),50,Z0_new)
Eqn SmallSignal_Data_S11=conj(stos(SP1.SP.S(3,3),50,Z0_new))
Eqn Freq_resp_LE_Model = dB(SP2.SP.S(1,1))
Eqn LE_Model_Zin = stoz(LE_Model_S11,Z0_new)
Eqn SP_Data_Zin=stoz(SP_Data_S11,Z0_new)
Eqn SmallSignal_Data_Zin=stoz(SmallSignal_Data_S11,Z0_new)

Figure 3. Input LE model extraction graphs for the input resonance frequency and source pull data impedances.

Figure 4 shows the schematic used for extracting the LE replacement model from the output circuitry of the RF LDMOS transistor. The output resonance frequency is measured in small signal measurements for pre-matched devices at 100-300 MHz below the band of interest due to high capacitance comparing with large signal to avoid the resonance within ISM band. As shown in the figure 4 the topology is used to ensure the physical behavior of the model is the same as the actual transistor with the correct parasitics like Cpackage (Capacitance of an empty package.), Cpostmatch and CIp (Capacitance value of the post-match and Inshin capacitors. Multiply the capacitance by the number of output capacitor dies included in the package) and Cds (The output capacitance of the active die. Multiply the capacitance by the number of dies used.).

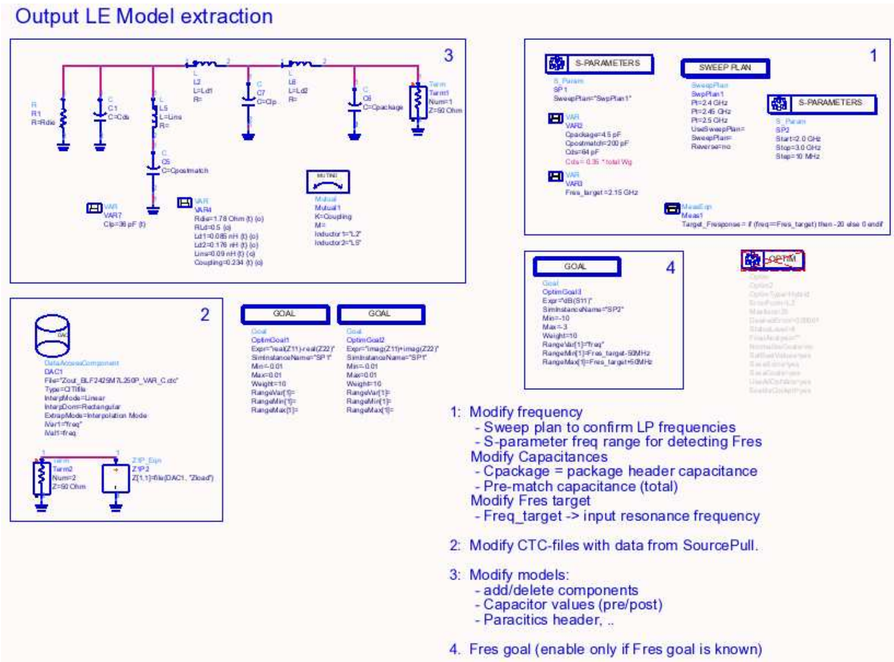


Figure 4. Output LE model extraction schematic of Inshin with low pass topology.

Figure 5 shows the extracted passive LE model for the output nicely fitted in the resonance frequency and the load pull data on the Smith chart.

