Modeling of CPW based passive networks using Sonnet for Non-linear MMIC circuit design using AlGaN/GaN HEMT technology

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Abstract: Accurate modeling of CPW based passives and design of matching networks using Sonnet is discussed in this paper. Excellent agreement between Sonnet simulations and measured s-parameter data from fabricated resonators and matching networks were obtained. The matching networks designed using this method were used in an AlGaN/GaN HEMT class E MMIC power amplifier designed at 4 GHz and excellent power performance was obtained from the circuit.

Keywords: Sonnet, EM Simulation, Passives, Matching Network, CPW, Lumped Element, Monolithic, MMIC, High Power, Non-linear, GaN

1. Introduction

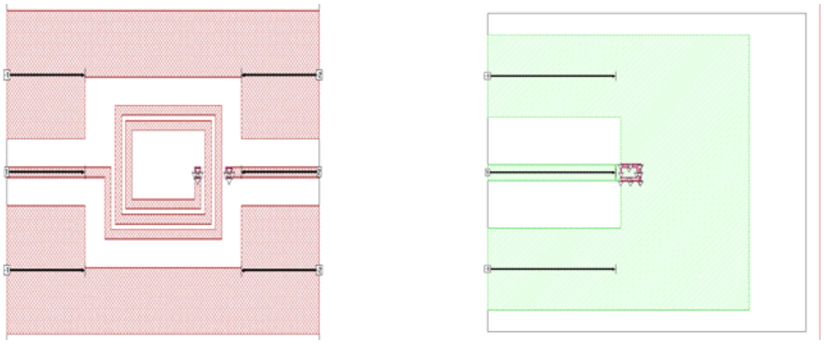
High output power and high efficiency are two desirable factors for RF/microwave power amplifiers (PAs). Higher power added efficiency (PAE) leads to less DC power consumption by the circuit, therefore increasing the battery life and also relaxing the heat dissipation requirements. Monolithic Microwave Integrated Circuits (MMICs) are of great interest in RF/Microwave application due to their much smaller size compared to the competing hybrid circuit technology. Among the existing microwave device technologies, AlGaN/GaN HEMTs are particularly suitable for MMIC power amplifier applications due to their superior power-density and much higher breakdown voltage [1, 2, 3], and they have been successfully used in the past in MMIC power amplifier circuits [4,5].

Class B, C and switch mode amplifiers such as Class E and Class F topologies are popular choices for high efficiency power amplifier applications. The issue of accurate input and output matching is especially important for these circuits since they are inherently narrow band tuned circuits and the gain, efficiency and output power of the circuit are very sensitive to mismatches in the matching networks. In order to obtain optimum circuit performance, it's essential to use accurate models for both the active HEMTs and the passive matching networks.

In this paper accurate modeling of the passive elements including the input and output matching networks and the tuning elements using Sonnet is discussed. Due to lack of via technology in our fabrication process, coplanar waveguide (CPW) environment was used for the implementation of all matching networks. Also at lower microwave frequencies, only lumped-element matching networks are feasible for MMIC design due to very large size of distributed elements at this frequency. The HEMTs used in the circuits were modeled using a scalable EE_HEMT based non-linear large signal model for multi-finger AlGaN/GaN HEMTs and the modeling procedure is discussed in detail in [6].

2. Fabrication

The matching networks and tuning elements consist of capacitors and multi-turn spiral inductors. The capacitors were fabricated using parallel a plate configuration with a 130 nm thick SiN layer used as the dielectric. The dielectric constant of the SiN layer was experimentally determined to be about 7 at the RF/microwave frequencies of interest. The Multi-turn inductors were implemented using a 3 μm thick gold interconnect layer and a 1 μm thick bridge metal separated by a 3 μm PMGI bridge post. The PMGI may be etched away after fabrication to create true air-bridge at the overlap area but most often it is left in place considering its large thickness and low dielectric constant. Process variations that most often effect the performance of the passive circuits include the thickness variation of the deposited SiN which effects the capacitance values and to a lesser extend the thickness variation of the deposited interconnect metal, which can effect the inductor losses. All circuits were fabricated at the UCSB Nanofabrication Facility.



