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RESEARCH ARTICLE

An integrated cascode DE power amplifier for RF calibration system towards measurement of bio-sensor applications

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Abstract

The integrated cascode DE power amplifier for RF calibration system toward measurement of bio-sensor applications is presented in this paper. The proposed architecture includes cascode class-D and class-E amplifier stages that could provide better calibration accuracy in terms of wide bandwidth, power efficiency, high gain, minimum group delay, and lowest calibration system. The achieved high performance of proposed amplifier overcomes conventional measurement issues toward bio-sensor application. The inductive π-shape matching network drives RF input to class-D stage and provides wide bandwidth of operation. While class-E stage with T-shape matching network maintains stable gain and high efficiency in desired band of operation. The performance of the CMOS proposed amplifier is executed in RF ADS simulator along with fabricated chip using commercial TSMC 65 nm manufacturing process. The simulated and measured data achieves Ku band (12 GHz to 18 GHz) with almost flat gain of 30 dB. The DE amplifier provides an output and saturated power of 17 dBm with highest power efficiency of 45%. The measured calibration factor at maximum resonant frequency of 13.5 GHz achieves best value of less than 2 dB within input power range of −50 dBm to 0 dBm. The lowest calibration factor provides best accuracy along with the other parameters and could be beneficial toward bio-sensor measurement in the various applications. The calculated area of the fabricated chip is as $0.45*0.45\text{mm}^2$ where class-E consuming area of 38% and class-D of 44%. The fabricated chip consumes less power consumption of 3.2 mW under power supply of 1 V.

KEYWORDS
bio-sensor, calibration system, complementary metal oxide semiconductor (CMOS), power amplifier (PA)

1 | INTRODUCTION

Nowadays, biomedical sensors and its applications are wants to be explore various electrical activity observed by skeletal muscles in the human body. Although such biomedical sensors are needs to be accurate measurement and calibration system that could provide better diagnosis environment to the nature. Recently, some biosensors are focused on applications such as prosthetic devices, environmental monitoring, etc. where they require as high-performance RF power calibration equipment's those can do better and accurate measurements.[1] The typical block diagram of the RF power calibration system toward measurement of bio-sensor applications is shown in Figure 1. The proposed class-DE power amplifier is contributing its block inside the RF power calibration system for better accuracy toward bio-sensors applications. The cascode combination of class-D and class-E with CMOS technology is introduce first moment in this work. From last few years, several studies on the development of CMOS power amplifiers has been introduced[2–15] whose brief description are follows next. For example, in the study of Koo et al[2], a fully integrated dual-mode power amplifier with a back-off region of 10 dB and very low

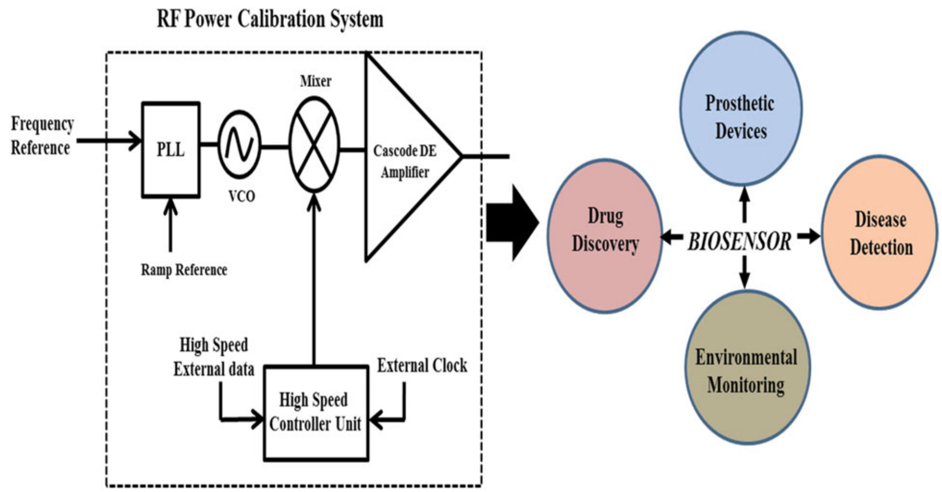

FIGURE 1 The typical block diagram of RF power calibration system towards measurement of bio-sensor application where proposed cascode DE amplifier unit provides best accuracy in terms of performance parameters [Color figure can be viewed at wileyonlinelibrary.com]

