M.S. THESIS

A Highly Linear X-Band GaN HEMT Transformer-Based Doherty Power Amplifier

GaN HEMT 소자를 이용한 X-대역 트랜스포머 베이스 선형 도허티 전력 증폭기

BY

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SCHOOL OF ELECTRICAL ENGINEERING AND
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SEOUL NATIONAL UNIVERSITY

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기반 선형 도허티 전력 증폭기

지도교수 권 영 우

이 논문을 공학석사 학위논문으로 제출함
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전기컴퓨터 공학부
이 승 엽

이승엽의 공학석사 학위논문을 인준함
2015 년 8 월

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부위원장 ______________________ (인)

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Abstract

This thesis presents an X-band Transformer-based Doherty Power Amplifier(PA) with a phase linearizer. Doherty PA used Cree inc. 6 W GaN HEMT bare die and implemented on 7-layer PCB. The phase linearizer compensates a phase distortion of Doherty PA.

X-band Conventional Doherty PA is designed at 10 GHz for performance comparison with the X-band Transformer-based Doherty PA. The Conventional Doherty PA used Cree inc. 6 W GaN HEMT bare die and has been implemented using RT/Duroid 5880 10 mil thick substrate. The continuous wave (CW) measurement results show the peak output power of 40.3 dBm with a 40 V drain supply voltage at 10 GHz, the peak drain efficiency (DE) of 51% and the peak power added efficiency (PAE) of 40.3%. And the DE and PAE at 6 dB output power back-off are 41% and 33% respectively.

X-band Transformer-based Doherty PA has been measured. The CW measurement results show the peak output power of 39.6 dBm with a 40 V supply at 9.56 GHz. The peak DE is 50.4% while the peak PAE is 38.5%. The DE and the PAE of the amplifier is still as high as 40% and 32.5% respectively at 6 dB output power back-off.

Linearity of the X-Band Transformer-based Doherty PA has been measured and the linearizer has been designed to improve the linearity of the Transformer-based Doherty PA. The linearizer used varactor diode from MACOM technologies. The X-band Transformer-based Doherty PA with linearizer has been measured with 20 MHz LTE and 40 MHz LTE-A signals respectively. 20 MHz LTE measurement result shows -40.1 dBc ACLR at the output power of 32 dBm and 40 MHz LTE-A measurement result shows -35.4 dBc ACLR at the output power of 31 dBm.

Key words : X-Band, Doherty Power Amplifier, Linearity,
Transformer-combining, LTE

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Chapter 1

Introduction

A future communication standard such as 5G is expected to be realized at frequency-band of millimeter-wave due to the lack of frequency resource in low frequency band (< 3 GHz). However, designing a millimeter-wave power amplifier (PA) that covers wideband modulation signal requires many challenges due to the high peak to average power ratio (PAPR) of the communication schemes. Doherty PA which has a high efficiency at back-off power is an attractive solution to handle the high PAPR signals [1-3]. Recently, a transformer-based Doherty PA has been reported which replaces bulky input coupler and output Doherty network to the balun and transformer [4]. Compared to the conventional Doherty PA, the transformer-based Doherty PA has much compact size, and simpler matching network. Also, uneven Doherty PA can be easily realized by adjusting the turn ratio of the balun and transformer [5]. Linearity is another important matric in designing Doherty PAs. Even though there have been researches about Doherty PAs to handle modulated signals in millimeter-wave, most of their work employs digital pre-distortion to linearize PAs which is not effective especially in wideband signals [6].

Figure. 1.1 is a simplified block diagram of this work, a hybrid type 9.56 GHz transformer-based Doherty PA using commercially available Cree's 6 W GaN HEMT has been developed to handle 40 MHz bandwidth (BW) LTE-A signal. A gain distortion during the Doherty operation is minimized by carefully investigating gate biases of main and auxiliary amplifiers. To linearize the phase distortion of the PA, a varactor based phase linearizer is employed in front of the PA that utilizes the re-shaped envelope signal as a control voltage for the varactor. The entire Doherty PA with a linearizer is tested with 40 MHz BW, 9.66 dB PAPR, two carrier aggregated LTE-A signal and shows 23% PAE and -35.4 dBc CA EUTRA ACLR at the output power of 31 dBm. The proposed linearizer improves ACLR by 7 dB, which clearly demonstrates the effectiveness of the linearizer.