(a) **(b)**

Figure 1- (a) Inductor layout in Sonnet and (b) capacitor layout in Sonnet

3. Lumped Element EM simulation and Modeling

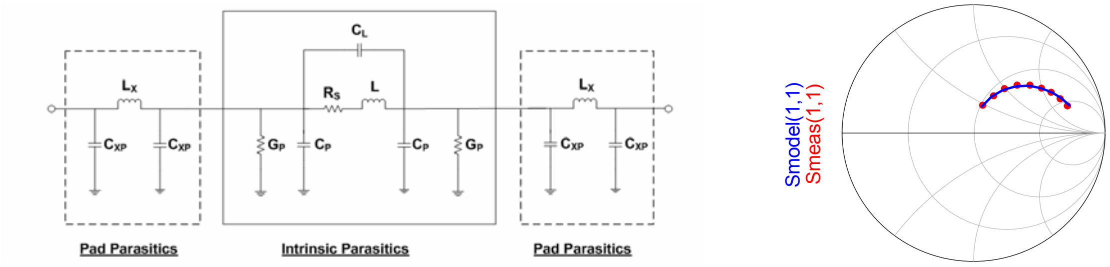
There are a few approaches for designing passive networks. One approach relies on creating inductor and capacitor libraries based on measured s-parameters from fabricated inductors and capacitors of various sizes and geometries. In the absence of accurate EM simulation software, this is probably the most accurate approach. However, it can be a very time consuming process and requires fabrication of a large number of passive elements in order to obtain a complete library. Moreover, when these elements are used in the circuit, such libraries can not accurately predict effects such as mutual coupling between the elements, the variations in the current paths (especially important in CPW environment) and the effects of all the interconnecting elements.

An accurate EM modeling software can alleviate the problems mentioned above and allow for much faster and more accurate way of modeling complex matching networks. The Sonnet software has proven to be a very accurate and powerful tool for planar EM simulations. When the modeling is carried out in a systematic way, we will show that complex matching networks and tuning elements can be designed with excellent accuracy and minimum effort using Sonnet simulations.

Sonnet uses the Method of Moments applied directly to Maxwell's Equations to solve planar problems. Detailed mathematical description of the Method of Moments and the theory used in Sonnet are found in [7] and [8] respectively and an overview of its operation can be found in [9]. This works quite well in modeling of our passive elements because of their planar geometry.

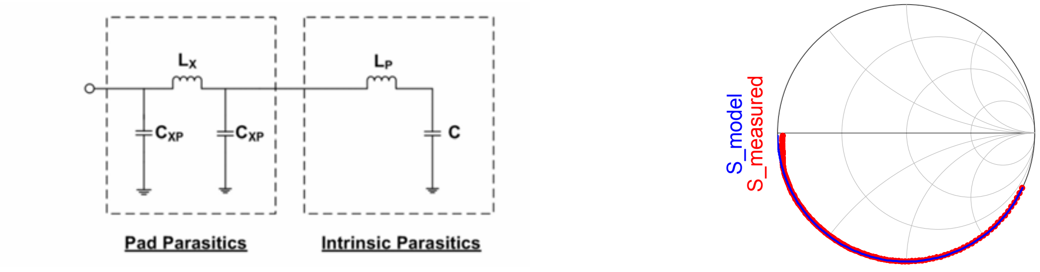
For accurate modeling it is important to simulate the elements exactly the same way that they are fabricated in the circuit. This will ensure that the currents flow in the right directions and all fields are terminated correctly. Figure 1-(a) shows the layout of an inductor simulated in Sonnet. The inductor simulation setup consisted of four dielectric layers: a 1000 μm glass plate where the substrate is mounted on ($\varepsilon_r = 3.9$), a 300 μm sapphire substrate ($\varepsilon_r = 9.8$, Loss Tan = 1.0×10^{-4}), a 3 μm layer PMGI ($1 < \varepsilon_r < 2$) used for the bridge spacer, followed by a 3000 μm air column ($\varepsilon_r = 1$) on the top. The dielectric constant of PMGI had negligible effect on the outcome of simulations and was fixed at $\varepsilon_r = 2$. The metal layers consisted of a 3 μm thick metal layer used for fabrication of the main body of the inductor and a 1 μm layer bridge metal layer. The metal type in the Sonnet simulation was set to NORMAL and current ratio of 0.5 or larger resulted in the most accurate loss in the simulations.