quiescent current are achieved for practical wireless communication environment. A digitally controlled bias generator-based CMOS power amplifier achieved peak output power of 22 dBm for WCDMA.[3] The RF power amplifier with 40% of global efficiency achieved −5 dBm output for autonomous wireless sensor nodes.[4] The designed power amplifier topology included asymmetrical series power combiner with LC tuning circuits and achieved 16.2 dBm of output power with a P1dB of 15.2 dBm.[5] An on-chip transformer-based CMOS power amplifier provides a saturated output power of 21.5 dBm with power-added efficiency (PAE) of 20.3%.[6] The frequency and phase generation scheme have successfully developed tunable, multiband CMOS receiver and achieved wideband of 6-18GHz.[7] In the study of Bohn et al.,[8] A integrated phased array receiver is implemented using 130 nm CMOS process and achieved wide band of 6-18 GHz. A three-stage monolithic microwave-integrated circuit (MMIC)-based power amplifier achieved saturated output power of 32 dBm with small signal gain of 23 dB within range of 6-18 GHz.[9] A two stages PA hybrid class provided wide bandwidth from 1.5 GHz to 3 GHz with output power of 19 dBm and more than efficiency of 37%.[10] A new Class-E PA is designed with π-shape matching network and targeted at low output power wireless applications. The achieved output power levels vary from −3.2 to 5.7 dBm with overall efficiency of 55%.[11] A cascode solution for class-E power amplifier has been proposed is to achieve the best trade-off between power efficiency and device reliability. The experimental data demonstrated 67% of PAE when delivering 23 dBm of output power at 1.7 GHz and a PAE higher than 60% over the 1.4 GHz-2 GHz frequency band.[12] In the study of Choi et al.,[13] a CMOS S/X dual band PA has been developed using 0.13 μm 1P8M CMOS technology. It provides a saturated output power of 24.8 dBm and 25.3 dBm with a PAE of 27.2% and 36.4% at 8.4 GHz and 3.0 GHz, respectively. The 3 dB bandwidth is 2.5 GHz (7.4-9.9 GHz) and 2.3GHz (2.7-5.0 GHz). While in Chen et al. study,[14] A Ku-band wideband PA for FMCW radar application demonstrates output saturation power of 13.9 dBm. This FMCW transmitter achieves amplitude ripple less than 2 dB and output power larger than 9 dBm from 13.8 GHz to 15.8 GHz. In the study of Wang et al.,[15] a CMOS Ku-band FMCW transceiver for UAV SAR imaging applications is designed and achieved saturated output power of 14 dBm. This paper proposes integrated cascode DE power amplifier for the measurement of bio-sensors application. The implemented integrated circuit provides best accuracy in terms of performance parameters and overcomes conventional issues towards measurement of bio-sensors in the various application. The results data demonstrate flat gain and linear output power response over wide bandwidth of 12 GHz to 18 GHz. The paper organization is follows as: Section 2 describes about architecture design and its consideration, while Section 3 discuss about simulated and experimental data. Finally, Section 4 is followed by conclusion.

2 | ARCHITCHURE DESIGN AND CONSIDERATION

In this section, architecture design and consideration of the proposed amplifier would be main purpose. While issues concering on the conventional PAs used in RF calibration system towards bio-sensor measurement is first discussing on the subsection 2.1.