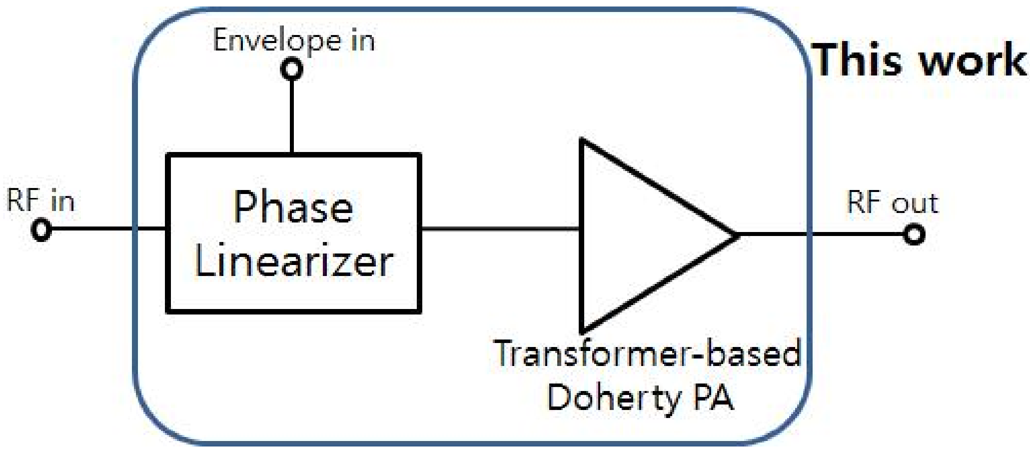


Figure 1.1 Block diagram of this work

Chapter 2

X-band Conventional Doherty PA

2.1 Design of conventional Doherty PA

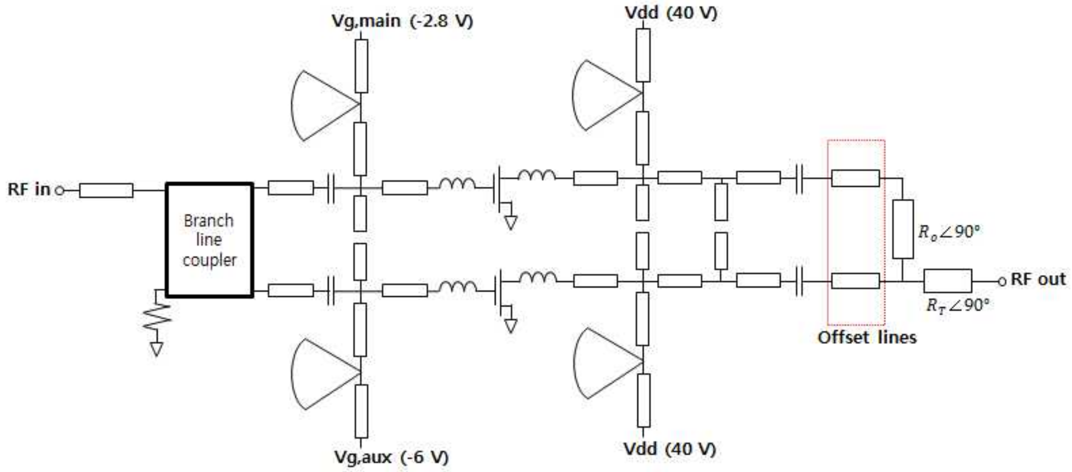


Figure 2.1 Schematic of the Conventional Doherty PA.

The schematic of the conventional Doherty PA is plotted in Figure 2.1. The PA used Cree's 6 W GaN HEMT bare die (CGHV1J006, gate length=0.25 μm) and implemented using RT/Duroid 5880 10 mil thick substrate. Branch line coupler is used as input power divider and output matching is performed based on ADS harmonic load pull simulation. Main amplifier is biased at Class AB(-2.8 V) and auxiliary amplifier is biased at Class C(-6 V).

2.2 Measurement results of conventional Doherty PA

The conventional Doherty PA is measured at 10.08 GHz and the module photograph is shown in Figure 2.2 and the continuous wave(CW) signal measurement results in term of DE, PAE, and gain are plotted in Figure 2.3. Measurement results show 40.3 dBm of maximum output power at 40 V supply with 40.4% of peak PAE. The PAE maintains 33% at 34 dBm of output power.

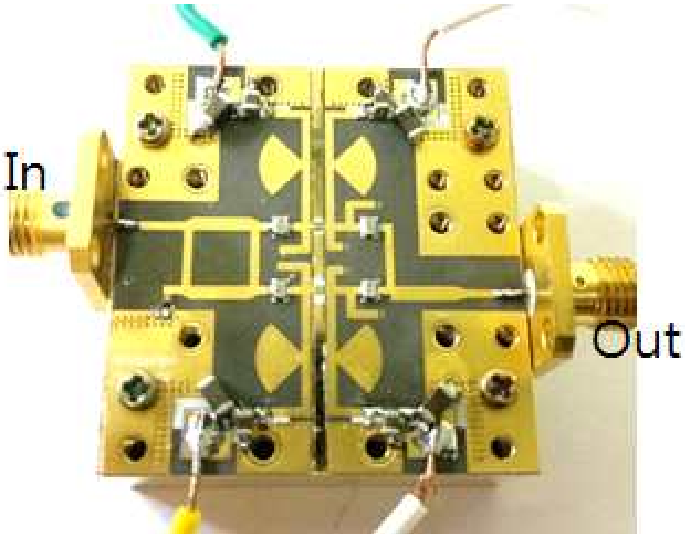


Figure 2.2 Module photograph of the conventional Doherty PA.