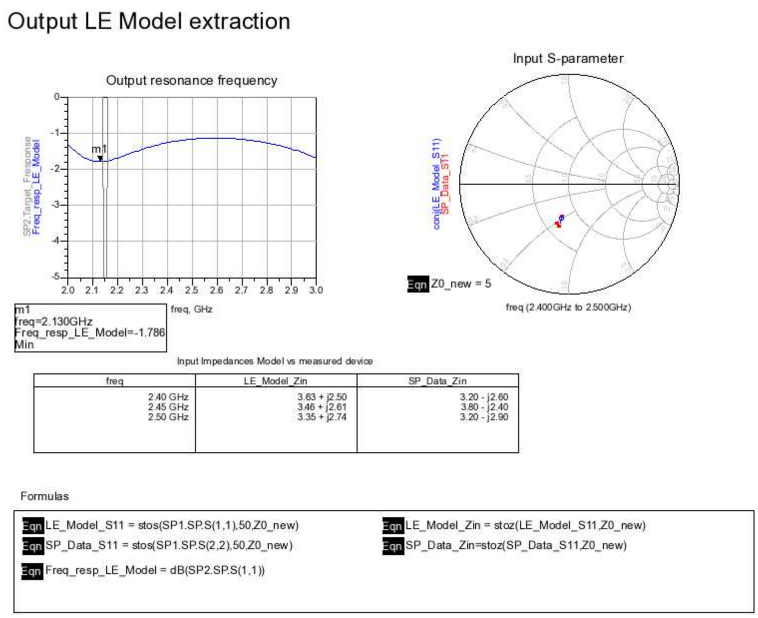


Figure 5. Output LE model extraction graphs for the output resonance frequency and load pull data impedances.

The schematic used for input data set generation is shown in the figure 6. This data will be very useful for brand band matching network hunt in the following steps.\

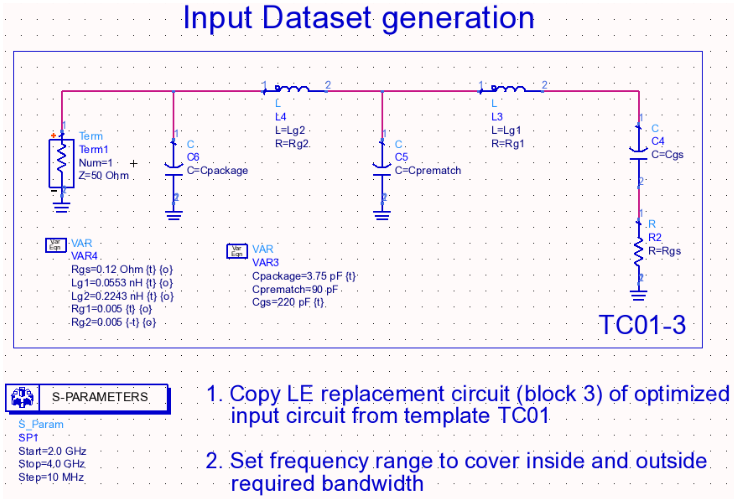
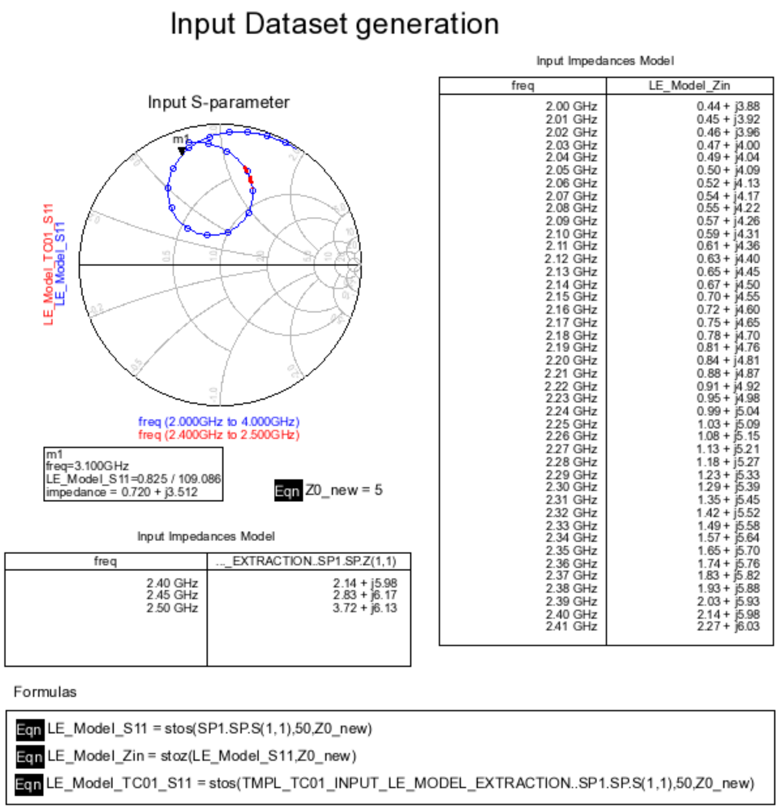


