High Power Amplifier Design with RF-MEMS Output Switch using Sonnet^{TM}

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Abstract: A single-stage GaN HEMT power amplifier with a tunable stub output-matching network using a high power RF-MEMS switch is discussed. A design methodology for testboards including EM effects such as parasitics and coupling and for simulating large- and small-signal performance using Sonnet is given. This reconfigurable PA offers the advantage of providing a stub tuner from 0.9 GHz up to 2.5 GHz, which covers standards for analog and digital cellular telephony. Using the RF-MEMS SPDT switch, the P_{1dB} is increased by over 4 dB. Maximum measured P_{1dB} and drain efficiency are 34.8 dBm and 42 %.

Keywords: Gallium nitride, power amplifier, tunable circuits and devices, radiofrequency microelectromechanical systems.

1. Introduction

Sonnet^{TM} [1] is a powerful EM simulation tool that can be used in the design of design printed circuit boards. Sonnet allows internal ports to be included which are then used in a standard circuit simulator to include effects of SMTs, bond wires, active devices, and MMICs. The designer can layout a board, EM simulate it, and then optimize the SMT values for optimum performance. This procedure can be carried out using only one or two EM simulations of the test board and is similar to tuning methods [2]. Sonnet uses co-calibrated ports in the interior of the circuit. During the simulations, these ports are de-embedded so that the coupling between the ports is removed. This allows for external components like chip inductors, capacitors, and resistors to be connected to the circuit outside of the Sonnet environment. This is useful in the board design because it allows a wide range of SMTs having different values from different vendors to be considered in the test board design. In our earlier paper [3], Sonnet was used to optimize the small signal performance in test boards. In this paper, the design procedure is applied to large signal performance such as P_{1dB} for a power amplifier.

The next generation of wireless applications requires tunable or reconfigurable components to realize multifunctional RF systems. In current broadband RF systems, filtering dominates size and cost [4]. These filters are not tunable and hence limit the usable frequency range of most RF front ends. An alternative to the use of static filters before or after power amplifier is a reconfigurable PA, which can be difficult to design for high performance. The conventional approach for amplifier tuning has been with the use of varactor diodes. The drawback with varactors is that they require a wide analog voltage range for tuning and they are also prone to intermodulation thus decreasing linearity.

In [5], frequency reconfigurability is implemented using an RF-MEMS switch located at the input to the amplifier. In [6], a three-stage reconfigurable PA is described. Here, FET SPST switches are used in the matching networks and a saturated output power of +34 dBm is achieved. In [7], a multi-band matching scheme using a multisection transformer is used for high efficiency power amplifier. The PA is able to achieve 30 dBm output power with maximum power added efficiency of 54%. In our earlier paper [8], a multiband PA with narrow bandwidth was achieved by employing a tunable T-section or π-section interstage matching network whose structure is a bandpass filter. These topologies enable the impedances to intersect with high Q-factor contours on the Smith chart resulting in narrower bandwidth.

In this paper, a reconfigurable GaN power amplifier using an RF-MEMS output switch is described. The advantage of GaN devices is that their load line resistance is higher than conventional pHEMTs resulting in greater bandwidth. The advantage of using a MEMS RF switch over solid state switches is their ability to switch high power levels with high linearity.

2. PA Design Methodology and Fabrication

The power amplifier is a single stage and uses a Cree 40006P 6 watt GaN HEMT [9]. An RF-MEMS switch is used in the output to select shorted stubs for tuning. A high pass matching network is used to tune the input to the amplifier and includes resistive loading to help provide broadband stability. A single-pole double throw (SPDT) high-power RF MEMS switch is used in the output for tuning. The MEMs switch is a Radant RMSW220HP [10]. This switch can handle more than 10 watts of RF power with less than 0.5 dB insertion loss at 10 GHz. The switching speed is less than 10 μsec and the IIP3 is greater than 65 dBm. An actuation voltage of 90 - 100 VDC is required to operate this switch.

