Design of CMOS Power Amplifier for Millimeter Wave Systems at 70 GHz

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***Abstract*— In this paper, a new CMOS power amplifier that can operate at 70 GHz is designed and developed. The advantages of using 70 GHz at millimeter wave (mmW) band is the huge amount of bandwidth available for various purposes whether they are in the cellular industry or manufacture devices such as high bandwidth wireless LAN and low attenuation of bandwidth frequencies around 70 GHz bands comparing with 60 GHz. Design power amplifiers at 70 GHz are quite challenges task. The complication such as the stability of the amplifier is difficult and hard to be achieved. In this paper, we design power amplifier with 3 single ended, common source stages biased in class A. The proposed circuit resulted in a stable power amplifier capable of working at 70 GHz frequency. The purpose of using three stages is not only to maximize gain but also to increase isolation against reflections. We found that this configuration has many advantages in terms of lower power supply required, leading to higher efficiency and good linearity. The first stage is biased at a peak F_{max} biased of 0.2 mA/μm to maximize the gain to 10.58 dB. The second and third stages are biased at optimum linearity current density of 0.28 mA/μm.**

Keyword- mmW, Power amplifier, Radio frequency, CMOS

I. INTRODUCTION

Power amplifiers are typically the most power-hungry blocks of RF transceivers. An RF power amplifier is a type of electronic amplifier used to convert a low-power radio-frequency signal into a larger signal of significant power, typically for driving the antenna of a transmitter. It is usually optimized to have high efficiency, high output power compression, good return loss on the input and output, good gain, and optimum heat dissipation [1]. Being high power devices and having large gain, RF amplifiers give large output signal power while requiring very small amounts of RF input power which is normally available from any commercial signal generator. Because of this, the power amplifier (or the amplifier chain) itself is commonly known as "the RF source" or sometimes "the transmitter". The basic applications of the RF power amplifier include driving to another high power source, driving a transmitting antenna, microwave heating, and exciting resonant cavity structures [2]. Among these applications, driving transmitter antennas is most well-known. The transmitter–receivers are used not only for voice and data communication but also for weather sensing (in the form of RADAR). Microwave or RF heating is an industrial application which is also benefiting our homes in the form of microwave ovens. Exciting cavity resonators is quite a research lab and industrial application of an RF source. Particle accelerators utilize RF sources extensively [3].

Extremely high frequency (EHF) is the highest radio frequency band. EHF runs the range of frequencies from 30 to 300 gigahertz, above which electromagnetic radiation is considered to be low (or far) infrared light, also referred to as terahertz radiation. This band has a wavelength of ten to one millimeter, giving it the name millimeter band or millimeter wave (mmW). The band is essentially undeveloped and available for use in a broad range of new products and services, including high-speed, point-to-point wireless local area networks and broadband Internet access. Wireless HD is another recent technology that operates near the 60 GHz range. Highly directional, "pencil-beam" signal characteristics permit systems in these bands to be engineered in close proximity to one another without causing interference [4]. Potential applications include radar systems with very high resolution. Compared to lower bands, terrestrial radio signals in this band are extremely prone to atmospheric attenuation, making them of very little use over long distances.

In this paper, we design power amplifier with 3 single ended, common source stages biased in class A. The proposed circuit resulted in a stable power amplifier capable of working at 70 GHz frequency. The purpose of using three stages is not only to maximize gain but also to increase isolation against reflections.

The remainder of the paper is organized as follow: Section II presents the related work. Section III introduces the system model and design. Section IV presents the measurement and result of proposed PA and section V concludes the paper.

II. RELATED WORK

In particular, signals in the 57–64 GHz region are subject to a resonance of the oxygen molecule and are severely attenuated.