Figure 6. Input data set generation schematic of low pass topology.

Figure 7 shows the input data set generated. The simulated impedances of the LE model are shown at the opposite of the horizontal axis as compared to figure 3 which is conjugate impedances. Data set generated is verified in the table and on the Smith chart.



freq	..._EXTRACTION.SP1.SP.Z(1,1)
2.40 GHz	2.14 + j5.98
2.45 GHz	2.83 + j6.17
2.50 GHz	3.72 + j6.13

freq	LE_Model_Zin
2.00 GHz	0.44 + j3.88
2.01 GHz	0.45 + j3.92
2.02 GHz	0.46 + j3.96
2.03 GHz	0.47 + j4.00
2.04 GHz	0.49 + j4.04
2.05 GHz	0.50 + j4.09
2.06 GHz	0.52 + j4.13
2.07 GHz	0.54 + j4.17
2.08 GHz	0.55 + j4.22
2.09 GHz	0.57 + j4.26
2.10 GHz	0.59 + j4.31
2.11 GHz	0.61 + j4.36
2.12 GHz	0.63 + j4.40
2.13 GHz	0.65 + j4.45
2.14 GHz	0.67 + j4.50
2.15 GHz	0.70 + j4.55
2.16 GHz	0.72 + j4.60
2.17 GHz	0.75 + j4.65
2.18 GHz	0.78 + j4.70
2.19 GHz	0.81 + j4.76
2.20 GHz	0.84 + j4.81
2.21 GHz	0.88 + j4.87
2.22 GHz	0.91 + j4.92
2.23 GHz	0.95 + j4.98
2.24 GHz	0.99 + j5.04
2.25 GHz	1.03 + j5.09
2.26 GHz	1.08 + j5.15
2.27 GHz	1.13 + j5.21
2.28 GHz	1.18 + j5.27
2.29 GHz	1.23 + j5.33
2.30 GHz	1.29 + j5.39
2.31 GHz	1.35 + j5.45
2.32 GHz	1.42 + j5.52
2.33 GHz	1.49 + j5.58
2.34 GHz	1.57 + j5.64
2.35 GHz	1.65 + j5.70
2.36 GHz	1.74 + j5.76
2.37 GHz	1.83 + j5.82
2.38 GHz	1.93 + j5.88
2.39 GHz	2.03 + j5.93
2.40 GHz	2.14 + j5.98
2.41 GHz	2.27 + j6.03

Figure 7. Input data set generated for band of interest.

The low pass matching topology is used for the input and the schematic is shown in the figure 8. Since a complete theoretical approach with computer aided design is lacking in selection of matching topology. Matching can be achieved different number of ways.

Figure 8 drives the matching network to be broadband by limiting the maximum Q factor and take into account the contributions of parasitic inductance and capacitance of the gate-lead landing pad. W-shaped return loss achieved by tuning LE components and the landing pad dimensions.