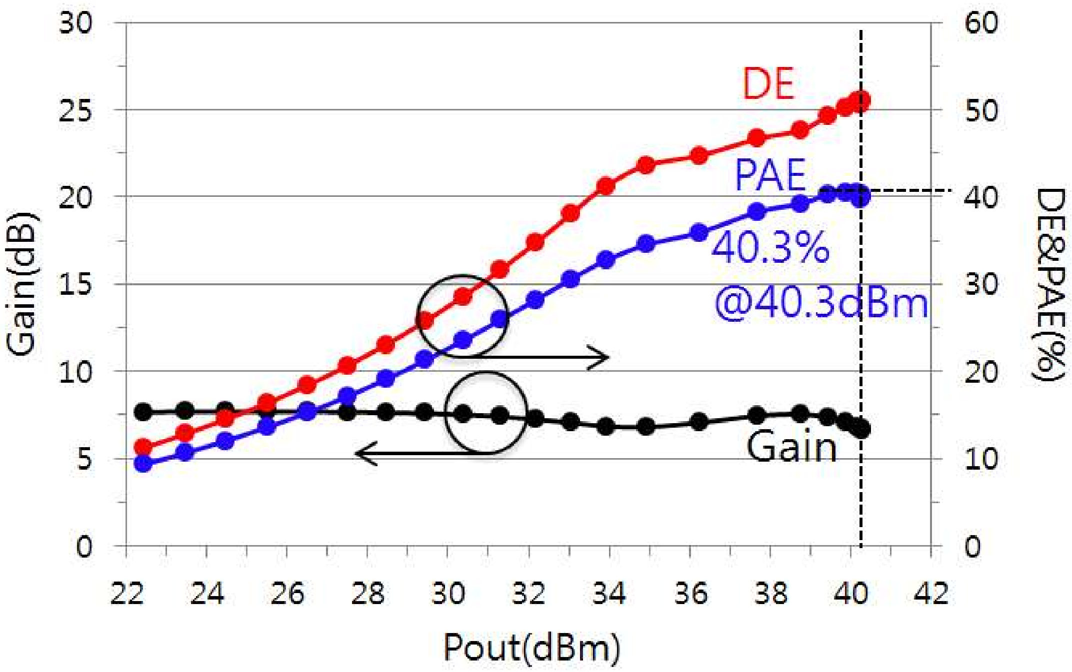


Figure 2.3 Measurement results of the conventional Doherty PA.

By this experiment of hybrid type 10.08 GHz conventional Doherty PA, we verified that the development of hybrid X-band Doherty PA is possible.

Chapter 3

Transformer-based Doherty power amplifier

3.1 Load modulation with Combining Transformer

Figure 3.1 shows a simplified block diagram of the transformer-based Doherty PA, and a detail drawing of an In-phase type ideal series-combining transformer is shown in Figure 3.2. Equations of current and voltage are arranged (1a~1d) by the transformer equation and load impedances seen at the input plane of each input node of transformer are expressed in (1e) and (1f) assuming N1 and N2 are primary and secondary winding ratio respectively :

$$V_3 = V_2 + V_2^{'} \ (1a)$$

$$I_1 = \frac{N_2}{N1} I_2,\ I_1^{'} = \frac{N_2}{N_1} I_2 (1b)$$

$$V_1 = \frac{N_1}{N_2} V_2 = \frac{N_1}{N_2} (V_3 - V_2^{'}) \ (1c)$$

$$V_1^{'} = \frac{N_2}{N_1} V_2^{'} \ (1d)$$

$$R_{main} = \frac{V_1}{I_1} = \frac{V_2}{I_2}\left(\frac{N_1}{N_2}\right)^2 = \frac{V_3 - V_2^{'}}{I_2} = \left(R_{load} - \frac{V_2^{'}}{I_2}\right) \bullet \left(\frac{N_1}{N_2}\right)^2 \ (1e)$$

$$R_{aux} = \frac{V_1^{'}}{I_1^{'}} = \frac{V_2^{'}}{I_2}\left(\frac{N_1}{N_2}\right)^2 \ (1f)$$

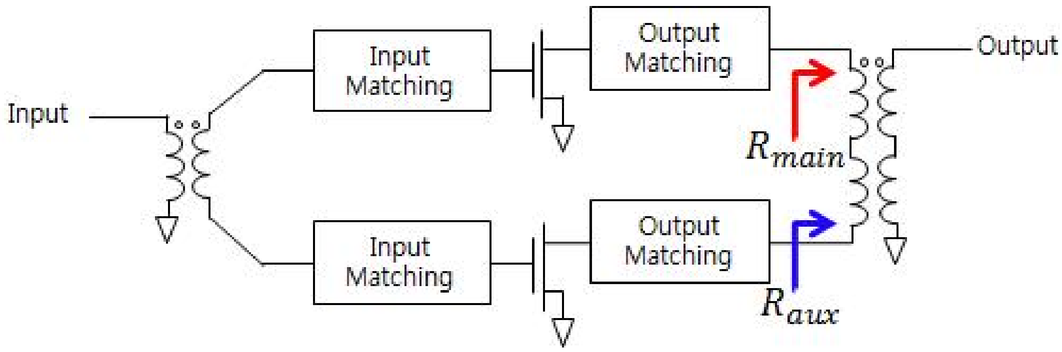


Figure 3.1 Simplified block diagram of transformer-based Doherty PA

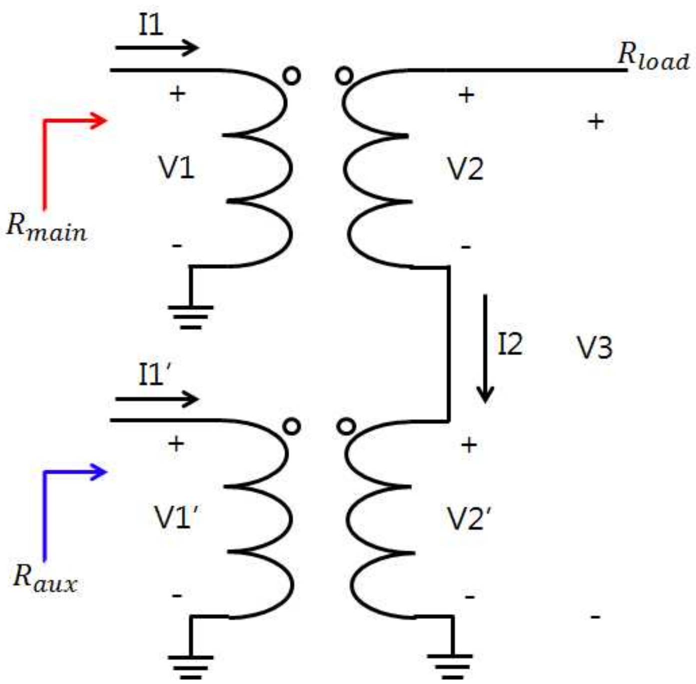


Figure 3.2 Schematic of the in-phase type Series combining Transformer.