A millimeter wave power amplifier (PA) design in CMOS processes has only recently gained research interest. Millimeter wave PA has been discussed in many researches [5-7]. In [5], Yao et al. developed three stages Class A power amplifier in common emitter topology. Hajimiri and Hajimiri in [6] presented a 77 GHz class AB power amplifier that had a four stages common emitter configuration. The millimeter wave PA relied on 300 Ω base resistance to raise the collector-emitter breakdown (BVcer) to 4 V by using power combining in the last stage to increase the output power. Later, Pfeiffer et al. in [7] developed 61.5 GHz transformer matched class AB power amplifier with single stage differential cascade topology, in which the cascade base was grounded to overcome the breakdown voltage and allow supply voltage 4 V. Hajimiri and Hajimiri in [6] and [8] developed a wideband PA at 77 GHz a peak power gain of 17.5 dB with 50 Ω input and output matching is fabricated in a 0.12 μm SiGe BiCMOS process [1]. However Komijani is optimized the PA to give wideband frequency while he did not give much concern for efficiency and gain.

III. SYSTEM MODEL AND DESIGN

The PA circuit diagram consists of three stages as can be seen in the Fig. 1. The purpose of these stages is to improve stability and provide better isolation along with improving the overall gain of the amplifier. A CMOS transistor developed in 90 nm technology. It consists of three stages biased in class A. Cascading provides high gain and larger output impedance. Linearity is maintained by the tail currents in three stages based on the P1dB for that stage. The first stage is biased at the peak F_{max} bias of 0.2 mA/um to maximize gain while its source degeneration inductance is set to $L_s = Z_0/2\pi fT$ for 50 Ω matching. The second and the third stages are biased at optimum linearity current density of 0.28 mA/um. The transistor width and bias current of the last stage are chosen based on the load line theory. The input matching network consists of the inductor L_s which matches the real part of the input impedance to 50 Ω and L_g which cancels out the imaginary part of Z_{in} at 70 GHz. Next at the output a first stage L-match network consisting of the load inductor L_d and capacitor C_c performs the impedance transformation to 50 Ω. Simplicity in the matching networks is critical in minimizing series parasitics, whose effects are more pronounced at 70 GHz. Inter-stage matching maximizes power transfer between stages and improves linearity through the degeneration inductor, L_s.