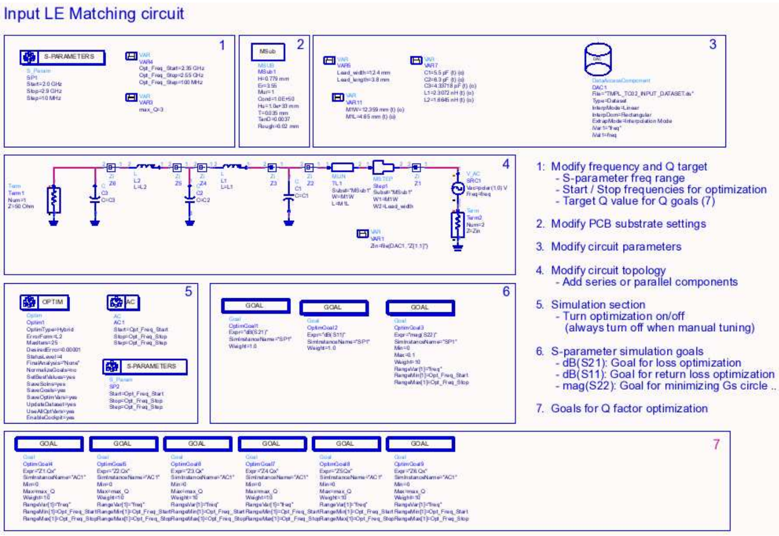


Figure 8. Input LE low pass matching topology.

Figure 9 shows the important parameters simulated for the input low pass matching network. The return loss plot is the important parameter since it indicates how good the network matches the device input model over the frequency band. To make sure that the gain of the device is not jeopardize due to mismatch loss at the input we ought to have return loss more than 10 dB. Circuit loss is also plotted which is important parameter and should be as minimum as possible. Q factor is investigated and shown in the figure 9. The behavior of impedances is shown on the Smith chart. Matching impedances are compared in the tables in the figure 9.

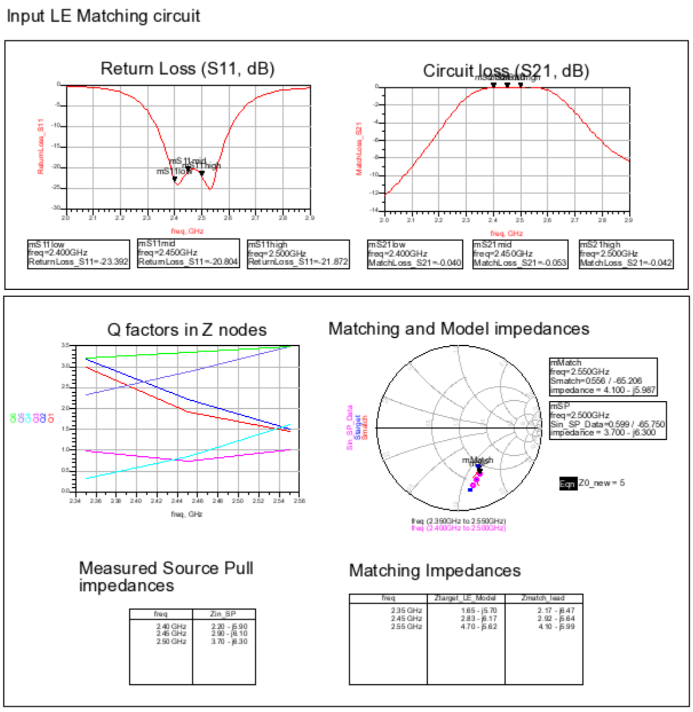


Figure 9. Input simulated data for LE low pass matching circuit topology.

LE matching networks are optimized in ADS for the input and output circuits. Further optimization is done in replacing the LE matching components to strip lines one by one. As shown in the figure 10 the ADS test bench used for the final optimization of output matching network (similarly for the input) to achieve the desired impedances in 3D electromagnetic solver.

Figure 11 compares the load pull impedances and the simulated by momentum in ADS on the Smith chart. The sensitive area has been identified where the metal stub can move the impedances on the Smith chart which is help full for the fine tuning on the bench.

