A Survey on RF Power Amplifier Designing with CMOS Technology

More Prachi Gopalrao
VLSI and Embedded System
Smt. Kashibai Navale College of Engineering, Pune-41

A.A. Yadav
Assistant Professor
Smt. Kashibai Navale College of Engineering, Pune-41

ABSTRACT
Today'scommunication system has many of advanced features, which gives faster rate of information trans-reception. The trans-receiver has different blocks like Filter, (Voltage controlled oscillator) VCO, (Low noise amplifier) LNA, (Power amplifier) PA. Among these the most power hungry device is the PA. The efficiency of PA theoretically can be 100% but practically it is just 55%. The scope of improvement in the efficiency in the PA will be the interesting and the most challenging task. At the radio frequencies i.e. 1GHz to 80 GHz PA can work more efficient way with the different technologies GaAs, GaN, p-HEMT, and CMOS. The technology scaling with increasing features will give the compactness and system on chip concept. Use of CMOS technology will have ability to shrink in size with low cost and better design results. PA can be designed on CMOS 130nm Technology with the tool (advanced design system) ADS with graphical results.

General Terms
(Radio Frequency) RF, CMOS technology, trans-receiver, system on chip,VCO, LNA.

Keywords
CMOS technology, RF power amplifier, ADS, p-HEMT, Drain efficiency, Power added efficiency.

1. INTRODUCTION
PA has wide application area like Wi-Fi, Bluetooth, mobile communication, Radar system, WLAN, as well as medical and military applications. Low power consuming devices are the main aim of designing any analog system devices at radio frequencies. The key building blocks of communication system include the VCO, PA, Mixer, LNA [1]. PA shows the growing interest of most efficient and robust design.The design equations can be verified with the results obtained with the tool ADS 2009 Agilent.The designing part as well as layout design will be more convenient with this tool for PA.

2. BACKGROUND
The first CMOS RF power amplifier which delivered the hundreds of MW power reported in 1997, implemented on the single ended configuration with 0.8 μm CMOS Technology, the power amplifier was able to give 62% drain efficiency of (824~ 849) MHz using the supply voltage of 2.5V. The first GHz range differential power amplifier was reported in 1998, implemented using 0.35 μm CMOS Technology. In 2001, 130 nm CMOS technology came into notice. Today's Scientist working on 14 nm CMOS technology, in few years scale will down to 10 nm, which is very tiny.

3. POWER AMPLIFIER
Radio frequency (RF) power amplifiers are an essential part regarding the base station and also in the communication networking devices energy consumption and power dissipation. There is also the environmental impact of the PA, as the power consumption affects the environmental impact to get a reduction of the radio access network [2].The main goals for the further improvement in the PA are as follows:

1. High linearity to satisfy higher-order modulation scheme.
2. Greater average output power levels
3. Broader operating bandwidth
4. Low consumption of radio network energy reduces the environmental impact.

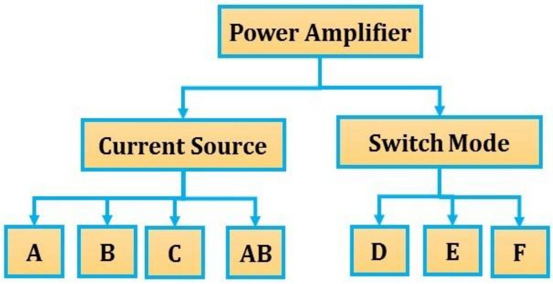

Figure 1 Power Amplifier Division

Figure 1 showthe classification based on the basic operations of different classes of a power amplifier. There are two modes of the power amplifier used for two different operations as shown in the flow diagram. Switch mode PA basically used for high frequency operation. The switch mode Power amplifier has the nonlinear characteristics but has better efficiency and gain. There are some of the linearization techniques with help of that the PA can be working linear for the given frequency range.