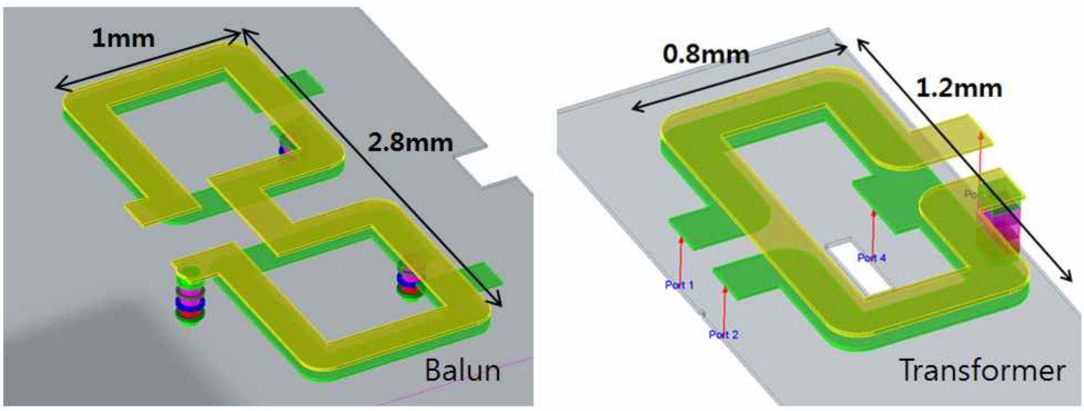
As equations 1e and 1f, load modulation occurs by the ratio of V2′ and I2. In other words, the load of main amplifier decreases when input power increases and the load of auxiliary amplifier increases when input power increases.

3.2 Design of Transformer and Balun

The transformer and the balun are designed by overlaying a second and a third metal layer of 7-layer PCB and each of components comprises a lower primary winding and an upper secondary winding.

The size of transformer and balun is optimized considering its power combining efficiency and power dividing efficiency respectively. Self-inductance of the transformer is an important design consideration since it is used as a load matching component.

Figure 3.3 shows 3D EM layout of the designed transformer and balun used in this work.



(a) (b)

Figure 3.3 3D EM view of (a) Transformer and (b)Balun.

3.3 Circuit design

Figure 3.4 shows a schematic of the Transformer-based Doherty PA. It contains a compact size of balun and transformer at input and output network respectively and output tuning components. In comparison with the conventional Doherty PA, bulky passive components at input and output are replaced with compact size of balun and transformer, thus this topology takes advantage of a structural simplicity and a areal compactness.

In this topology, self-inductance of the transformer is used for load matching and shunt inductance optimizes the matching. Thus the output matching network can be simplified.

The drain bias voltages for both amplifiers are supplied at the same time through a center-tap of the primary winding of the transformer.

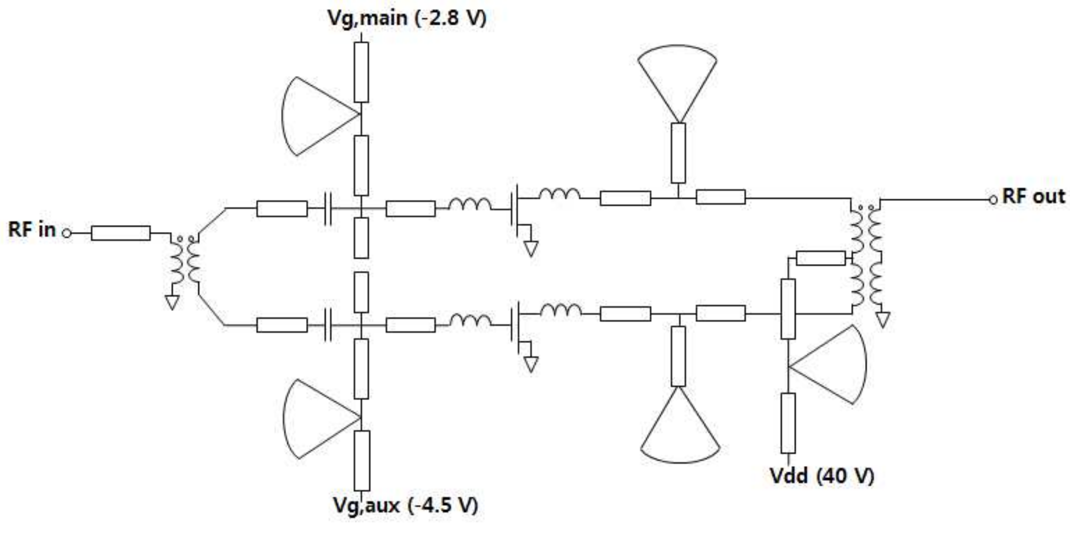
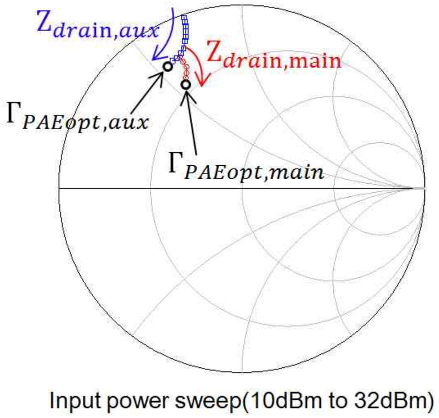
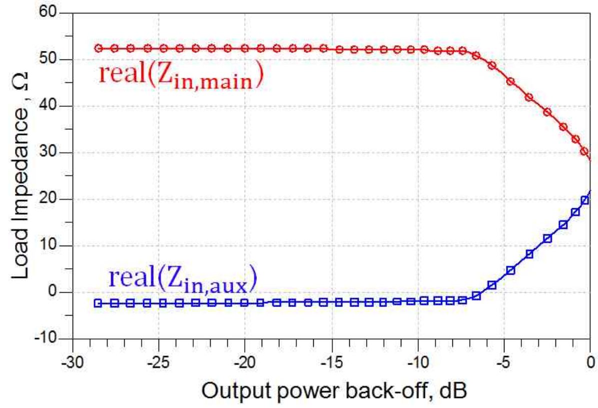