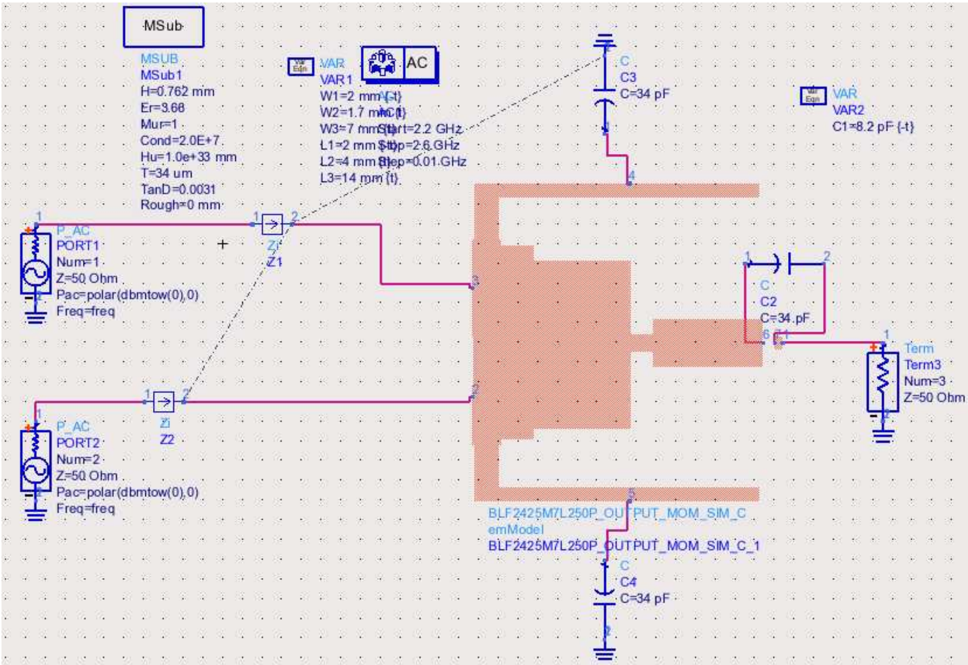


Figure 10. Test becnh for output tuning in 3D electromagnetic solver in ADS.

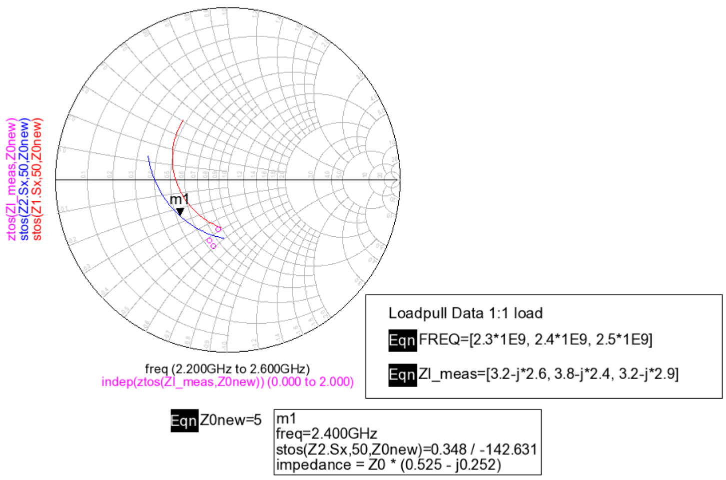


Figure 11. The simulated matched impedances and load pull impedances for broad band matching.

Measured Results

This section contains measurement results of a 2400 MHz - 2500 MHz class-AB RF LDMOS PA design as shown in the figure 12.

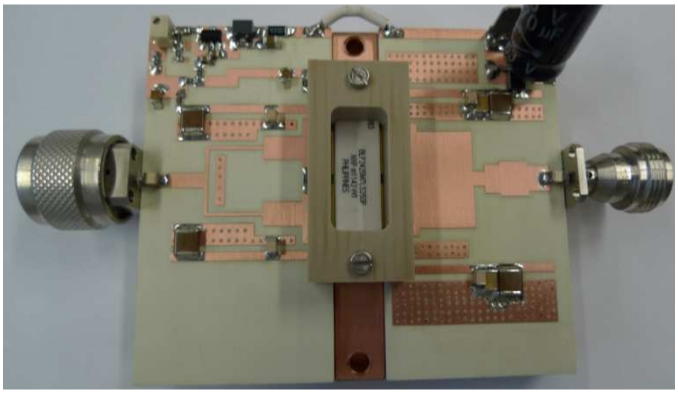


Figure 12. High performance RF LDMOS PA for ISM niche applications.

