A New Approach for RF Power Amplifier Design including Nonlinear Properties

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Abstract— In this paper, a new approach is presented to design a Radio Frequency (RF) Solid State Power Amplifier (SSPA) from Scratch to Printed Circuit Board (PCB) using the commercial software Advanced Design System 2011.01 (ADS). An example is introduced to show the efficiency of the proposed approach.

Index Terms— Advanced Design System (ADS), Finite Element Method (FEM), Harmonic Balance (HB), Momentum Method (MM), Radio Frequency (RF), Solid State Power Amplifier (SSPA).

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1 INTRODUCTION

SSPA is an essential component, playing a key role in the realization of many microwave and millimeter-wave systems. Its applications span a broad range of areas [1], among which telecommunications, radar [2], [3], [4], electronic warfare, heating [5] and medical microwave imaging [6], [7]. Therefore, a quick and simple approach is needed to fulfill the required specifications in a short time by using the commercial software ADS.

The approach is organized as follows; a flowchart showing the whole approach Fig.1, explanation of its steps and finally an example is introduced to illustrate it. After that, it will be clear how beneficial to adopt the new approach for complete and quick method in designing RF SSPA.
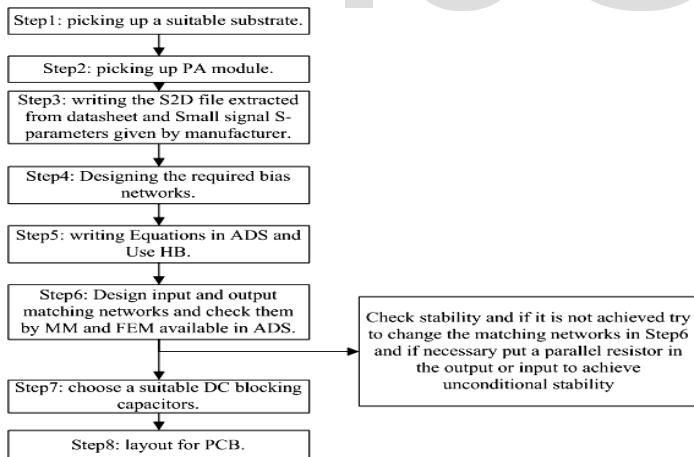

Fig. 1. Flow chart for the proposed approach

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2 Explanation of the Proposed Approach

This approach is divided into eight steps as follows:

2.1 Picking up a suitable substrate.

Substrate must be chosen carefully to be suitable for your PA, Table 1.

Table 1
Most important substrate parameters considered for RF power applications.

Substrate Parameter	Remarks
Relative Dielectric Permittivity ε_r	Suitable for 50 Ω line and less frequency dispersive
High thermal conductivity in $W/(K*m)$ (more than 1.4 is a good choice)	Improves dielectric heat dissipation, so it can enable lower operating temperatures for high power applications
Low loss tangent $tan(\delta)$ (Dissipation factor) (includes dielectric and copper loss at a specified frequency range)	Must be as low as possible and excellent performance at high frequency (almost higher than the operating frequency)
Thermally stable low profile and reverse treated copper foil	Lower insertion loss and excellent thermal stability of traces
Advanced filler system	Improves drillability and extends tool life
Temperature rise per RF Power in ºC/W above ambient temperature	Must be known for a specified power for designing heat thinks in addition to the other heat parameters for the picked PA module.

2.2 Picking up a suitable power Amplifier (PA) module.

PA module can be chosen from different companies like (CREE, Toshiba, …) to meet the required specifications (frequency range, Power Added Efficiency (PAE), 1 dB compression output power, output power 3rd order intercept point OIP3, …). Recently, there is an increasing interest in wide-bandgap materials (especially gallium nitride GaN and silicon carbide SiC), which can sustain intrinsic high breakdown field with typical values in the range of hundreds of volts as compared to the few tens of the traditional GaAs-based devices [8],[9]. Summarized in Table 2 are the main properties of some of the leading microwave transistors for high-power and high-frequency applications. Consequently, due to the limited actual value of the maximum output power achievable from a single device, combining structures often become mandatory to fulfill PA design specifications.

Table 2
Device Summary [10].