Figure 3.4 Schematic of the Transformer-Based Doherty PA.



(a)



(b)

Figure 3.5 The simulated load matching seen by the main amplifier and the auxiliary amplifier.

Figure 3.5(a) shows simulation results at 9.56 GHz of load modulation seen by drain node of main and auxiliary amplifiers. High power optimum impedances of both amplifiers are optimized individually since they are operating in different class, class AB and class C.

Figure 3.5(b) shows simulation results of load modulation seen by the input nodes of transformer at the same frequency. At low input power, only the main amplifier delivers power to the output and impedances of both amplifiers move to optimum loads as the input power increases thus delivers same power to the output at peak input power.

The total layout of the circuit is shown in Figure 3.6. The hybrid type transformer-based Doherty PA used Amitec's 7-layer PCB. The PCB divided as input and output section. Square shaped dummy metals as shown in layout are filled at each layers to satisfy metal density rule. The layout of Bare die GaN HEMTs are placed at the center of input and output PCBs.

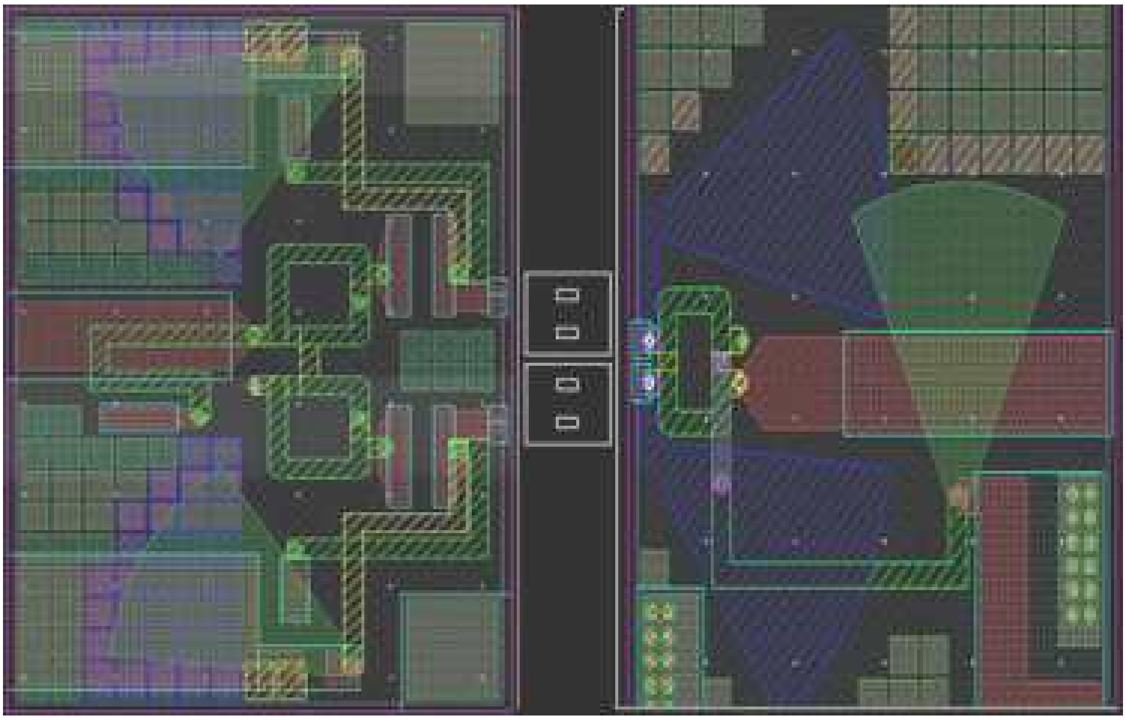


Figure 3.6 Full circuit layout with transistor outline used in ADS simulation.

3.5 Simulation results

3.5.1 Efficiency of transformer and balun

In the Transformer-based Doherty PA, the Combining efficiency of a transformer is important to get outstanding performance of power amplifier since the most of output power loss occurs at the stage of power combining transformer. In this design, transformer efficiency is as high as 90% thanks to low loss of copper metal layer and a proper distance between primary winding and secondary winding layers. And this is outstanding efficiency comparing other transformers used CMOS and other technologies in previous works. Also the balun showed the efficiency of exceeding 80% as shown in Figure 3.7.