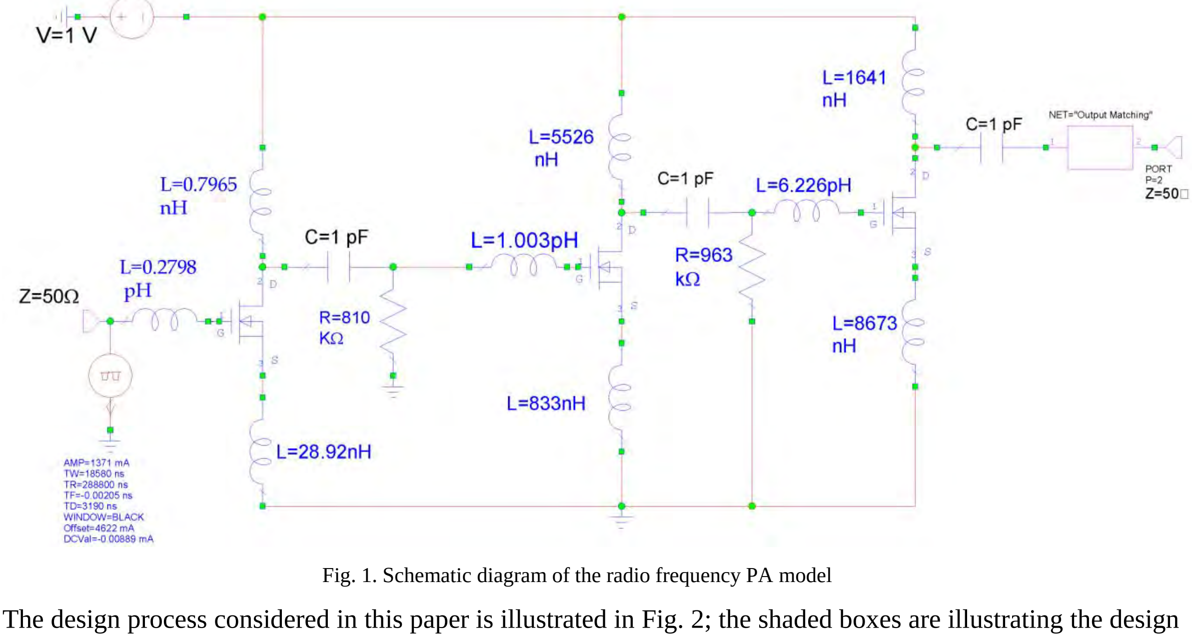

Fig. 1. Schematic diagram of the radio frequency PA model

The design process considered in this paper is illustrated in Fig. 2; the shaded boxes are illustrating the design path. In this paper we emphasize on getting higher gain with maximum efficiency. Stability is also important factor we took into consideration during design. An amplifier's stability refers to its resistance to oscillation which is a common concern in PA design. Coupling between nodes, particularly with the high-powered output node combined with the high gain of the design can create conditions that cause the amplifier to have oscillation behavior (unstable).

A. S-Parameters

S-parameters are a two port analysis tool, much like the usual engineering parameters *h*,*y* and *z* , but *S*-parameters are used to describe microwave components. The name "*S*-parameters" was derived from the word "scattered" from the reflected waves. *S*-parameters are better interpreted with a pure resistance matched termination. In *S*-parameters, the terms used are S_{11}, S_{12}, S_{21} and S_{22}. Fig. 3 below shows microwave signals entering and exiting a microwave component in both directions. If a microwave signal is incident on the input side of the component, some of the signal is reflected and some is transmitted through the component. The ratio of the transmitted electric field to the incident electric field is the transmission coefficient.

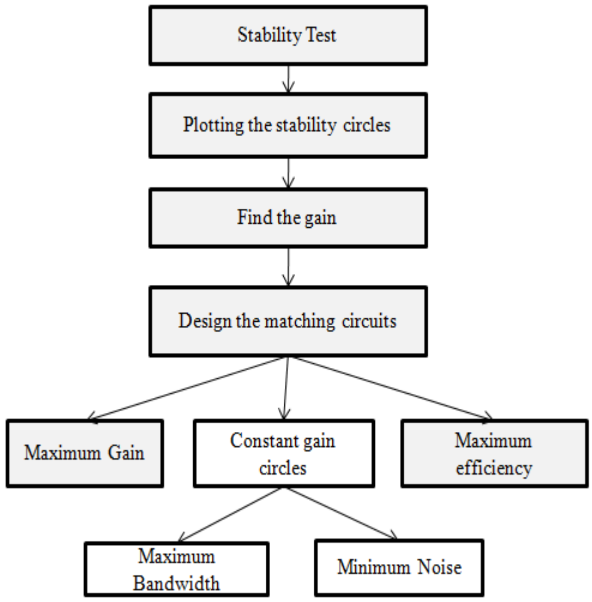

Fig. 2. The design process for the proposed PA

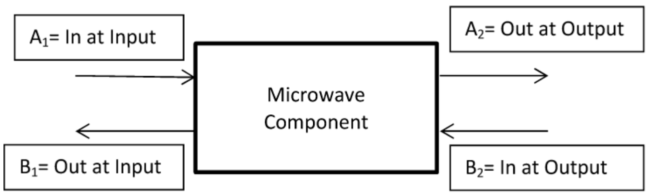

Fig. 3. Microwave signals as input/output for microwave component

The signal entering the input and leaving the input and output are easily understood in terms of reflection and transmission coefficient. To characterize the component completely, the reflection and transmission coefficient must be specified in both directions. Thus, *S*-parameters are used to substitute these long descriptions:

A_1 electric field of the microwave signal entering the component input
B_1 electric field of microwave signal leaving the component input
B_2 electric field of microwave signal leaving the component output
A_2 electric field of the microwave signal entering the component output

By definition, thus;