2.1 | Issues facing on CMOS PAs for calibration system towards bio-sensor

Generally, various biosensors applications, such as prosthetic devices, drug discovery, disease detection, environmental monitoring, etc., require high gain and linear output power (without any distortion) over wide bandwidth

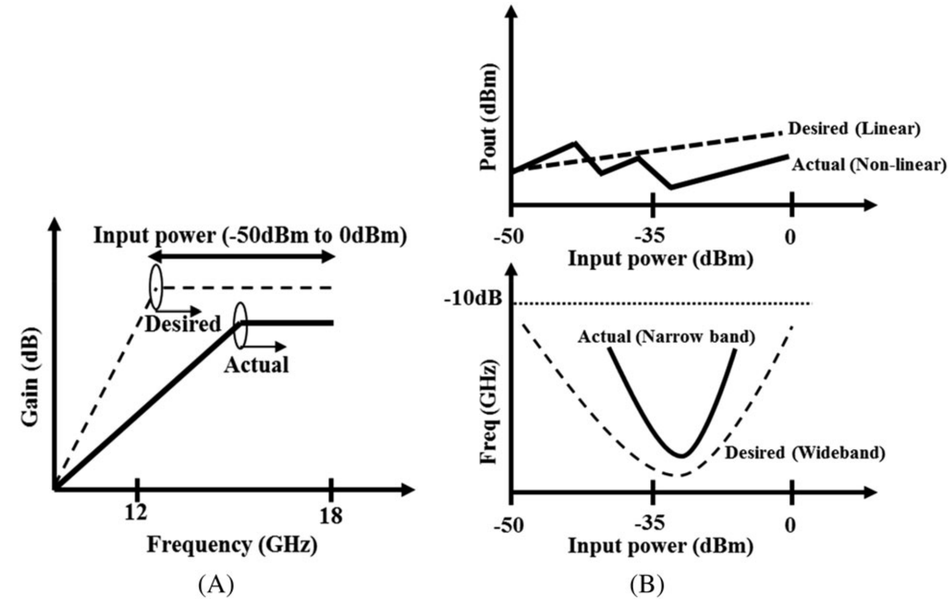

FIGURE 2 Concerning parameters during calibration accuracy toward biosensor (A) desired flatness gain over wide range (B) linear output power corresponding wide bandwidth

whenever doing measurement from RF power calibration system. However, at the same time, measurement using calibration system should be provide best accuracy. The conventional CMOS Pas, such as Class-A, Class-B, Class-C and Class-D, in calibration systems provided high load efficiency up to 50%, but they sacrifice all other parameters over wide band range and also its not more suitable for bio-sensors measurement in various application. Although gain problem in Ku-band systems during calibration towards biosensor is more serious because still only 40% flatness achieved in desired band of operation with input power range of −50 dBm to 0 dBm and due to this, proper biological information is lost. The desired flatness gain over wide range is required toward biosensor measurement and which is shown in Figure 2(A). The second issue concern on the linear output power in Ku band systems where mainly distorted power have been achieved specially in the measurement of biological applications. The desired linear output power respective to wide bandwidth and input power is shown in Figure 2(B). The required two main parameters, that is, gain and linear output power improves RF accuracy in calibration system toward biosensor application by using combination DE power amplifier stages. The designing and analysis of proposed cascode DE stages PA would be discuss in the next subsection 2.2.

2.2 | Cascode DE stages PA

The proposed Class-DE amplifier as the main building block for RF power calibration system and whose schematic is shown in Figure 3. The schematic of amplifier includes Class-D stage, Intermediate LC series network, and Class-E stage. The input RF signal is drive to Class-D stage by using inductive π-shape matching network and provides wideband

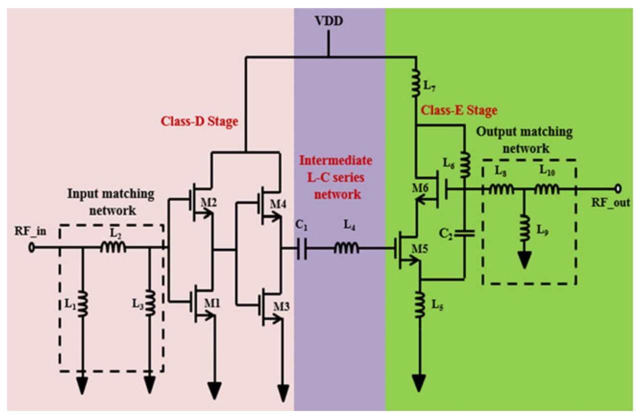

FIGURE 3 Proposed schematic of the cascode DE power amplifier [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Component values of the proposed cascode DE amplifier