The Capacitors were similarly modeled with the glass plate and the sapphire substrate, followed by a 130 nm SiN dielectric layer ($\varepsilon_r = 7$) between the capacitor plates, a 3 μm PMGI bridge layer used for decreasing the parasitic capacitance due to the interconnect metal, and a 3000 μm air layer on top. All connections between the layers were made using vias through the dielectric layers. Figure 1-(b) shows the layout of a capacitor simulated in Sonnet.



(a) (b)

Figure 2 – (a) High frequency circuit model for the inductors and (b) Sonnet simulation vs. extracted model for an inductor.



(a) (b)

Figure 3 – (a) High frequency circuit model for the capacitors and (b) Sonnet simulation vs. extracted model for a capacitor

4. Passive Component Simulation and Modeling

Initially, inductors of various sizes and geometries were simulated in Sonnet, and a high frequency equivalent circuit model was extracted from each simulation in order to create a simulation based inductor library. Figure (2-a) shows the high frequency equivalent circuit model used for modeling the inductors in ADS. The intrinsic section of the model consists of a pie network. The series resistor models the conductor loss in the metal, and the shunt conductances account for the loss in the substrate. All resistor models consist of a frequency dependent component that accounts for high frequency losses. The shunt capacitors are used to model the parasitic capacitance between the inductor and ground. These capacitors are the main factors in determining the inductor's self resonance. The capacitor parallel with the inductor is used for modeling the capacitance between the inductor's loops and its value is usually negligible. The pad parasitic terms are not needed for model extraction from Sonnet simulations, since Sonnet allows de-embedding up to the inductors terminals, and their corresponding values should be set to zero. They are only used for model extraction from measured data (test structures), in which case they need to be extracted separately using open and short pad structures prior to the intrinsic model extraction. All parameter extractions were carried out in ADS using optimization routines. Figure 2-b shows the extracted vs. Sonnet simulation results for an inductor.

The capacitor modeling and parameter extraction procedure is similar to that of inductors. Figure (2-a) shows the high frequency circuit model used for modeling capacitors in ADS. Since our designed matching networks just required shunt capacitors, only one-terminal simulations with capacitors terminating in the ground plain were performed. The high frequency circuit model consists of the capacitor in series with a parasitic inductor. Due to the small size of the capacitors, the value of the series inductor is normally very small. The capacitance values scale quite well with geometry, and hence the formation of a capacitor library was unnecessary. Figure (2-b) shows the extracted vs. Sonnet simulation results for a capacitor.

The simulated inductors had conductor widths of 30 μm or 50 μm, and separation of 10 μm between the loops. The inductor loop size was varied form 100 x 100 μm to 800 x 800 μm and n = 0, 1, 2 and 3 turn inductors were simulated. In some resonator designs both inductor leads had to be on the same side and a separate inductor library had to be extracted for that inductor geometry. Due to the fast speed of the Sonnet simulations, such extensive libraries can be obtained in a relatively short period of time. Comparison between simulations and measured inductors showed excellent agreement.