Power dissipation = $\int_0^{2\pi} Vm * Im\, sin(\emptyset - \pi)\; d\emptyset$……eq. (1)

3.1 Switch mode power amplifier
The switch mode power amplifier included classes are class E, F, D The key idea behind the switch-mode PA technology is to operate the transistor in the saturationregion depending on amplifier class is switched on and off, waveform shows isolated signals of either voltage or current. The switch is open, only voltage is present over the transistor while the switch is close, only current flows through it. The figure 6 will tell better demonstration about switching. Therefore, there is no any overlapping of current and voltagewaveform, so the dissipation of power will be as low as possible. But some of the overlapping portion will give dissipation as given in equation 1. The less power dissipation will give better efficiency. Theoretically the 100% efficiencyis possible with the design equations [2].

3.2 Current source power amplifier

The classes A, B, C, and AB are applicable as a constant current source. The drawback of power dissipation more in these amplifiers they used in the restricted area of a low-frequency range. These four types of amplifier further classified according to their biasing conditions and the conduction angles [2]. Regardless of conduction angle, the active devices are used as the "Trans conductance" PA.

3.3 Hybrid Class power amplifier

The hybrid classof apower amplifier has their advantages and disadvantages respectively of the combination of two different classes. To overcome these limitations and further improvements will be done with several classes like a class BD power amplifier, class EF power amplifier are the particular classes of the interest. To design this PA the use of Class EF will give special attention to get better performance with low voltage supply. This operating class also have the advantage of getting high bandwidth with frequency range is from 1.5 to 3 GHz [18].

4. PERFORMANCE MATRICS

The performances matrices like gain, output power, ruggedness, linearity, efficiency, sizes, and noise can be measure different for different type of applications, in these applications most commonly used matrices for measurements are efficiency and the linearity. The different analysis will show different results like AC (small signal analysis) will give the parasitic arise or the second order effects, DC analysis will give KVL and KCL operation and also the biasing conditions can also be tested. The S-Parameter analysis will give the gain, reflection coefficient for input and output side as well as the reverse isolation will give results with graphically as well as theoretically.

4.1 Efficiency

It is the most important measurable parameter for the power amplifier, will measure how well a device converts one energy source to another. In the power amplifier, the efficiency can be calculated in the form of drain efficiency and the power added efficiency. Equations (2) and (3) show the definition of efficiency in the form of drain efficiency and the power added efficiency.

$$\text{Drain efficiency} = \eta_D = \frac{P_{out}}{P_{supply}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots eq.(2)$$

$$\text{Power Added Efficiency} = \eta_{PAE} = \frac{P_{out} - P_{IN}}{P_{supply}} \ldots\ldots\ldots\ldots eq.(3)$$

4.2 S-Parameters analysis

It is one of the important measurable performance aspectswith the measurement of the S-Parameters. To design of the power amplifier, one should have to consider a large signal S-Parameters and to be aware of the nonlinear effects. The S-Parameter includes quantities like S_{11}, S_{22}, S_{12} and S_{21}, which means that input return loss, output return loss, reverse isolation and the power gain respectively. Graphically one can measure the S-Parameters, which will be easy to measure the circuit performance and also avoid the complexity of equation calculations [1]. The smith chart will also be useful to calculate the matching conditions of source to load impedance to transfer maximum power at the output.

5. DESIGN ENVIRONMENTS

There are different types of design tools commercially used for the analog/RF simulation and the design environment. The flow diagram of figure 2 shows the different design environments [3].

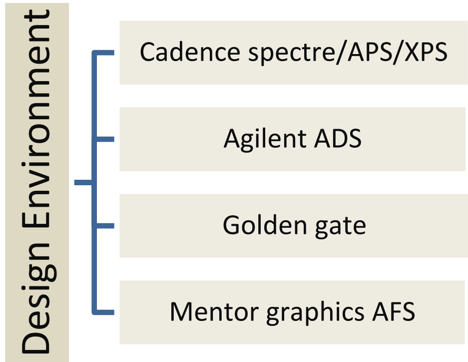

Figure 2 Different Design Environments

5.1 Agilent Advanced Design System (ADS)

For RF Systems (advanced design system) ADS offers one of the best solutions for circuit design and simulations like best harmonic balance simulation engines.The most of the RF designers also prefer to use ADS simulator due to the availability to run specialized RF analysis with special library functions which will give relief from the complex equations.The users can also link the cadence schematic into specternet-list that ADS can read, while still leveraging ADS to build test benches and view simulation results. ADS is best suited to simulate circuits like LNA, Mixer, and PA in the frequency domain with large frequency range [3].