Components	Values
M_1 & M_2	30/0.065 μm
M_3 & M_4	60/0.065 μm
M_5 & M_6	30/0.065 μm
C_3	1.19 pF
C_4	1.20 pF
C_5	1.98 pF
C_1	1.0 pF
C_2	1.12 pF
L_1	1.0nH
L_2 & L_7	1.5nH
L_3 & L_6	1.95nH
L_4 & L_5	1.55nH

of operation. The inductive matching network is composed of L_1, L_2, and L_3 cascaded with next subsequent Class-D stage. The MOSFETs M_1 to M_4 are operated in Class-D

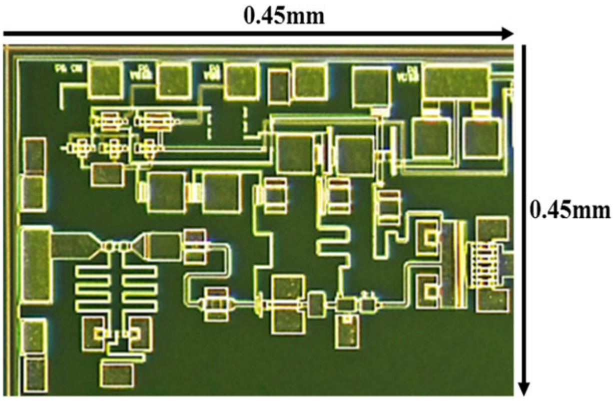

FIGURE 4 Microchip photograph of PA [Color figure can be viewed at wileyonlinelibrary.com]

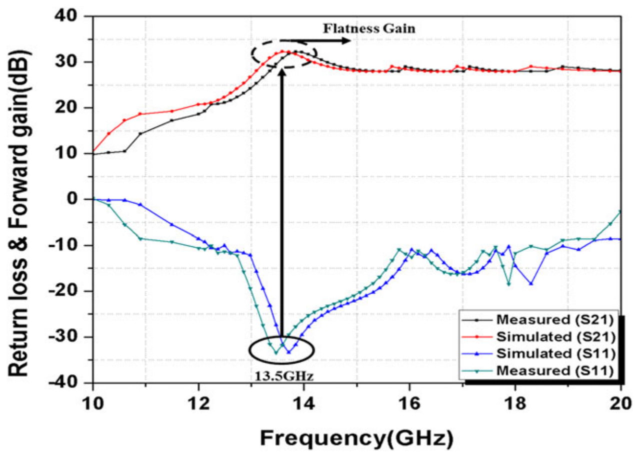

FIGURE 5 Variation of S-parameter with respect to frequency [Color figure can be viewed at wileyonlinelibrary.com]

operation and provides stable flat gain with maintain bandwidth of the previous subsequent stage. The resonance mechanism of intermediate series L_4C_1 network provides operated resonant frequency of 13.5 GHz in the desired band of operation. The achieved resonant frequency is now

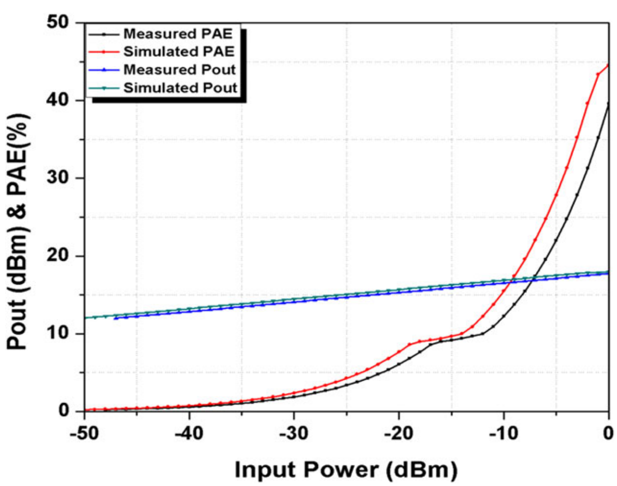

FIGURE 6 Output power and efficiency versus input power [Color figure can be viewed at wileyonlinelibrary.com]

