Nonlinear Analysis and Design of a mm-wave Wideband Doherty Power Amplifier

Fatemeh Taghian, Abdolali Abdipour, Parisa Momen Roodaki, Abbas Mohammadi
Microwave/MMW and Wireless Communications research Lab. Electrical Engineering dept.
Amirkabir University of Technology Tehran, Iran
f.taghian@aut.ac.ir,
abdipour@aut.ac.ir,
parisa.roodaki@yahoo.com,
abm125@aut.ac.ir

***Abstract*-This paper presents the design and nonlinear analysis of a mm-wave wideband Doherty power amplifier at 22 to 29GHz with 7GHz bandwidth, the design is done using 0.15µm GaAs PHEMT transistor to support a variety of mm-wave applications including point to point digital radio, LMDS/LMCS , ka-band satellite spacecraft and ISM applications. The wideband Doherty power amplifier provides greater than 21dBm of output power across 22-29 GHz, with a typical PAE of 35% and typical gain 15dB over the frequency range. The designed Doherty power amplifier also showed acceptable linearity when induced with two tone signal. Analysis results show that the Doherty power amplifier significantly improves both efficiency and linearity in power amplifier in comparison with the main amplifier.**

Keywords-wideband; millimeter wave; Doherty power amplifier; GaAS PHEMT

I. INTRODUCTION

There is some applications in the Industrial, Scientific and Medical (ISM) band at 24GHz such as wireless communication transceivers and automotive vehicular radar[1].

Also, there have been several standards for radio transmitters and receivers for Local Multipoint Communication System (LMCS) in the 28 GHz band (25.35-28.35 GHz) and point to point and point to multipoint broadband systems in the 24GHz (24.25-24.45 GHz and 25.05-25.25 GHz). Figure1 shows the spectral masks for various systems that operate between 22-29 GHz. Although the 7 GHz bandwidth allocated by the FCC enables significant improvement of range resolution, short-range automotive radar systems in this band are constrained by low transmit power levels [2].

The power amplifier is last section of the transmit path. Power amplifier's linearity decides total system linearity, For achieving these objectives, different linearization and efficiency enhancement techniques such as Doherty, envelope elimination and restoration, predistortion, and etc have been developed[3]. Among these techniques Doherty power amplifier (DPA) is very popular, since it enhances both linearity and efficiency and is specially suitable for signals with high PAPR.

On the other hand, accurate evaluation of nonlinear behavior of PAs is very important. Therefore we need an accurate CAD tool to perform nonlinear analysis of PAs.

Up to now a number of power amplifiers have been reported with good performance for ISM band or for LMDS application and or for UWB applications [4], But most pervious works have been focused on one of these bands and these amplifiers are not suitable for modulated signals with high PAPR such as OFDM.

In this paper, we present the design and nonlinear analysis of a mm-wave wideband Doherty power amplifier, for the frequency range from 22GHZ to 29GHz with 7GHz bandwidth for variety of mm-wave applications.

The wideband Doherty power amplifier provides greater than 21dBm of output power across 22-29 GHz, with a typical PAE of 35% and typical gain 15dB over the frequency range. The third-order intermodulation of Doherty power amplifier when excited by two tone signal is less than -30dBc at output power 15dBm, that shows good linearity.

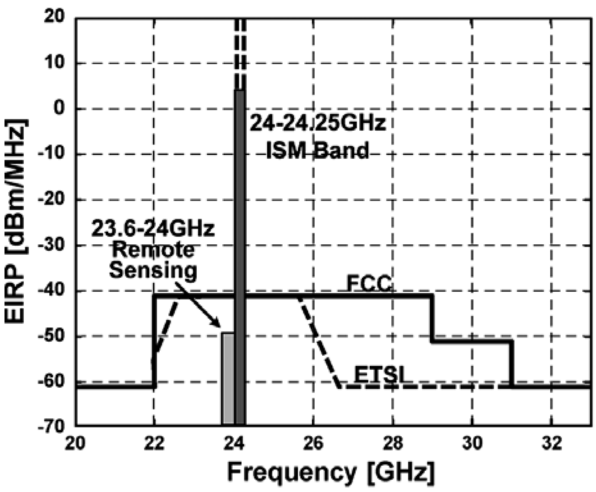

Figure 1 spectrum allocations for systems operating in the 22–29-ghz band _eirp _ effective isotropic radiated power_.

II. WIDEBAND DOHERTY POWER AMPLIFIER DESIGN

The block diagram of the designed wideband Doherty power amplifier is shown in figure 2. The DPA is composed of a Wilkinson power divider, a λ/4 transmission line with a characteristic impedance of 50 ohm and a λ/4 impedance transformer line with a characteristic impedance of 35 Ω [5].