The function of the MEMS switch is to select shorted stubs near the drain of the GaN HEMT and tune the output capacitance C_{DS} . At higher frequencies, the presence of C_{DS} (= 1.1 pF) lowers this impedance and must be resonated out to maintain a power match. The two stubs lengths used are 555 mils (14.097 mm) and 200 mils (5.08 mm) and their widths are both 15 mil (0.381 mm). The stubs and MEMS switch were placed close to the HEMT so their simulated resonance frequencies are 1.5 and 2.3 GHz for the long and short stubs, respectively. Stability analysis was performed on the amplifier to ensure unconditional stability. Rollet's condition, where K > 1 and |Δ| < 1 over broadband, is satisfied to achieve stability.

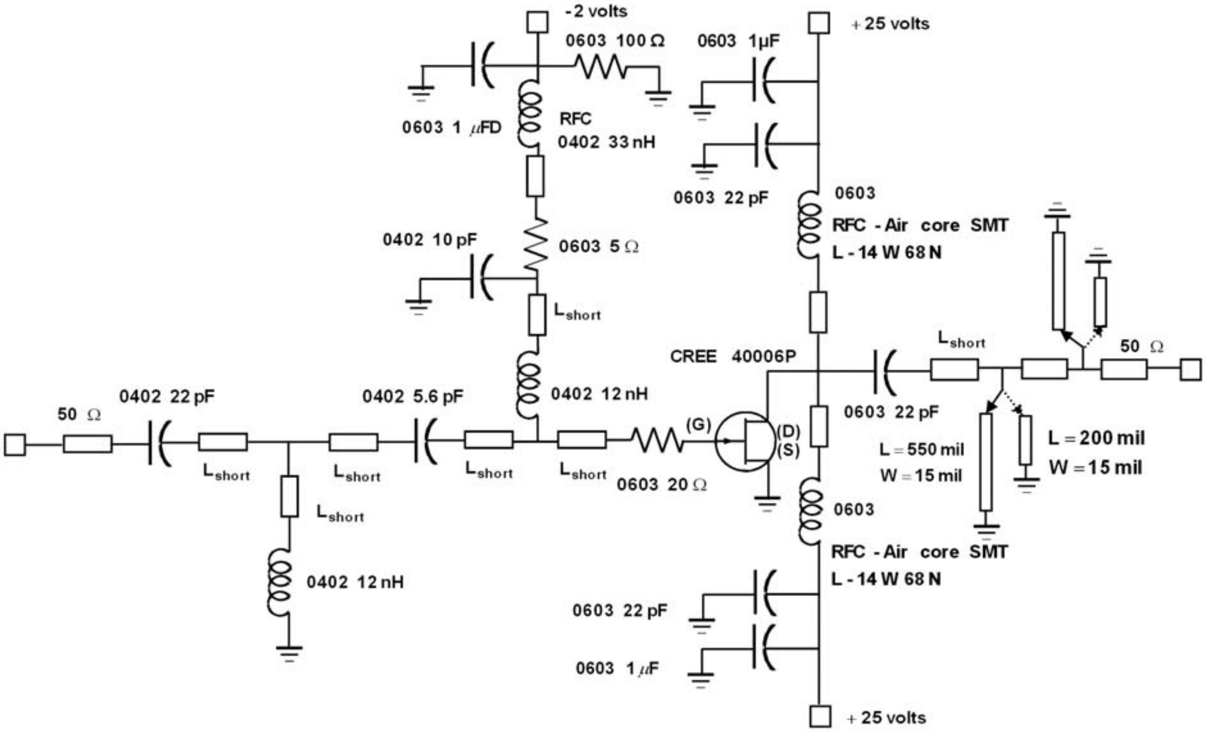


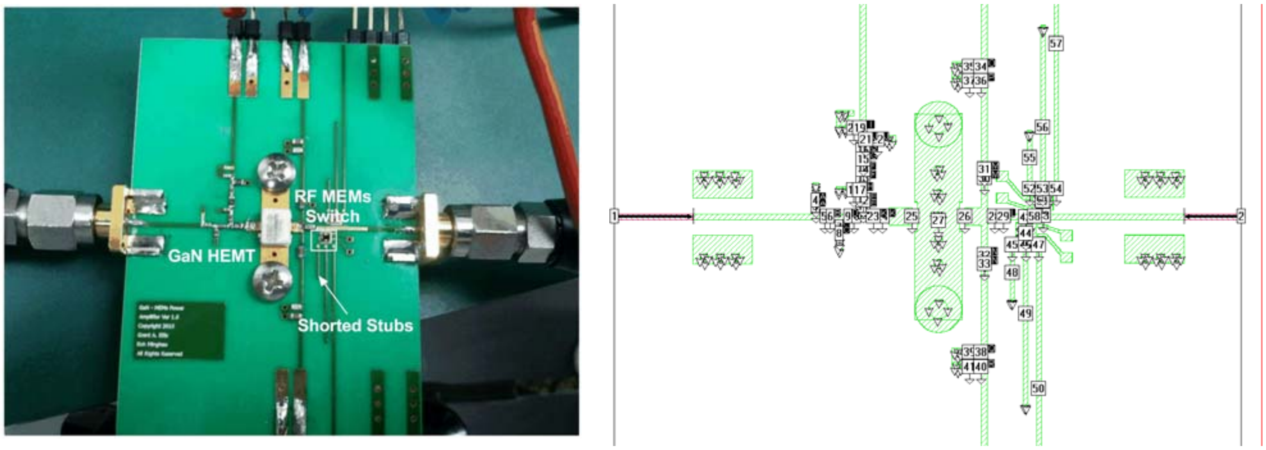
Fig 1. Detailed Schematic of GaN RF-MEMs PA.

A detailed schematic of the GaN RF-MEMs power amplifier is shown in Fig 1. It shows the input matching network and the DC biasing networks. The drain bias network uses two bias feed lines to handle the large amount of DC current. Series inductors and shunt capacitors are placed in the DC power supply lines as RF choke and bypass elements. Also, a 1 μFd bypass capacitor was included in the gate bias line to help provide broadband stability. The gate bias, $V_{gs} = -2$ V, $I_g = 28$ mA and quiescent drain bias, $V_{ds} = 25$ V, $I_d = 288$ mA ($\sim 0.33\ I_{dss}$) are used to operate the amplifier (see Fig 1). Circuit design and DC analysis were done using Agilent Advanced Design System (ADS). Electromagnetic analysis of the PCB board was performed using Sonnet^{TM}.