$S_{11} = B_1 / A_1; \quad A_2 = 0$
$S_{21} = B_2 / A_1; \quad A_2 = 0$
$S_{12} = B_1 / A_2; \quad A_2 = 0$
$S_{22} = B_2 / A_2; \quad A_2 = 0$

where S_{11} is the electric field leaving the input divided by the electric field entering the input, under the condition that no signal enters the output. Since B_1 and A_1 are electric fields, their ratio is reflection coefficient. Similarly, S_{21} is the electric field leaving the output divided by the electric field entering the input, when there is no signal enters the output. Therefore, S_{21} is a transmission coefficient and is related to the insertion loss or the gain of the component. In similar case, S_{12} is a transmission coefficient related to the isolation of the component and specifies how much power leaks back through the component in the wrong direction. S_{22} is similar to S_{11}, but looks in the other direction into the component.

IV. MEASUREMENTS AND RESULTS

For simulation purposes, we used AWR high-frequency design software [9] which contains MWO that we used for the PA design and visual system simulator (VSS) which we use it for system simulation. The maximum small signal gain of 10.62 dB was noted at 70 GHz. The simulated and measured small-signal scattering parameters (S_{11}, S_{12}, S_{21}, S_{22}) gain of the amplifier is shown in Fig. 4 (a), (b), (c), and (d) respectively and the tabular measurements is shown in Table I The measurements shown are in polar form. The data obtained is matches the expected results of a power amplifier and are hence satisfactory. It can be seen that S_{11} is about -4.09 dB at 70 GHz which means that the input is well matched whereas S_{21} shows a power gain of about 10.6 dB. The bandwidth of the power gain is about 6.1 GHz. The improved isolation of the cascading gives the S_{12} a reverse isolation of about -14.9 dB at 70 GHz. The S_{22} shows a -4.09dB value which shows a well matched output as well at 70 GHz. The resemblance in the value of S_{11} and S_{22} is due to the fact that both the input and output ports have been kept at 50 ohm impedance for ease in calculation.

TABLE I
Tabular Measurements

Frequency (GHz)	S(2,2) Circuit PA Unitless data (dB)	S(2,2) Circuit PA Unitless data (Ang: Deg)	S(2,1) Circuit PA Unitless data (dB)	S(2,1) Circuit PA Unitless data (Ang: Deg)	S(1,1) Circuit PA Unitless data (dB)	S(1,1) Circuit PA Unitless data (Ang: Deg)	S(1,2) Circuit PA Unitless data (dB)	S(1,2) Circuit PA Unitless data (Ang: Deg)
40	-0.28451	50.838	-5.3894	-19.636	-0.2826	-90.126	-18.629	160.36
45	-0.89803	32.549	0.62124	-48.109	-0.89697	-128.78	-15.208	131.89
50	-2.4515	18.256	5.4187	-86.044	-2.4516	169.65	-12.728	93.956
55	-4.045	15.527	7.9436	-126.1	-4.0463	92.277	-12.298	53.903
60	-4.3673	15.946	9.0977	-159.3	-4.3688	25.443	-13.057	20.697
65	-4.3728	15.003	9.9807	172.11	-4.3743	-30.783	-13.934	-7.8882
70	-4.0953	15.843	10.627	143.66	-4.0966	-88.523	-14.917	-36.338
75	-3.0362	15.733	10.544	114.58	-3.0366	-146.58	-16.517	-65.422
80	-1.7793	10.226	9.502	88.196	-1.779	166.16	-18.978	-91.804
85	-0.96311	1.8664	7.8868	67.333	-0.96232	132.8	-21.926	-112.67
90	-0.53408	-6.4607	6.1574	51.723	-0.53295	109.91	-24.912	-128.28