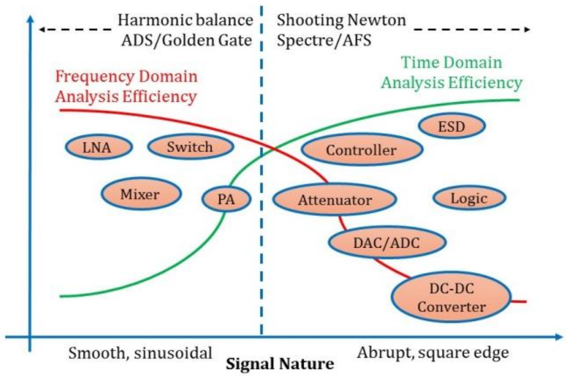

Figure 3 Design Environments [3]

Figure 3 shows the graph in the y-axis is of the design environment, and the x-axis is of signal nature, which may be in frequency domain or time domain analysis and the most specific summary of different design environments. The diagram shows the different devices which can be designed with a different tool. The tool gives compatibility to analyze the different characteristics. There are two domains as shown in figure 3 that is time domain and frequency domain.

6. BASIC TERMINOLOGIES

The analogy of the matching is similar to the light reflection in optical systems, such as the reflected signal maypose problem and power in the reflected signal reduces the transmitted power.

6.1 Matching Concepts

The matching concept best explained by the Philip Smith using the Smith chart [4]. Basically the matching of impedance of input and output side is very important to transfer maximum power to the output according to the maximum power transfer theory. There are different matching networks like L- Network matching, distributed Networks, T-Network match, π −Network matching. These matches will give the operating frequency range. At resonant frequency these types of matches will get synchronize to get the required frequency. The impedance matching network is essential to complete transfer of power to the load from source. For designing the power amplifier the first think of matching network is essential one of matching with high-frequency range i.e. broadband matching networks with input and output matching networks. The match can be formed by using lumped-distributed networks and also with the micro-strip lines [5]. The unmatched device has a disadvantage of very small gain with large values of input and output reflection coefficient (S_{11}, S_{22}) which rise to incorrect operations in the communications network unlike in matching. The comparison between matched and unmatched can be found in ref [5].

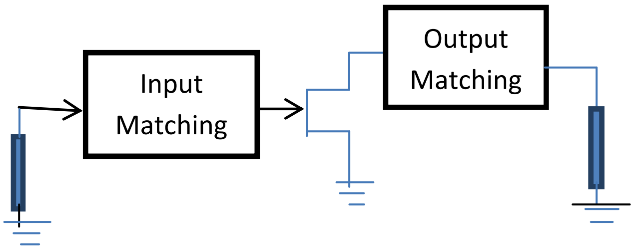

Figure 4 Basic topology of PA

Matching of input signals with the RF input, output signals with RF output and also the intermediate networks also formed with matching concepts. The simulation results of matching network will give the convergence idea of the desired values [6] [7] [8].

6.2 Current and Voltage Waveforms

The classes used for higher frequency switching power amplifier are E and F, in which a class E PA boosts both efficiency and output power by the use of harmonic resonators at the output network such that the load appears to be short at even harmonic and open at the odd harmonic. It shapes the drain waveforms with flat-top response.