The power amplifier was fabricated on a printed circuit board as shown in Fig 2 (a). The 3 - layer board consists of a 10 mil thick Duroid top layer ($\varepsilon_r = 3.48$), a 52 mil. thick FR4 backing layer, and a ground plane is located between the Duroid and FR4. The top, inner and bottom metal layers are made of copper. Top and bottom metal are exposed in certain places with immersion gold finishing for wire-bonding and soldering purposes. Half-ounce copper (Cu) with 15 µm thickness is used for all three metal layers. Gold finishing is sputtered on top of nickel (Ni) layer, which is adhesive to copper. The substrate material used between top metal and inner metal is the Roger 4350 with 10 mil thickness with dielectric constant (ε_r) of 3.48, and loss tangent ($\tan\delta$) of 0.004. Between the inner metal and back metal, FR4 is used as the support layer with 52 mil thickness. Initially, layout design of prototype board was done using AutoCAD. The layout was imported to Agilent's Advanced Design System (ADS) 2008, which was then converted to Gerber file (standard file format for PCB fabrication). The back side of the FR4 is used to route the control lines for operation of the MEMS switch and isolate the RF signals from the MEMS control voltage lines. Plated through via holes are used to route the control voltages between the top- and back-sides. Two large stainless steel screws on opposite sides of the HEMT are used to conduct heat to a copper block located on the backside of the board. Wire bonds are used to connect the MEMS switch to the microstrip lines at the output of the HEMT. The PCB dimensions are 4.2 cm x 5.9 cm.