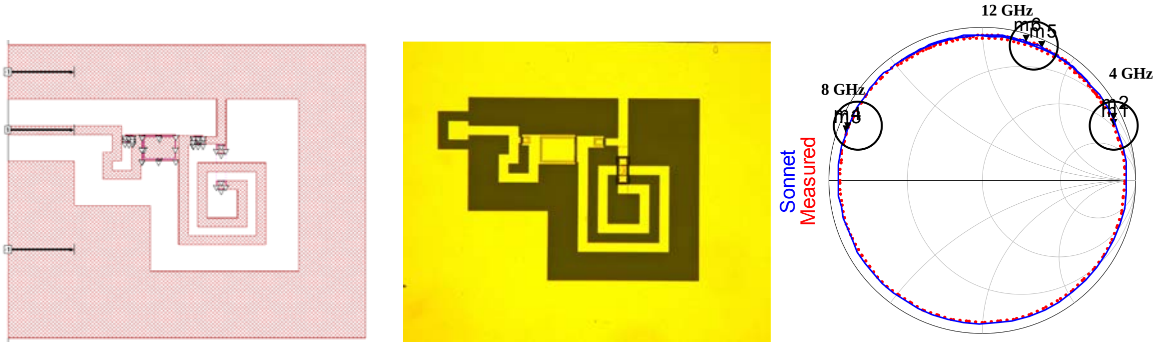


Figure 4 – Sonnet Simulations vs. measured s-parameter result from the resonator (1 – 14 GHz)

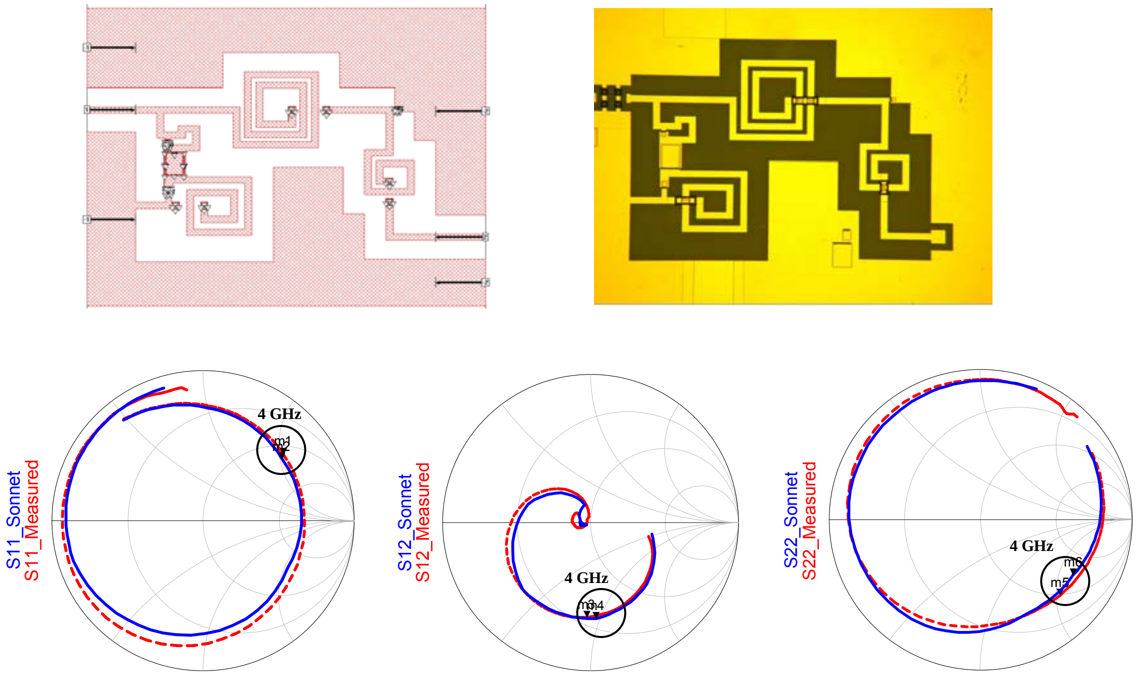


Figure 5 – Sonnet Simulations vs. measured s-parameters from the combined network (2 – 10 GHz)