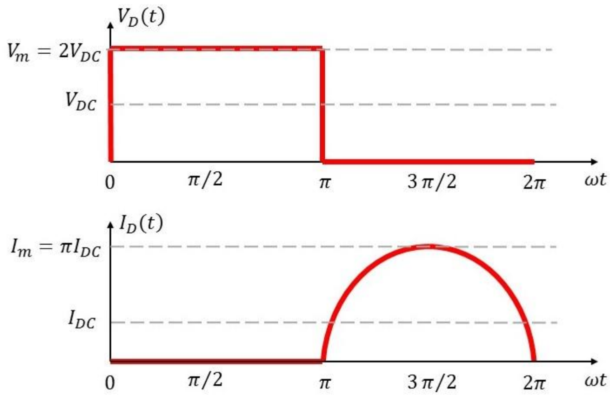

Figure 5 class F second harmonic voltage and current waveforms [11]

The switch mode of amplifier shows the non-overlapping current and voltage waveforms; parallel LC resonator designed with the load network, which can be tuned to the second harmonic of switching frequency. The circuit with properlylumped matching network will give the flat-top voltage and current waveforms. The advantage of the flat-top voltage waveform is that thepeak transistor voltage and peak current for a given output power reduced so the stress is also reduced, or with the same amount of stress, more output power can be obtained [8] [9].Switching type of amplifiers achieve the high power efficiency of power amplifier and also the desirable for the portable communication devices and systems such as cell phones, global position systems (GSM), and wireless local area networks(WLAN). Figure 5 shows the ideal current and voltage waveforms of 50% duty cycle.

Class F RF power amplifiers for acquiring the drain-source voltage wave shaping, the multiple resonator circuits are used with output network. The drain current flows when the drain-source voltage is low, and the drain-source voltage is high where the drain current is zero which can be called as a switching mechanism. The flatten response can be obtained by driving the active devices into triode or cut off regions [11] ~ [15].

6.3 Switching Operations

The second harmonic of class-F PA is used for tuning to get perfect flatten response of switching transistor's drain current and voltage waveforms, which will be able to give the efficiency from 63.7 % to 84.9% [11]voltage stress of the amplifier can be reduced to get maximum efficiency well explained in the Ref. [12] The need of double resonance circuit used for the harmonic control shown in [12]. The finite number of harmonics with class-E, class-F, and class C shows detailed analysis in[13]. There are different methods for efficiency enhancement like the PWM with differential class E the importance of shunt capacitance and the series inductances will give the idea ofgetting stability and quality factor as high as possible in circuit design [14].

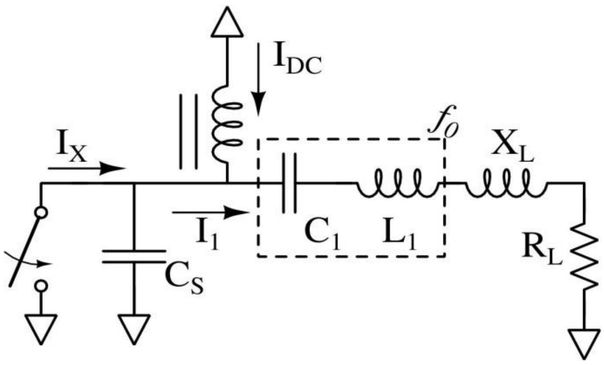

Figure 6 Basic class E power amplifier switching operation [15]

The interesting combination of designing the circuit of PA is the Hybrid class ofEF which has different advantages and also has issues. The zero voltage switching and zero differential voltage switching can be obtained by incorporation of transistor parasitic capacitances into circuits, exact truly switching [15]. The switching is made to conduct with 50% duty cycle at frequency F_0, and switch parallel capacitance $C_s$is used to absorb into a parasitic output capacitance. The figure 6 shows the basic resonator basic components consisting L_1 & C_1 used to block the harmonic frequency F_0. The assumption of ideal choke, it only conducts the DC current I_{DC}. The current into the switch capacitor combination I_x much than be a dc offset sinusoid. The strong switching operation is important to get the desired circuit to get good results of ZVS and ZDS.The analysis of different families of class E_3F and transmission line class E_3F_2, EF_2 PA,was shown in Ref. [16] the proposed idea in the [17] gives the continuous analysis of Class E, Class E/F_2, class EF_2 with the detailed analysis. The concept of conduction angle with a generalized equation with different waveforms shapes given in Ref. [17].