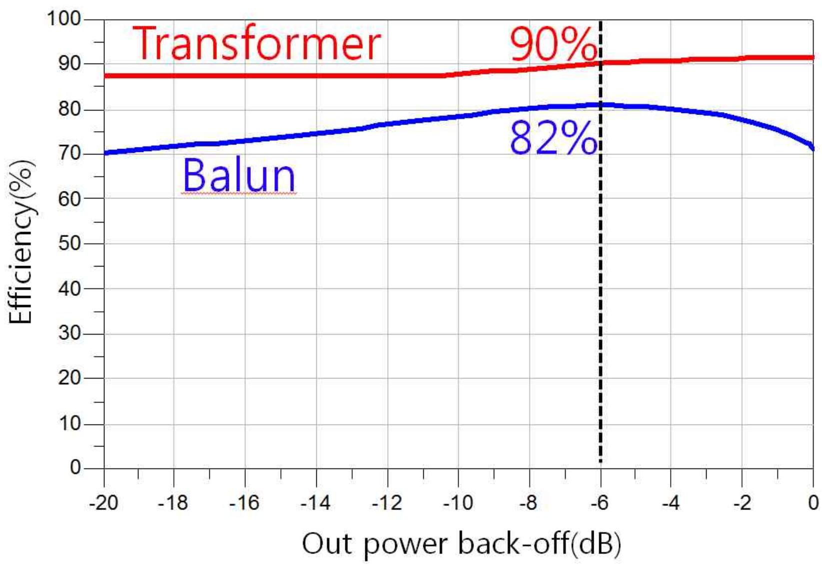


Figure 3.7 Simulation results of the transformer and balun efficiency

3.5.2 Simulation results of Transformer-based Doherty PA

Figure 3.8 shows the simulated performance with full EM simulated data of input and output circuits in term of gain, drain efficiency, and power added efficiency at 10 GHz. The main amplifier was biased at Class-AB and the bias of auxiliary amplifier was adjusted to compromise the peak efficiency and the back-off efficiency maintaining Class-C. In simulation, the Transformer-based Doherty PA achieves a peak output power of 40.4 dBm with a peak PAE of 39.6% at 40 V supply. In addition, the PAE is maintained higher than 32.5% at 6 dB output power back-off.

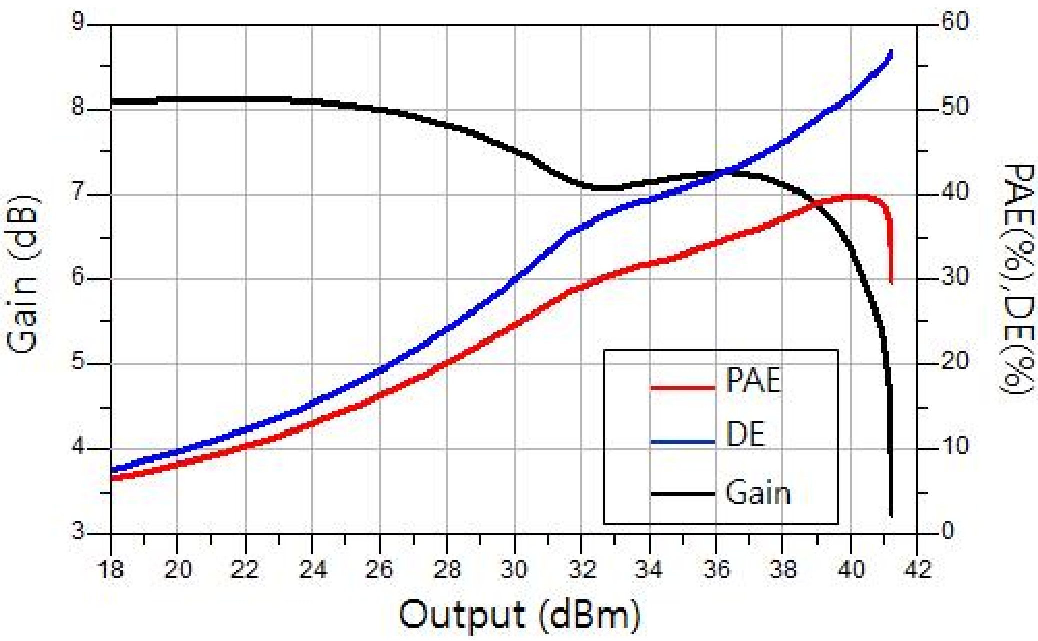
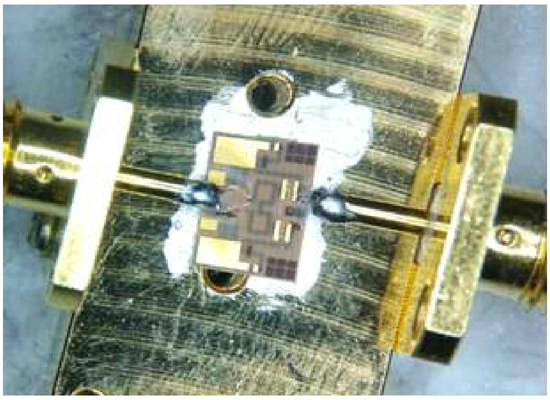