5. Matching Networks Results

In this section design of an output network for a class F power amplifier is discussed. This relatively complex output network serves as a good example to demonstrate the capabilities of our design approach. The detail of the class F amplifier operation is beyond the scope of this paper and here we will suffice in showing the accuracy of the designed matching network. The output network consists of an L matching network and a resonator circuit at the drain side of the transistor. The L matching network and the resonator were initially designed separately, and then combined and optimized to obtain the complete output network. The final optimization is required because although the capacitors and inductors were accurately modeled individually, when combined with other elements in a circuit effects such as the changing of the current paths in the ground plains, the coupling between various components, and the added interconnects will change the overall performance of the circuit and need to be compensated.

The passives were initially designed in ADS using the equivalent circuit models for the inductors and capacitors, taking into the account all the parasitic elements. The layout of the resulting passive networks were then simulated and optimized in Sonnet by tweaking the values of the capacitors and inductors as needed in order to obtain the desired response. Figure 4 shows the Sonnet simulation vs. measured results obtained from the resonator circuit alone. We can see that excellent match is obtained over a wide frequency band for the simulated and measured data. Finally the two sectioned were combined to form the complete output network and final optimizations were performed. At this point the circuit becomes quite large and Sonnet simulations can take up a lot of time. However, due to the previous optimization of the individual sections the final optimization should not take much iteration. Figure 5 shows the simulation vs. measurement results obtained for the complete output matching network. Again we can see that excellent agreement over a wide frequency range is achieved.

6. **Circuit Results**

The described method for designing matching networks was used in the design of an AlGaN/GaN HEMT Class E MMIC power amplifier [10]. The circuit was designed at 4 GHz using a multi-finger HEMT with a gate periphery of 0.5 mm (4 x 125 μm) and a gate length of 0.7 μm which results in f_t of about 17-18 GHz and f_{max} of more that 40 GHz for the HEMT. An EE_HEMT based scalable non-linear large signal model was extracted for the HEMTs [6] and was used to carry out the Harmonic Balanced simulations in ADS. Figure 6 shows a picture of the fabricated circuit along with the simulated vs. measured power performance of this circuit. This amplifier achieved PAE of 61%, output power of 33.8 dBm corresponding to more than 4 W/mm output power density and gain of 11.8 dB, which is excellent result for a MMIC at this frequency. Overall, very good match between the simulated and measured P_{Out} and gain is observed. The simulated PAE is slightly larger than measured PAE. This is mainly due to a minor deficiency in the EE_HEMT based large signal model which results in underestimation of the simulated harmonic balance DC drain current [6]. Figures 7 and 8 show the Sonnet simulation vs. measured results obtained from the input and output matching networks, respectively. Despite inconsistencies in the fabrication process, we can see that in both cases very good agreement is observed between the simulations and measurements, which is a major factor contributing to the excellent power performance of the circuit.

7. Conclusions

Accurate modeling of CPW based passive components and design of matching networks using Sonnet was discussed in this paper. Initially, individual inductor and capacitors of various sizes and geometries were simulated in Sonnet, and a high frequency circuit model was extracted from each components. These extracted results were consolidated into an inductor library and a scalable capacitor model, which were used in designing complex passive circuits including resonators and matching networks. Various sections of a larger matching network were individually simulated and optimized in Sonnet before being combined and optimized once more to obtain the final circuitry. This systematic step by step approach for the design of complicated passive networks resulted in obtaining excellent results with reduced time and effort spent. Excellent power performance was obtained from an AlGaN/GaN HEMT class E MMIC power amplifier designed using this procedure. Based on these results Sonnet proved to be a powerful tool in accurately simulating complicated passive circuits.