7. SPECIAL EFCLASS

For the desired output power, Class EFpower amplifier is designed, and it is driven by class AB, because of the RF signal DC voltage that delivers a square like voltage waveform with the adequate duty cycle.The power amplifier is matched with 50 Ω for measurement of antenna coupling for complete transfer of the load. The schematic shown in figure 7 is of class EF, which has a branch of C_2, and L_2 parallel with MOSFET.

The circuit shown in figure 7 is of class EF,which has the capability to reduce the voltage stress across the switch. This stress reduction has purpose of

- Further, increase the supply voltage maintaining the load, to obtain higher output power
- Further increase in the supply voltage and the load, to reduce the current through the passive components so that efficiency will increase
- Aiming a more robust design imply keeping the stress lower.

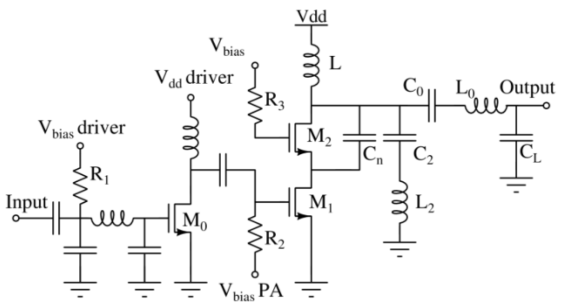

Figure7 Schematic of class EF circuit [18]

The circuit can be implemented in ADS simulator with the layout design with standard 130 nm CMOS Technology for the operating frequency of 1.5 to 3 GHz. The previous results show the comparative study which will give the best results to choose the way of PA designing.Comparison between the class E and class EFin the switching voltages required is as shown graphical form [18]. Figure 8 shows the switching voltage required for the class E and class EF. The output will be analyzed in the form of output power, power gain, power added efficiency, drain efficiency, and also the S-parameters graphical representation with simulating results using Agilent ADS simulator 2009.

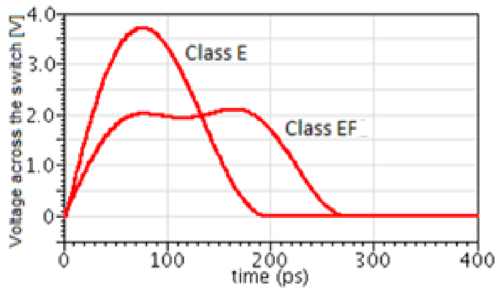

Figure 8 Comparison between class E and EF_2class [18]

The tabular form the comparison with different technology with different design methods are done with different terms numerical value comparisons.

Table 1 shows the comparative studies of different CMOS Technology. The different classes are used for designing the power amplifier with different classes; the comparison gives the idea of the scenario of history work done with advancements in the results. The new hybrid class which is proposed in the paper will give better performance with very less supply power.

8. CONCLUSIONS

The Survey of the power amplifier is done with the basics to get different terms and technology come to know across form that CMOS 130nm have been chosen, the comparative study of class E and Class EF as seen in schematics and the graphical changes. The idea of a class EF power RF amplifier for the frequency range of 1.5 to 3GHz with the 130nm CMOS technology addressed to design. Simulation tool of best suited also came to know with results of different simulations.

9. FUTURE SCOPE

The RF PA has future scope of getting maximum efficiency as possible. The table shows the result up till now achieved efficiency with higher frequency range for different application such as Radar system. By shrinking technology scaling we can get better advancement with less power dissipation. By hybrid of different classes can better performance such in the paper used class EF.

Table 1Comparative Studies

WORK	CLASS	Frequency [GHz]	Output power [dBm]	Supply voltage [V]	PAE [%]	CMOS Technology
[18]	EF	2.5	20	2	49.8	130nm
[19]	F	1.7	23	3	60	130nm
[20]	F	1.8	30	3.3	60	180nm
[21]	2 stage	2.4	43.74	2.5	44.669	130nm
[22]	Dual band	1.4 ~ 2.7	27	3	57	130nm
[23]	Two stage	2.4	10.1684~25.08	1~5	29.085 ~ 45.439	130nm
[24]	E	2.4	20	3	55	130nm
[25]	E	2.4	21.3	3.3	40	180nm

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