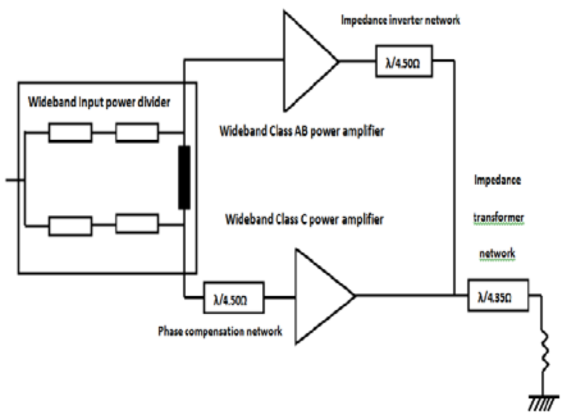

Figure 2 complete circuit of the wideband doherty power amplifier.

A. *Wideband Wilkinson Power Divider*

A wideband Wilkinson power divider provides equal power split, good output port isolation and good return loss at all three ports by using the matured transmission line dual-frequency design theory. The schematic diagram of Wilkinson power divider is shown in figure3 with the parameter values reported in[6].

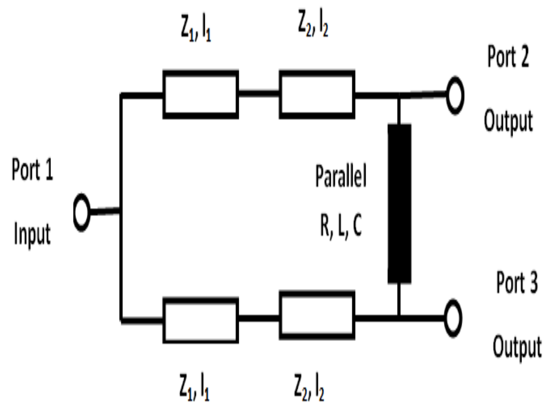

Figure 3 schematic diagram of wilkinson power divider.

Then, according to the concept of replacing the lumped passive components with transmission line sections, we replace the lumped components with transmission line.

B. *λ/4 Transmission Lines*

The fractional bandwidth of s 50Ω, λ/4 transmission line for inverting the impedance from Z_0=100Ω to Z_L=25Ω can be calculated using [7]:

$$\frac{\Delta f}{f_0} = 2 - \frac{4}{\pi}\cos^{-1}\left[\frac{\Gamma_m}{\sqrt{1-\Gamma_m^2}} \cdot \frac{2\sqrt{Z_0 Z_L}}{|Z_L - Z_0|}\right] \quad (1)$$

According to equation 1, the fractional bandwidth of 30% can be obtained for maximum tolerate reflection coefficient magnitude of Γ_m=0.17.

For impedance transformer network, that transforms the impedance from Z_0=25Ω to Z_L=50Ω with fractional bandwidth of 30%, maximum tolerate reflection coefficient magnitude of Γ_m=0.16 can be obtained.

So the conventional λ/4 transmission lines in combining network can be demonstrated with the maximum reflection coefficient magnitude 0.17 of a λ/4 line, that can be tolerated in a Doherty power amplifier.

The output combining network is designed by a conventional λ/4 transmission line with characteristic impedance of 50Ω at the output of the main power amplifier and 35.35Ω for impedance transformer network.

C. *Main and Peaking Power Amplifier*

There are several techniques for wideband power amplifier design such as Distributed amplifier, shunt series feedback, common gate, LC ladder filter matched and etc [8-10]. Ideally, the high power amplifier must be broadband matched to a 50Ω antenna and provide high efficiency and linearity.

For the main power amplifier a wideband class AB power amplifier with a center frequency of 26GHz designed, using 0.15μm GaAs PHEMT transistor due to it's high cutoff frequency and high current density [11] at $V_{ds,m}$=5.5V and $V_{gs,m}$=-0.2. wideband matching networks with series and shunt transmission lines and tapered transmission lines for input and output matching networks were designed as shown in figure 4.

The peaking power amplifier is designed in C class with wideband input and output matching networks with the same topology for easier compensating the phase difference between two power amplifiers. The bias condition of the peaking power amplifier is $V_{ds,p}$= 5.5V and $V_{gs,p}$=-0.5V.

After designing all parts of the Doherty power amplifier, we tuned and optimized the matching networks and bias conditions of the peaking power amplifier for higher efficiency and better linearity of Doherty power amplifier.

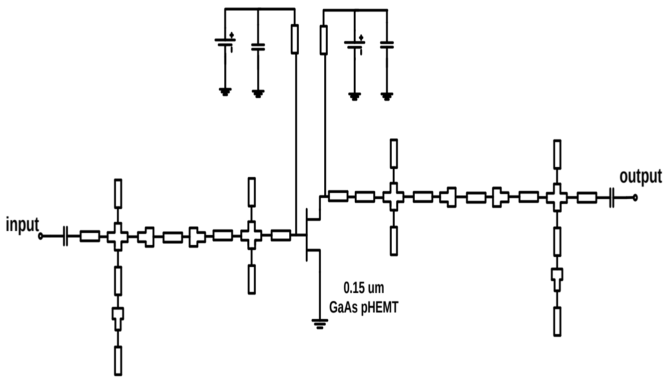

Figure 4 schematic of designed wideband power amplifier.