Pulsed continuous wave with 10% duty cycle, 100 µsec pulse width signal was used to measure the power in the compression. The drain voltage is 28 V and the gate voltage set to achieve 70 mA I_{dq}. Output power versus gain and efficiency are measured with the sweep of input power and the measured results are shown in the figure 13.

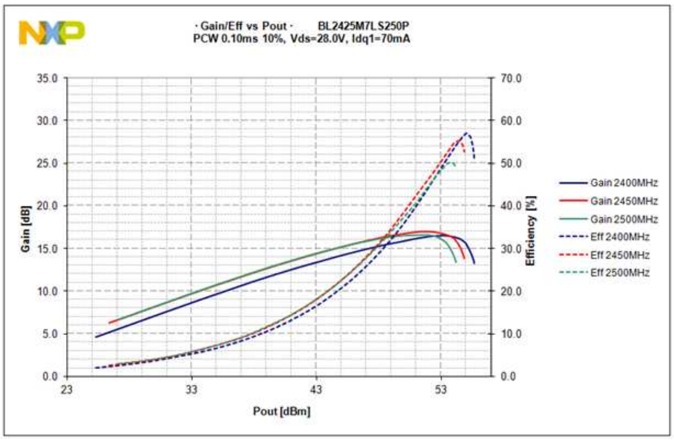


Figure 13. Output power versus gain and efficiency are measured with the sweep of input power.

The summary of target specs with achieved performance is given in the table II.

TABLE II. TYPICAL PERFORMANCE WITH THE TARGET SPECS

Symbol	Parameter	Pulsed CW	Target specs	Unit
V_{ds}	Power supply	28	28	V
f	frequency	2400	2400	MHz
I_{DQ}	Quiescent current	70	-	mA
G_P	Power gain	16.5	> 11	dB
η_D	Drain efficiency	57.0	> 50	%
RL_{in}	Input return loss	-20.1	< -10	dB
$P_{L(1dB)}$	1 dB compression point	55.0	> 54	dBm

Gain and efficiency performance are given in the table III at 1 dB compression point for the ISM band.

TABLE III. GAIN AND EFFICIENCY AT 1 DB COMPRESSION POINT

Freq (GHz)	Gain (dB)	Eff (%)
2.4	15.5	57.0
2.45	16.0	54.9
2.5	15.5	49.8

Peak powers achieved at 3 dB compression point for the ISM band and are given in the table IV.

TABLE IV. PERFORMANCE ACHIEVED AT 3 DB COMPRESSION POINT

Freq (GHz)	P_{-3dB} [dBm]	P_{-3dB} [W]
2.4	55.6	361.5
2.45	54.8	303.4
2.5	54.1	258.5

The performance achieved at 2.4 GHz can be tuned to the rest of the band.

Conclusions

Very high performance in power and efficiency RF LDMOS Class AB PA designed, prototyped and tested for ISM applications at 2.4 GHz-2.5 GHz. The design is based on the load pull data which is represented by the extracted input and output passive LE models of the transistor.

ADS used for LE matching networks optimization for the input and output matching circuits. Further optimization is done in the replacing the LE matching components to strip lines. The fine tuning of the RF LDMOS PA is done in 3D electromagnetic solver in ADS to achieve the desired performance.

The cost effective solution of ceramic package (SOT539A3) of Inshin with low pass device has achieved 315.3 W powers and 57 % efficiency at 2.4 GHz. This RF LDMOS PA can be used to replace the cost effectively not only magnetrons used in microwave ovens for cooking, heating, drying, plasma generator for automotive application and medical developed various probes and ablation tools but also niche applications in the ISM band.

Acknowledgment

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