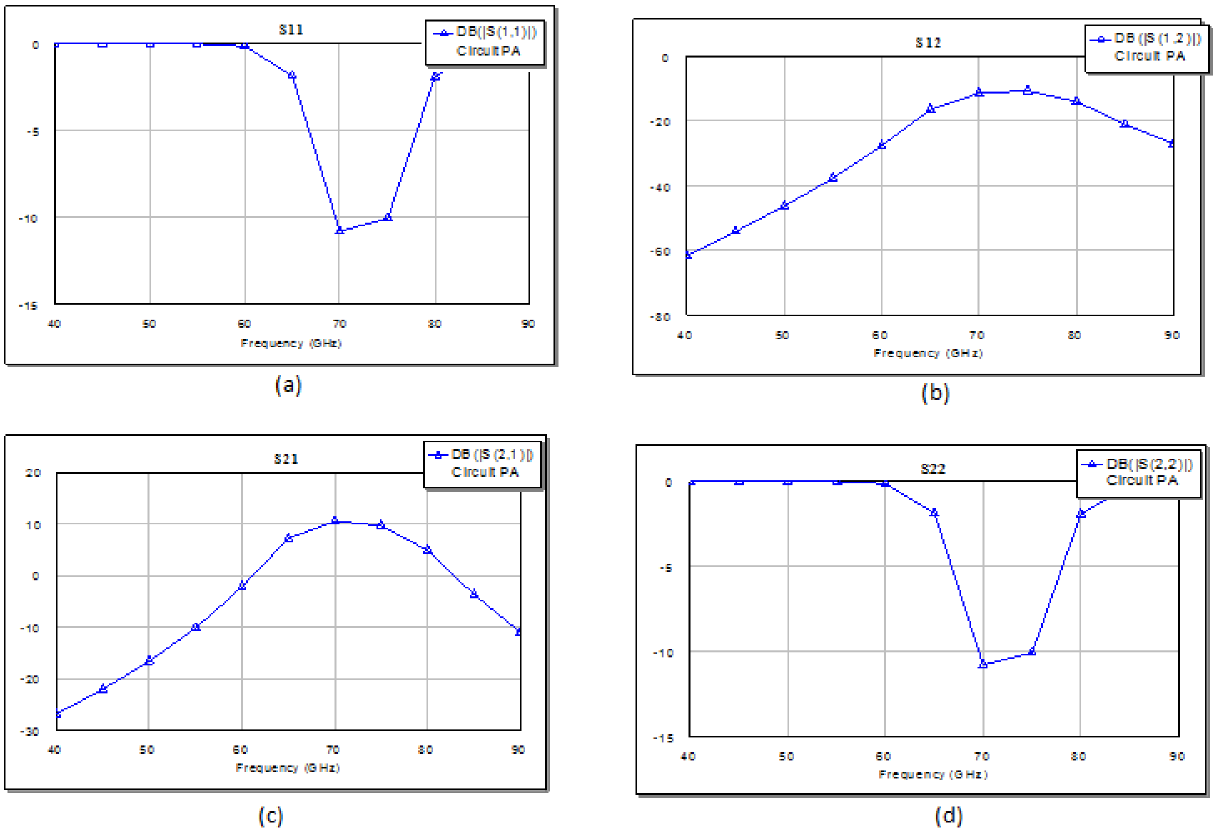

Fig. 4. Measured *S*-parameters of the proposed CMOS PA (a) S_{11}, (b) S_{12}, (c) S_{21}, (d) S_{22}

A. *Transducer Power Gain*

Transducer gain is the ratio of the power delivered by a network to a load (*Pl*) to the power available from the source (*Ps*). Transducer gain is a function of the source and load reflection coefficients and the network *S*-parameters. An amplifier with higher gain settings would be more sensitive as it would take less input signal to produce a given amount of power. Maximum power will be delivered to the load by the amplifier if the load is matched to the amplifier's output impedance. This can be expressed as shown in the following formula:

$$Gt = \frac{Pl}{Pavs} = \frac{|S21|^2(1-|Ts|^2)(1-|Tl|^2)}{[|1-(Ts)(Tin)|^2][|1-(S22)(Tl)|^2]} \quad (1)$$

As shown in Fig. 5, the value of transducer power gain at 70 GHz was noted to be 10.58 dB.