Acronym	Type of Device	Max Freq. for Power Amps GHz	Fmax GHz	NF (@ GHz) dB	Noise Corner Hz	Power Density (@ GHz) W/mm
Si BJT	Bipolar	10	50	2 (2)	5-50K	1.5 (5)
GaAs HBT	Bipolar	20	200	3 (10)	1-50K	4 (10)
GaAs FET	Field effect	15	100	1 (10)	1-10M	1 (10)
GaAs PHEMT	Field effect	50	200	1 (30)	1-10M	1.5 (30)
GaN HEMT	Field effect	>50	200	1 (30)	1-10M	>7 (30)
SiC FET	Field effect	10	60	3 (2)	100K-1M	5 (10)

2.3 Writing the S2D file relating the picked PA including a polynomial model for nonlinearity available in ADS

In the .s2d file, you describe small-signal data, optional noise data, optional nonlinear data and optional intermodulation data. You can describe nonlinearity as a function of drive power or nonlinear parameter consisting of some combination of third-order intercept point, 1dB gain compression, saturated output power, and gain compression at saturation [11].
For RF power amplifier, it is a good choice file type because some parameters given in datasheet describing the nonlinear properties, can be included in this file (of course, if X-parameters file is given, it is more convenient and more accurate but sometimes this file is not available).

2.4 Designing the required Bias circuit

Biasing an RF power amplifier is important. Forthat, careful considerations must be taken into account Fig. 2. The most important is the bias sequencing. The "Rg" shown in Fig. 2, is almost recommended by the manufacturer to assure unconditional stability. This resistance will be added to the negative resistance at the gate. Therefore, the sum will be positive which assures stability of the PA.
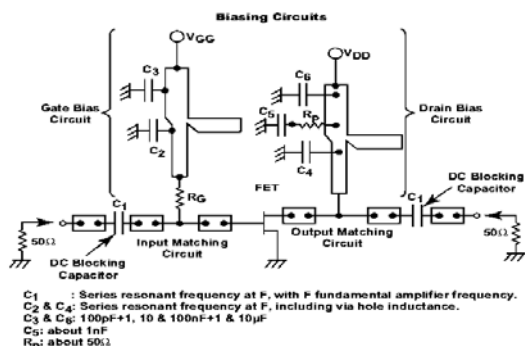

Fig. 2. RF PA with biasing circuits [12].

In gate and drain biasing circuits, isolation between RF and DC signals must be achieved by designing an RF chock and putting some capacitors to filter out the products and harmonics generated by the device input and output without affecting the input and output matching networks. Carefulness must be considered when designing the drain bias circuit because the width of the microstrip line has to sustain the high current required for drain biasing. The steps; 5, 6 and 8 will be explained later in more detail in the illustrated example.

2.5 Choosing suitable Direct Current (DC) blocking capacitors

Several types of DC blocking elements can be used in the input and output circuits. They can also have two functions: DC blocking and RF matching. For the output circuit they have to be specially selected for their low loss and ability to handle high power. It is desirable that capacitor has impedance very low in comparison to 50-ohm load. Coupled lines can be used at relatively high frequencies (F>3.0 GHz) where quarter-wavelength lines have acceptable physical length. They are cheap, low loss and do not require any assembly.

3 Design Example illustrating the proposed approach

In this example, it is supposed that we need to design a class-A power amplifier. Its specifications are; frequency range 8.5-9.5 GHz, output power > 39 dBm with transducer power gain >7.5 dB. In addition, we need not to disturb the linearity of the chosen PA. In the same time, both high gain and high output power must be kept. But, the power added efficiency (PAE), to some degree, can be tolerated.

In this example, the substrate RT/duroid 6035HTC from Rogers Corporation is chosen with the following parameters; $\varepsilon_r = 3.6, \tan(\delta) = 0.0013$, thermal conductivity= $1.44 \; W/(K*m)$, Substrate thickness h=0.762 mm (30 mils) and copper thickness t=33.02 μm (1 Oz/fts^2). The power module TIM8596-8 is picked from Toshiba Corporation that can meet the specifications. The basic step in this approach is to write the .s2d file which is formatted as follows:

BEGIN ACDATA
 # AC(GHZ S MA R 50.0 FC 1. 0.)
! Here we put the small signal S-parameters given for the picked PA from the company
! FC x1 x2 is for frequency conversion:
! Fout=x1*Fin + x2, here we put x1=1, x2=0.
! TIM8596-8 S-PARAMETER
! VDS=9V, IDS=3.4A
! FREQ.   S11   S21   S12   S22
!   MAG ANG MAG ANG MAG ANG MAG ANG
END
BEGIN GCOMP6
! This line includes the nonlinear properties
% IP3 1DBC PS GCS
* 49.5 39.5 40.5 6*
END

Where: *IP3* is the third intercept point in dBm referenced to output power (calculated as *1DBC +10*).
1DBC is the 1 dB compression point in dBm referenced to output power (given in datasheet).
PS is the output power at saturation in dBm referring to the maximum possible output power at fundamental frequency under normal operating conditions prior to breakdown due to high input device (usually it is 1 to 3 dBm above *1DBC* for simplicity it is taken as 1 dBm above *1DBC*).

GCS is the Gain compression at saturation in dB, refers to the amount of compression with respect to linear behavior at the onset of saturation of the output fundamental frequency.