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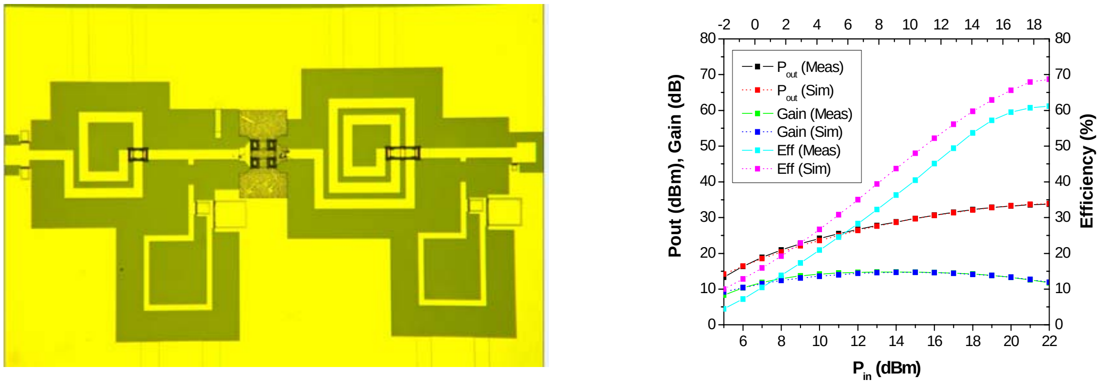

Figure 6 - Photo of the class E MMIC power amplifier and the simulated vs. measured power performance from the circuit

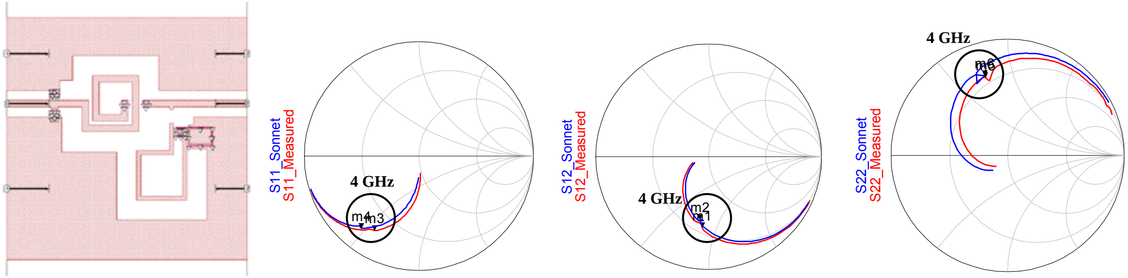

Figure 7 – Sonnet simulations vs. measured s-parameters from the input network of the class E MMIC (1 – 10 GHz)

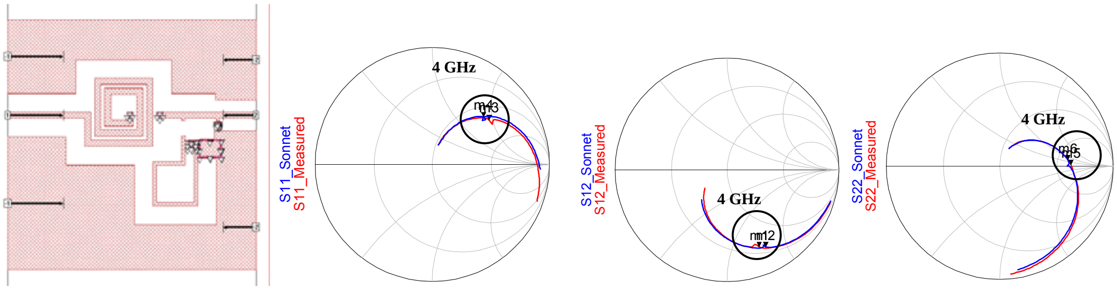

Figure 8 – Sonnet simulations vs. measured s-parameters from the output network of the Class E MMIC (1 – 10 GHz)