3. Electromagnetic Simulation of Amplifier PCB

Sonnet^{TM} release 12 and 13 were used to perform full-wave EM analysis including the parasitic effects from prototype board for use in the circuit simulations. The top metal layer is the most complex structure. Therefore, only the top metal layer was simulated to reduce the memory requirement of the simulation. The EM simulations were performed at frequency between 0.1 GHz to 14.5 GHz with 0.5 GHz steps to cover up to the 5th harmonic of the highest operating frequency. The field simulation was drawn with cell size of 1 mil. x 1 mil. and box size of 2120 x 2880 cells as shown in Fig. 2(b).



(a) Fabricated GaN HEMT - MEMs PA (b) Sonnet simulation layout of PA PCB

Fig. 2. Layouts of GaN HEMT - MEMS PA.

The simulation also includes the characteristics of Roger substrate as well as the copper layer (thickness and conductivity). Standard ports and co-calibrated ports were included in the simulation so that the Touchstone format data produced by the field simulator can be integrated in the schematic simulation. There are 56 co-calibrated ports (internal ports) included in the simulation. Fig. 3 shows the hybrid EM-circuit simulation for a reconfigurable power amplifier [3]. In addition to the SMTs and bond wires, this test board, also, has two MMIC die [3]. The Touchstone data from prototype board's EM-simulation was integrated in the ADS schematic simulation using the data file tool. The other parasitic effects that are not accounted for in the S-parameter block, such as wirebonds, bondpads, and vias between top metal to bottom metal, are included using the built in ADS models.