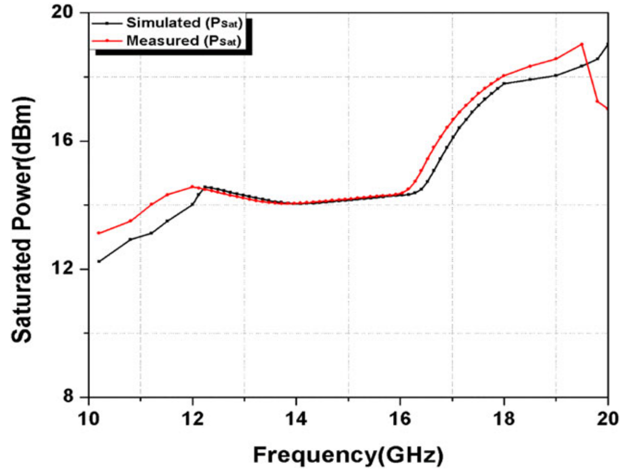

FIGURE 7 Saturated power versus frequency [Color figure can be viewed at wileyonlinelibrary.com]

become input drive of MOSFETs M_5 to M_6 that are operated in Class-E operation. The cascode Class-E amplifiers have become popular since they can overcome loss associated with drain parasitics of the transistor. The main advantage of Class-E design, that is, once switch is turned on, the voltage across it is zero therefore drain parasitic capacitance of the switch need not to be discharged. This is referred as zero voltage switching (ZVS). In fact, parasitic drain-source capacitance of the switch can be absorbed into shunt capacitor C_2 that required in a Class-E PA and this property makes amplifier less sensitive to component variations. Here, we applied microwave approach for Class-E stage to the T-shape output inductive stage because it is more important to maintain the whole Ku-band. Additionally, Class-E stage reduces distortion in the output signal and overcome the impact of load efficiency introduced by Class-D operation. The combination Class-DE operation achieves desired power efficiency with maximum output power. Moreover, inductive T-shape output matching network introduces additional resonating frequency in the desired Ku-band that enables multiband operation for biosensor applications. The

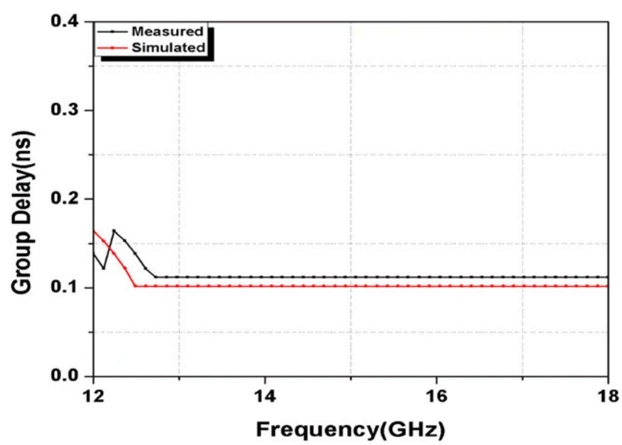

FIGURE 8 Measured GD over wide band [Color figure can be viewed at wileyonlinelibrary.com]

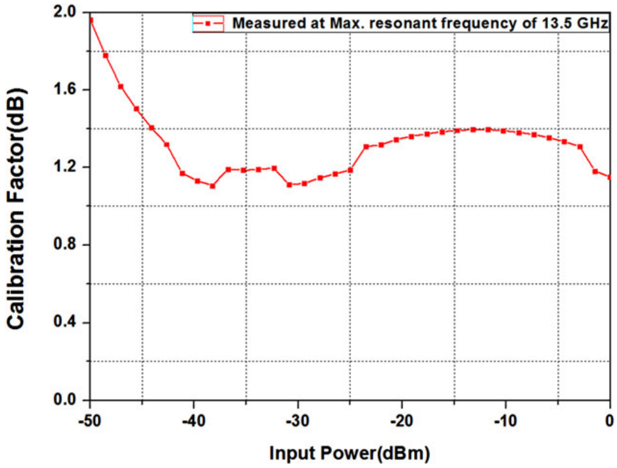

FIGURE 9 Measured calibration factor with respect to input power [Color figure can be viewed at wileyonlinelibrary.com]

component values of the proposed cascode amplifier stages is shown in Table 1.