The ADS software fits this file as 9th order polynomial including these four parameters mentioned in *GCOMP6* block, so a behavioral model is resulted from this file including the non-linear properties. This file is assigned to amplifiers2d block available in ADS software Fig. 3.
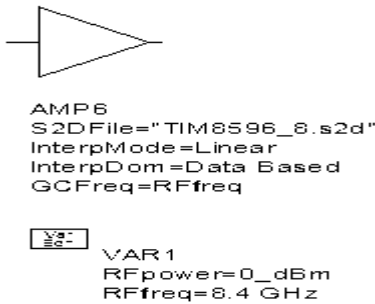
Fig. 3. Amplifier .s2d file assigned to amplifiers2d block.

Bias circuits (RF Chock) are designed for gate and drain. They are some kind of stop band filters in the specified frequency range and by adding the capacitors shown in Fig. 2, wider stop band can be obtained. So, a complete isolation between RF and DC can be obtained and no RF path toward DC. For this purpose, a high impedance line (quarter wavelength line) is used with radial line for the gate bias. The same is considered for the drain but with wider line (quarter wavelength line) to sustain the drain current, which is *3.4 A* for the picked PA. As a rule of thumb we can use Table. 4 and (1), w=0.5 mm for our substrate is a good choice.

Table 4
DC current Handling Capacity of 2 oz copper (0.068 mm thick) microstrip line [13].

Width (w) in mm	DC current Maximum (A)
0.25	4.5
0.5	9
1	18
2	36
3	54
4	72
5	89

$$R = \rho_{cu}(L/A) \qquad (1)$$

Where: $\rho_{cu} = 1.7 * 10^{-8} \Omega . m$ for copper.

L, is the length of line in m.

A, is the cross section of line in m^2.

Regard to DC blocking, ATC700A0R9CW150XT is chosen from American Technical Ceramics (ATC).

For a good simulation, some equations are needed to visualize the results like stability, gain, S11, S22, Output RF spectrum, PAE, Pout versus Pin, and Dissipation power.

The needed equations are listed in ADS's data display Fig. 4.

Pin_W is the power input to the network, at the node labeled "Vin", in Watts, at each frequency.

Eqn Pin_W=0.5*real(Vin*conj(Iin.i))+1e-20

Pdc is the DC power consumption in Watts.

Eqn Pdc=9*3.4 +1e-20

Pinput_total is the total power supplied to the network.

Eqn Pinput_total=sum(Pin_W)+Pdc

Pavs_W is the power available from the source, in Watts.

Eqn Pavs_W=10**((RFpower-30)/10)

Pout_fund_W is the power delivered to the load at the fundamental freq., in Watts.

Eqn Pout_fund_W=Pout_W[1]

PAE is the power-added efficiency, in percent.

Eqn PAE=100*((Pout_fund_W-Pin_W[1])/Pdc)

Pout_W is the power supplied to the load, in Watts, at each frequency.

Eqn Pout_W=0.5*real(Vout*conj(Iout.i))+1e-20

Spectrum is the power supplied to the load, in dBm, at each frequency.

Eqn Spectrum=10*log(Pout_W) +30

Poutput_total is the total power supplied to the load, in Watts.

Eqn Poutput_total=sum(Pout_W)

Pdiss is the thermal dissipation in the network, in Watts.

Eqn Pdiss=Pinput_total-Poutput_total

Transducer power gain is computed as power delivered to the load at the fundamental frequency (dBm), minus the power available from the souce (dBm.)

Eqn P_gain_transducer=Spectrum[1]-RFpower

Eqn vout=ts(Vout[RFindex_RFfreq_index,PowerIndex_RFpower_index,::])

Eqn vin=ts(Vin[RFindex_RFfreq_index,PowerIndex_RFpower_index,::])
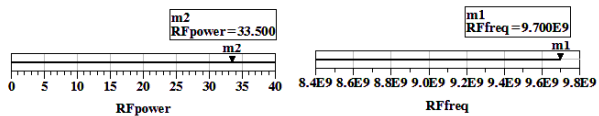
Fig. 4. Nedded equations written in ADS data display