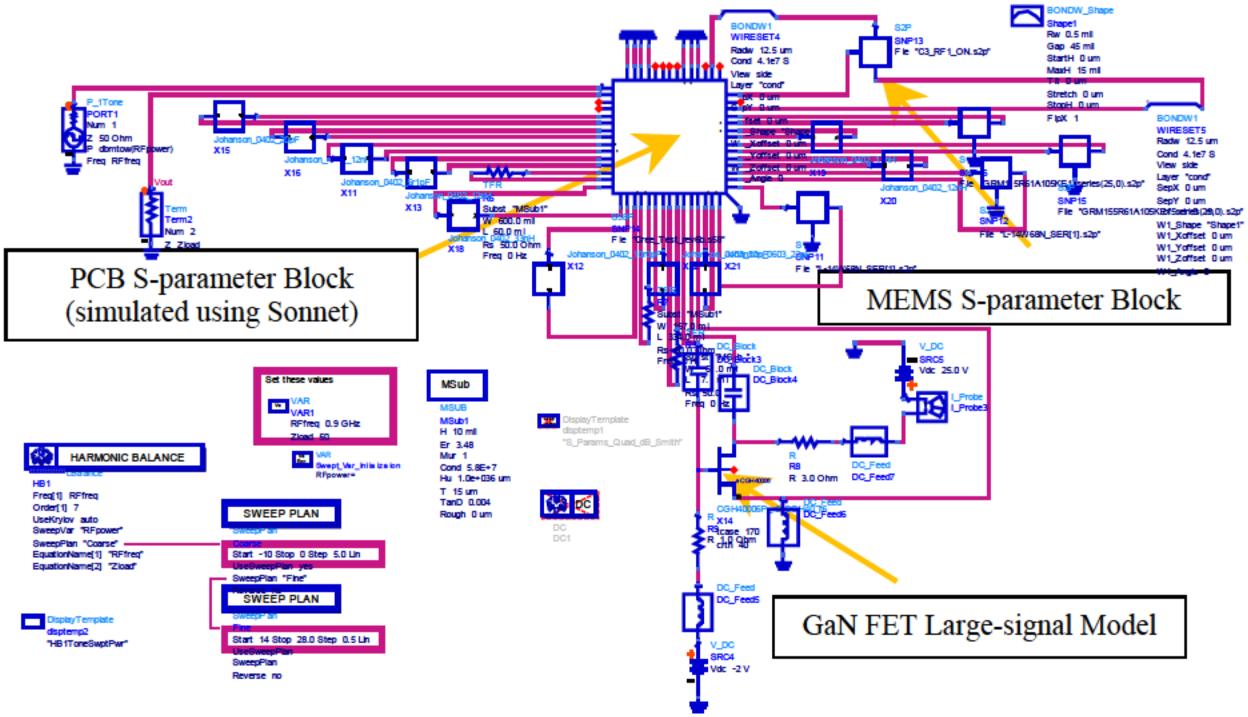
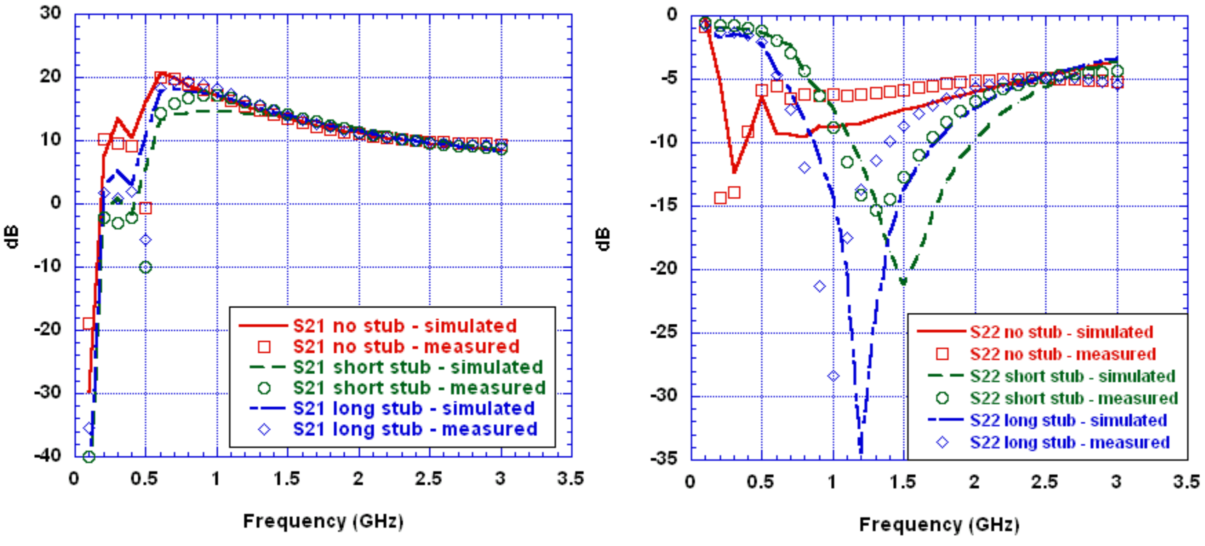


Fig. 3. Hybrid EM-circuit simulation for reconfigurable PA.

4. Simulation and Measurements

A. Small Signal Measurement and Simulation

The small signal response of the reconfigurable GaN PA were simulated and measured. Agilent E5071C Network Analyzer was used to measure the S-parameters. Fig. 4a and 4b show both measured and simulated S_{21} and S_{22} from 0.1 to 3 GHz for the cases of no stub and with either short or long stub. The measured circuit has 16 - 20 dB maximum gain and gives reasonable agreement with the simulated data. The input reflection coefficient (S_{11}) provides less than -10 dB at nearly all operating frequencies. Output reflection coefficient (S_{22}) varies between -4 dB to -35 dB for different cases. The minimum of reverse isolation (S_{12}) is -30 dB for all cases.



(a) S_{21} (b) S_{22}

Fig. 4 Measured vs. simulated S_{21} and S_{22}.

B. *Large Signal Measurement and Simulation*

P_{1dB} and associated drain efficiency (DE) were measured and simulated and the data are tabulated in Fig. 5 and Table 1. Agilent MXA N9020A Spectrum Analyzer and Agilent MXG N5181A Analog Signal Generator were used to measure large signal power performance. Maximum measured P_{1dB} and and DE are 34.8 dBm and 42 % at 1.5 GHz. At 0.9 – 1.25 GHz, the longer stub is used for tuning. Above 1.25 GHz, the shorter stub is used. The maximum improvement in P_{1dB} is more than 4 dB. The measured and simulated P_{1dB} agree to within 1 dB. The maximum DE with the stub is 42 % which is an improvement of 27 % without the stub. The average difference between the measured and simulated DE is less thn 3 %. The bias point chosen for these measurements was class-AB.