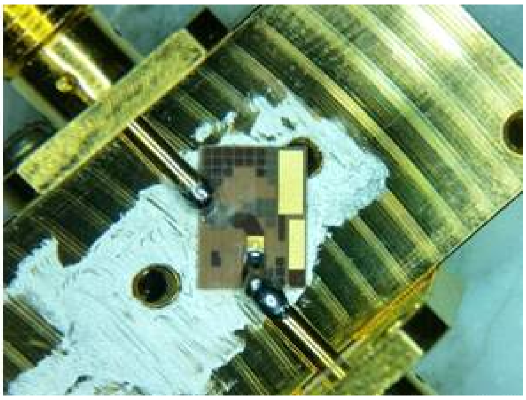
Figure 3.8 The simulated Gain, DE and PAE of the Transformer-Based Doherty PA at 10 GHz

3.6 Characterization of 7-layer PCB

Firstly, frequency characteristics of 7-layer PCB are checked because factors like dummy metals for metal density, cross over between layers, and fabrication errors hinder characteristics. Test modules are implemented for each input and output networks. For the test module of input network, SMA connectors are attached to an input feed line and a gate feed line of main path. And for the test module of output network, SMA connectors are attached to a drain feed line of main path and an output feed line of the circuit. Figure 3.9 shows input and output test modules.



(a)

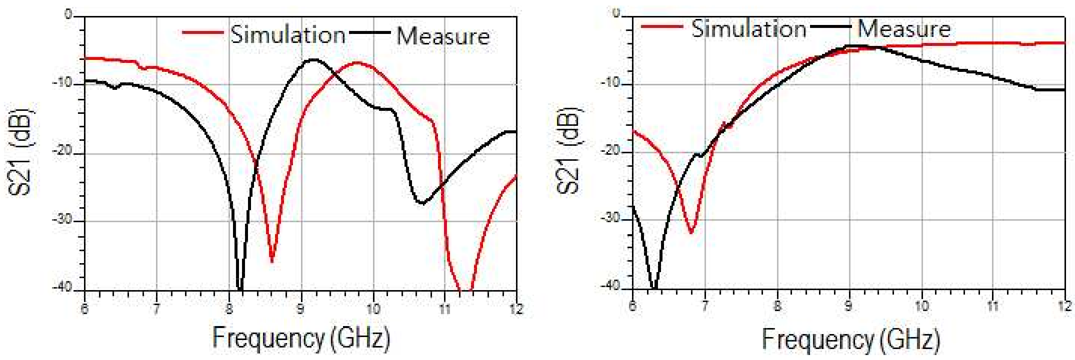


(b)

Figure 3.9 Photographs of Input and Output test modules.

The measurement results of two-port small signal characteristics are plotted in Figure 3.10 with EM simulation results for comparison. Magnitude of the measured S(2,1) follows the simulated S(2,1) for all frequency range but the critical thing in this comparison is frequency shift about 500 MHz which is lower than the EM simulation result.

This problem has been solved through down-sizing the balun and transformer about 10% for the size of the EM simulated balun and transformer.



(a) (b)

Figure 3.10 EM simulation results and measured results in terms of phase and magnitude of (a)input circuit and (b)output circuit

3.7 Measurement results

The implemented hybrid module photographs of the Transformer-based Doherty PA is shown in Figure 3.11. The overall module size of Transformer-based Doherty PA is $12 \times 7.7\,mm^2$. It takes only 7% of the size for the size of Conventional Doherty PA, $36 \times 36\,mm^2$.

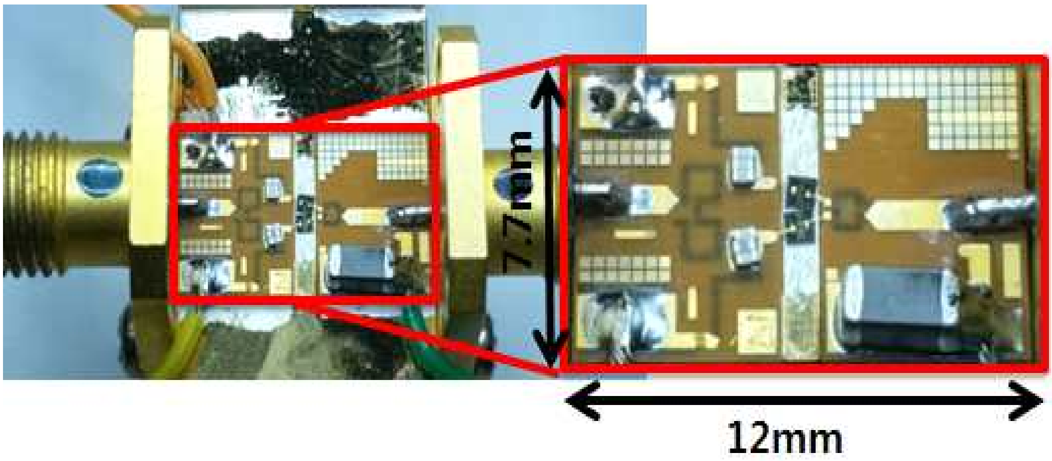


Figure 3.11 Module photograph of the 9.56 GHz Transformer-based Doherty PA.

3.7.1 CW measurement results

The continuous wave(CW) measurement results of the Transformer-based Doherty PA are plotted in Figure 3.12. Measured peak output power is 39.6 dBm with a 40 V supply at 9.56 GHz. The peak DE is 50.4% while the peak PAE is 38.5%. The DE and the PAE of the amplifier is still as high as 40% and 32.5% respectively at 6 dB output power back-off.