After doing the optimization in schematic window for matching, the results are checked by electromagmetic (EM) simulation. That is to compensate the end effects in stubs using MM and FEM methods, which are available in ADS. The results are shown in Fig. 5, Fig. 6 and Fig. 7.
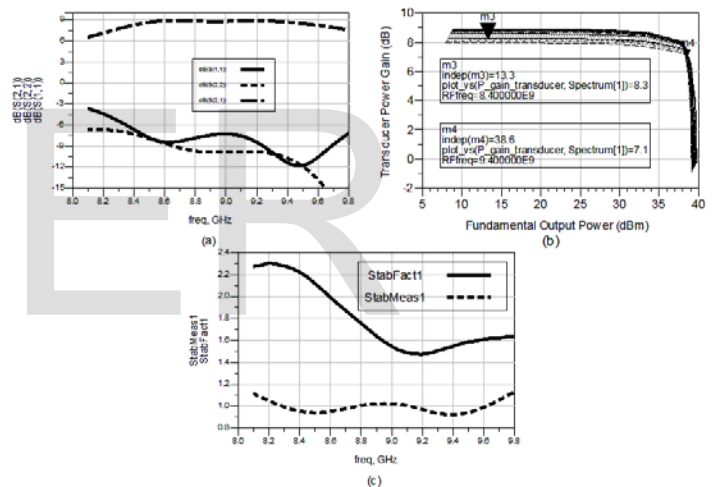
.Fig. 5. (a) S-Parameters versus frequency, (b) Transducer Power Gain versus Fundamental Output Power, (c) stability factor and stability meaure versus frequency (EM and HB Simulation Results).

The necessary and sufficient conditions for unconditional stbility are that the stability factor is greater than unity and the stability measure is positive.
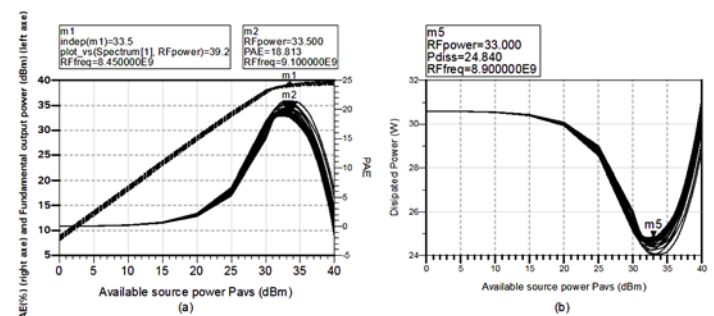
Fig. 6. (a) Fundamental Output Power (Left axis) and Power Added Efficiency (Right Axis) versus Available Source Power (b) Dissipated Power versus Available Source Power (EM and HB Simulation Results).

Dissipation power is very important to design or choose the suitable heatsink.
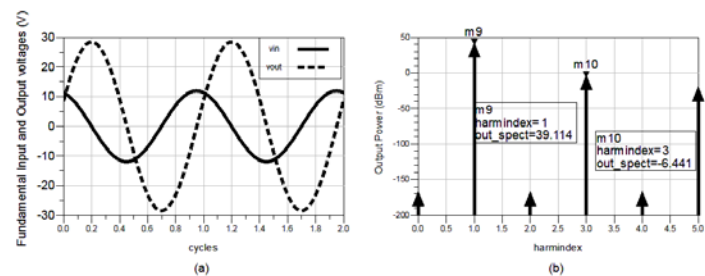

Fig. 7. (a) Fundamental Output and Input Voltages versus time periods, (b) Output Power Spectrum (EM and HB Simulation Results).

In Fig. 7, linearity can be noticed in two ways; in time domain Fig. 7(a), no distortion can be seen. In frequency domain Fig. 7(b), it can be noticed that, the difference between fundamental output power and 3rd order harmonic output power, is more than 30 dB. So, no distortion can be seen. After verifying all these parameters, and achieving the required sepecifications. Now, one can make the PCB and this is achieved using the layout window Available in ADS Fig. 8.
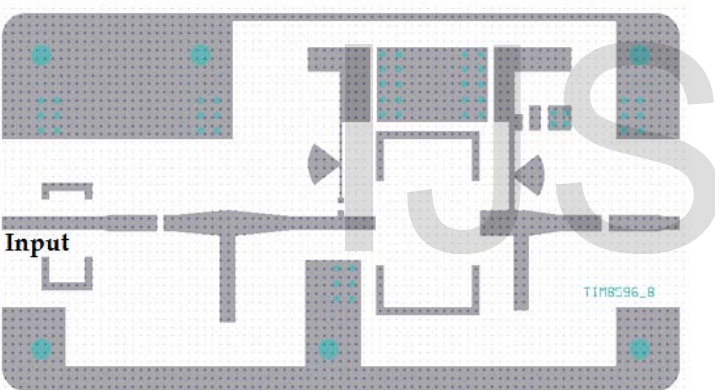

Fig. 8. Complete PCB ready for fabrication.

In Fig. 8, near the input there is a place for Isolator to be assembled after fabrication, a proposed isolator for this purpose is T8696/DA from TRAK Microwave Corporation.

4 CONCLUSION

In this paper, a simple and quick approach is proposed to design an RF SSPA using the commercial software ADS. The usefulness of this approach is that, one can see every change you make on the circuit. This can be done by watching the resulted curves from the written equations. So, one can concentrate on the more important parameters for the required application and reduce the time for production.

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