3 | RESULTS AND DISCUSSION

This section describes performation evaluation of proposed amplifier with simulated and measured results data. The die microchip photograph of the cascode Class-DE power amplifier is shown in Figure 4 where area of fabricated chip is 0.45 mm^2 including all testing pads. The proposed amplifier is implemeted and analyzed using Advanced design system (ADS) RF simulator v.2016. While measurements are done using RF probe station and Agilent vector network analyzer, respectively. The CMOS fabricated chip using TSMC commerical 65 nm manufacturing process where RF inductors and capacitors considered by Murata manufacturing co. ltd. A Layers of metal-insulator-metal are mounted for passive components in the fabricated chip. The experimental and simulated data are commences with S-parameters analysis where return loss and forward gain are examined. The variation of return loss provides Ku-band (from 12 GHz to 18 GHz) with multiresonatant frequencies while flatness in forward gain of 30 dB after first resonating frequency (ie, 13.5 GHz) is achieved and both are illustrated in Figure 5. It is clear at the point of observation that about 85% flatness in the gain over wideband range is achieved using Class-DE amplifier operation. While rest 15% of gain is monotinically increasing from 12 GHz to 13.5 GHz. The simulated and measured return loss and gain are made good correlation with each other. Figure 6 is shown measured and simulated output power of 18 dBm at input of 0 dBm, while highest power added efficiency of 45%. The linear and disortionless output power directly imapct on the load efficiency and achieves maximum percentage efficiency within input range of −50 dBm to 0 dBm. It is observed that less than 50% of efficiency is enough amount toward measurement of biosensor parameters with distortionless power. The variation of simulated and measured saturated output power less than 3 dB is achieved and can be seen in Figure 7. As per reported data, it is found that a flat group delay is diffcult to achieve over wide bandwidth. For accuarcy considerations, group delay is one of important factor for measurement calibration that significantly reduces the error. The variation of group delay with respect to frequency is shown in Figure 8 where value of 0.1 ns flat GD is achieved over whole Ku-band range. The calibration factor is also measured at the maximum resonant frequency of 13.5 GHz from input power range of −50 dBm to 0 dBm and it can be seen in Figure 9. The lowest value of 1.2 dB for calibration factor provides best accuracy toward measurement of biosensor applications. The performance comparison of current work with other reported ones is shown in Table 2.

4 | CONCLUSION

In this paper, an integrated Class-DE cascode power amplifier for RF calibration system towards bio-sensor measurement is concluded. The proposed combination of Class-DE amplifier stages provided best accuracy in terms various performance parameters for calibration system. The cascode PA stages achieved flatness in the gain and linearity with distortion less output power that overcomes issues to conventional PAs. The fabricated chip is made by using 65 nm TSMC commercial manufacturing process. The measured data

TABLE 2 Comparison performance of current work with other references papers

Design parameters	14	15	This work
Device technology(nm)	65	65	65
Frequency(GHz)	13.5-19(15)	15	12-18(13.5)
Peak power(dBm)	13.9	13.3	18
Gain (dB)	20.65	20	32.5 (85% flatness)
PAE_{avg} (%)	42	-	45
V_{DD}	1.2	1.2	1.0
Chip area(mm^2)	0.62	-	0.45
Target Application	FMCW radar sensor	FMCW transceiver with radar sensor	RF calibration system to bio-sensor

demonstrated high gain of 30 dB, output power of 18 dBm at input of 0 dBm, highest power efficiency of 45% and 1.2 dB calibration factor.

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