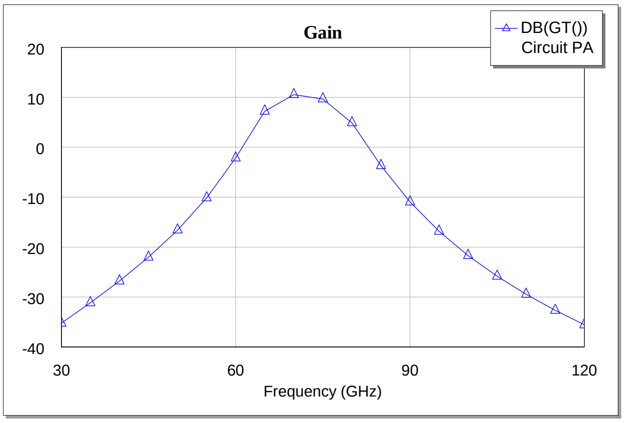

Fig. 5. Transducer power gain

B. Return Loss

Return loss is the difference, in dB, between forward and reflected power measured at any given point in an RF system and does not vary with the power level at which it is measured. The measured return loss for the proposed circuit is shown in Fig. 6.

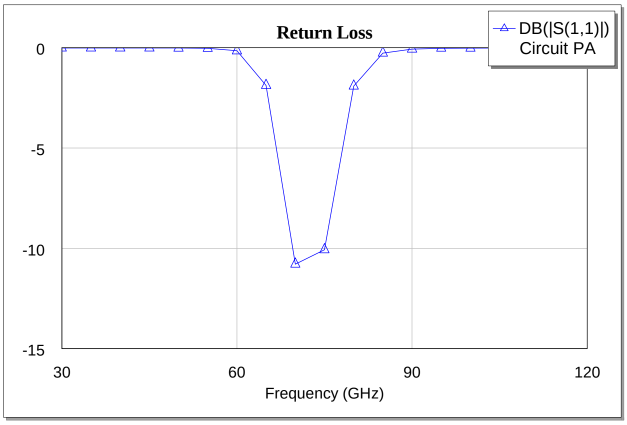

Fig. 6. Return loss

As can be seen from Fig. 6, the return loss is -10.7 dB which is very good. Since the circuit is not a reciprocal system but consists of a matched load to provide ease in calculation, therefore to calculate the return loss the following formula was used.

$$RL = -20\log|T| = -20\log|S11| \quad (2)$$

In case a matched load is not present the below equation will be used.

$$RL = -20\log|T| = S11 - \frac{(S12)(S21)}{1+S22} \quad (3)$$

An example of such a scenario is when the load impedance was changed to 20 ohm causing mismatch and resulting graph is shown in Fig. 7. It can be seen from the graph that the return loss has changed to -16.3 dB.

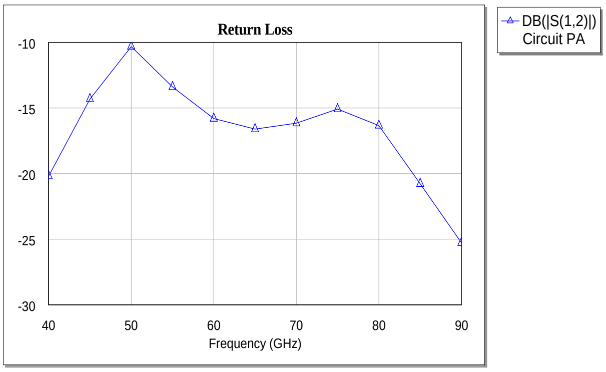

Fig. 7. Return Loss when the load changed to 20 ohm

V. Conclusion

In this paper, basic theory and operation of a millimeter wave PA has been presented together with the most important figures of merit and measurement methods. A PA is the most crucial part in the transmitter as it provides the signal with high power so that it can be retrieved at the receiver. A 70 GHz Class A power amplifier was designed. By taking advantage of cascade topology and load line matching technique a stable amplifier design was simulated having a gain of 10.58 dB and a return loss of -10.7 dB. The use of tune feature in AWR was utilized to improve the results.

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