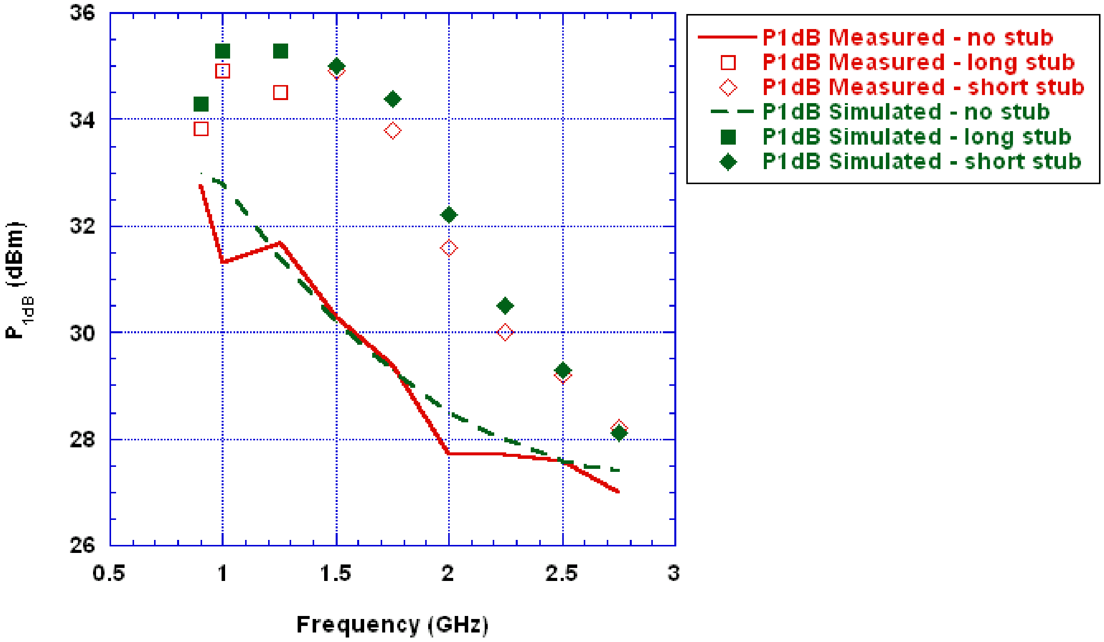


Fig.5 Measured and simulated P_{1dB} for the GaN –MEMs Power Amplifier.

TABLE I
MEASURED VS. CALCULATED DRAIN EFFICIENCY AT P_{1dB}

PAE	0.9 GHz	1 GHz	1.25 GHz	1.5 GHz	1.75 GHz	2 GHz	2.25 GHz
Without stub (simulated)	30 %	27 %	21 %	17 %	14 %	11.5 %	8.5 %
Without stub (measured)	26 %	23 %	19 %	15 %	12 %	9 %	10.5 %
With stub (simulated)	31 %	42 %	40 %	45 %	38 %	24 %	17 %
With stub (measured)	31 %	40 %	37 %	42 %	32 %	20 %	14 %

5. Conclusions

This paper presents the design of a reconfigurable GaN power amplifier with tunable output matching network using an RF-MEMs switch using Sonnet. This prototype operates at frequencies between 0.9 GHz to 2.5 GHz, which cover several standards of digital telephony. Using the RF-MEMs switch with shorted stubs, the P_{1dB} can be increased by over 4 dB for maximum P_{1dB} of 34.8 dBm. The measured and simulated P_{1dB} agree to within 1 dB. Future work includes integration of the power amplifier with SP4T MEMs switches and use of a higher thermal conductive board to improve power efficiency.

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