D. *Nonlinear Analysis Results*

First, the small signal analysis was performed to realize the wideband behavior of the designed Doherty power amplifier. As shown in figure 5, it has good performance in frequency range from 22GHz to 29GHz.

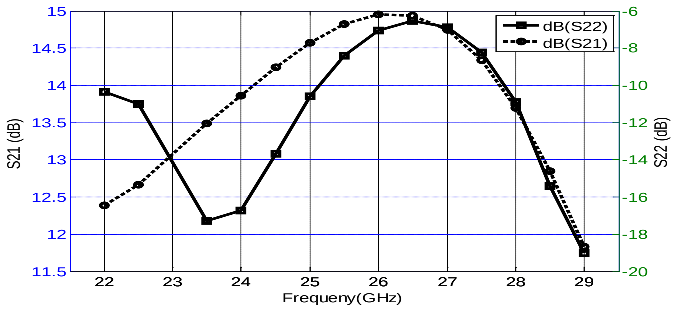

Figure 5 S-parameters of the wideband doherty power amplifier

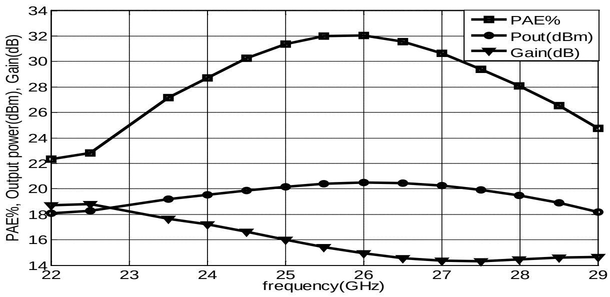

Figure.6 efficiency, gain, output power of the wideband doherty power amplifier at 6db output back-off from 1-db compression point.

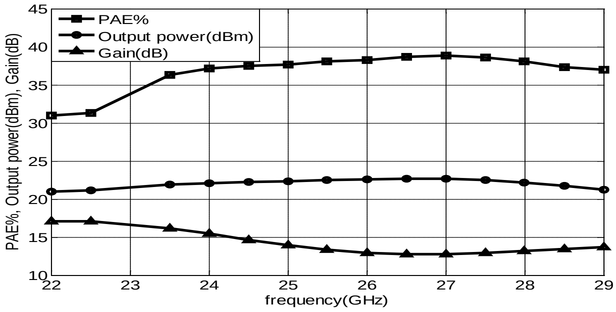

Figure 7 efficiency, gain, output power of the wideband doherty power amplifier at maximum output power.

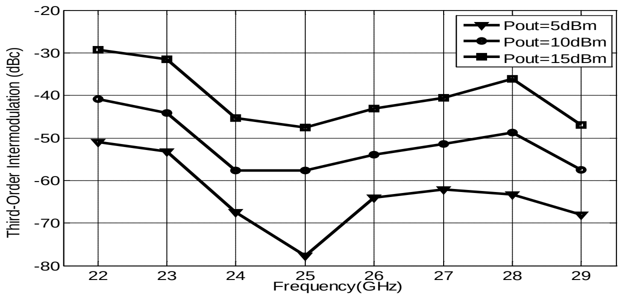

Figure 8 third-order intermodulation ratio(dBc) versus frequency(GHz)

Figure 6 shows PAE, output power(dBm) and gain(dB) versus frequency from 22 to 29GHz at 6dB back-off from the 1-dB compression output power. The PAE is over than 22% at all frequency range. The back-off efficiency ranges from a minimum PAE of 22% at 22GHz to the maximum of PAE=32% at 26GHz.

Figure7 shows PAE, output power and gain versus frequency from 22 to 29GHz at maximum output power, with the PAE ranging from 32% at 22GHz and 39% at 27GHz. The output power range is from 19.8dBm at 23GHz and 23dBm at 27GHz. Maximum gain is 17dB at 22GHz and minimum gain is 13dB at 27GHz.

For linearity assessment, the designed Doherty PA was characterized with a two-tone stimulus with 1 GHz frequency spacing. The two-tone signal was swept over the design band.

Figure 8 shows the third-order intermodulation ratio levels versus frequency(GHz), measured at two-tone output power levels 5dBm, 10dBm and 15dBm. The designed wideband Doherty PA shows acceptable linearity behavior, especially in the frequency range 22 to 29 GHz, with an intermodulation ratio less than -30 dBc at all frequency range due to gm3 cancellation of main and auxiliary amplifiers.

III. CONCLUSION

In this paper, a mm-wave wideband Doherty power amplifier designed and nonlinear analysis of this Doherty power amplifier was done by a CAD tool in frequency range 22 to 29GHz for variety of mm-wave applications including point to point digital radio, LMDS/LMCS, ka-band satellite spacecraft and ISM applications. Nonlinear analysis shows the designed Doherty power amplifier has good efficiency and acceptable linearity at 22-29GHz.

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