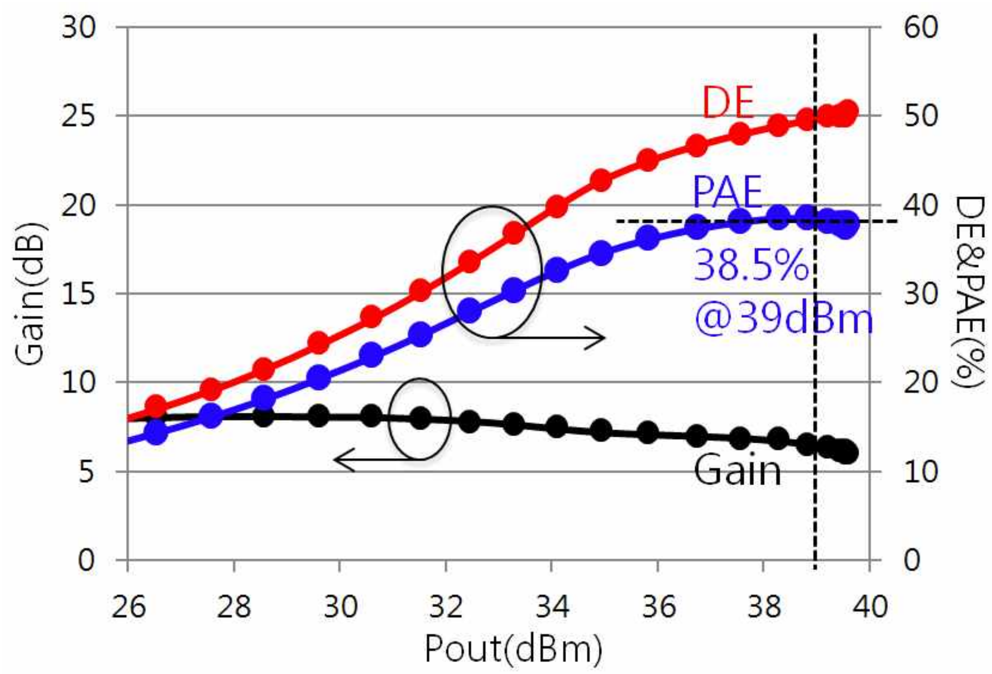


Figure 3.12 CW measurement results in terms of gain, DE, and PAE versus output power of Transformer-based Doherty PA

3.7.2 Modulation signal measurement results

In previous work, the hybrid Transformer-based Doherty PA has been presented. To applicate this PA to the real world mobile communication systems, performance test with LTE modulation signal is necessary.

In the measurement setup, the 20 MHz LTE signal is provided from RF signal generator(Agilent E8267D) and the measured gain and efficiencies are plotted in Figure 3.13. The measured performance with 20 MHz LTE signal is similar with the CW signal performance.

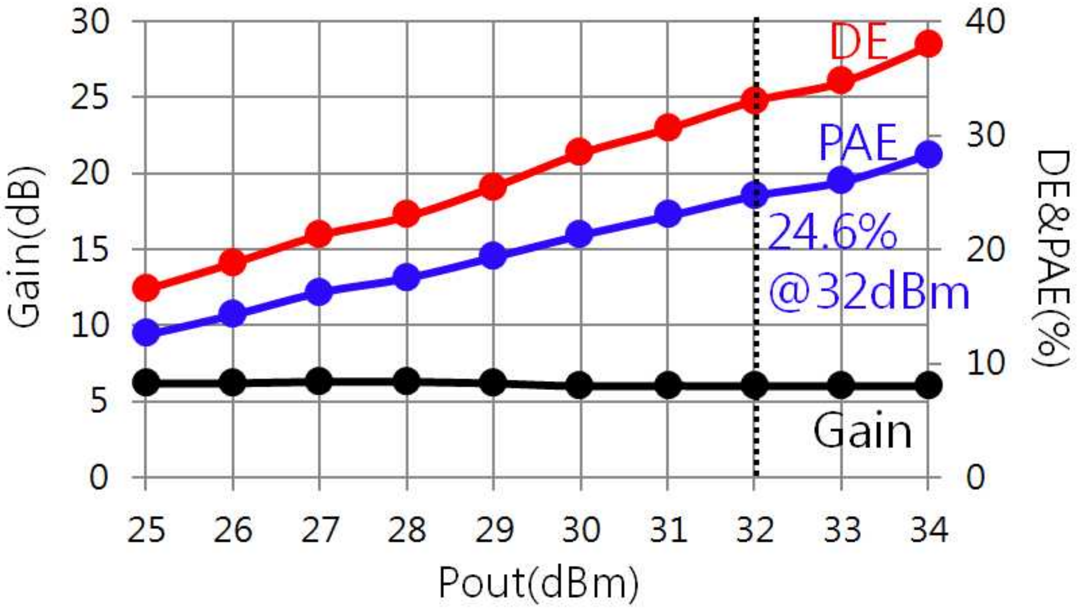


Figure 3.13 20 MHz LTE measurement results in terms of gain, DE, and PAE versus output power

A graph of ACLR by the output power is shown in Figure 3.14. Since the real world LTE communication system requires -40dBc of ACLR. this transformer-based Doherty PA shows not enough linearity performance. To verify AM-AM and AM-PM characteristics of the PA, dynamic measurement program(Agilent 89604 Distortion Suite) is used and the results are shown in Figure 3.15. From the measurement results of dynamic characteristics, we can know that the AM-PM is a dominant reason for bad ACLR. This AM-PM distortion should be solved, thus the phase linearizer which compensates the AM-PM distortion of the PA is presented in the next chapter.

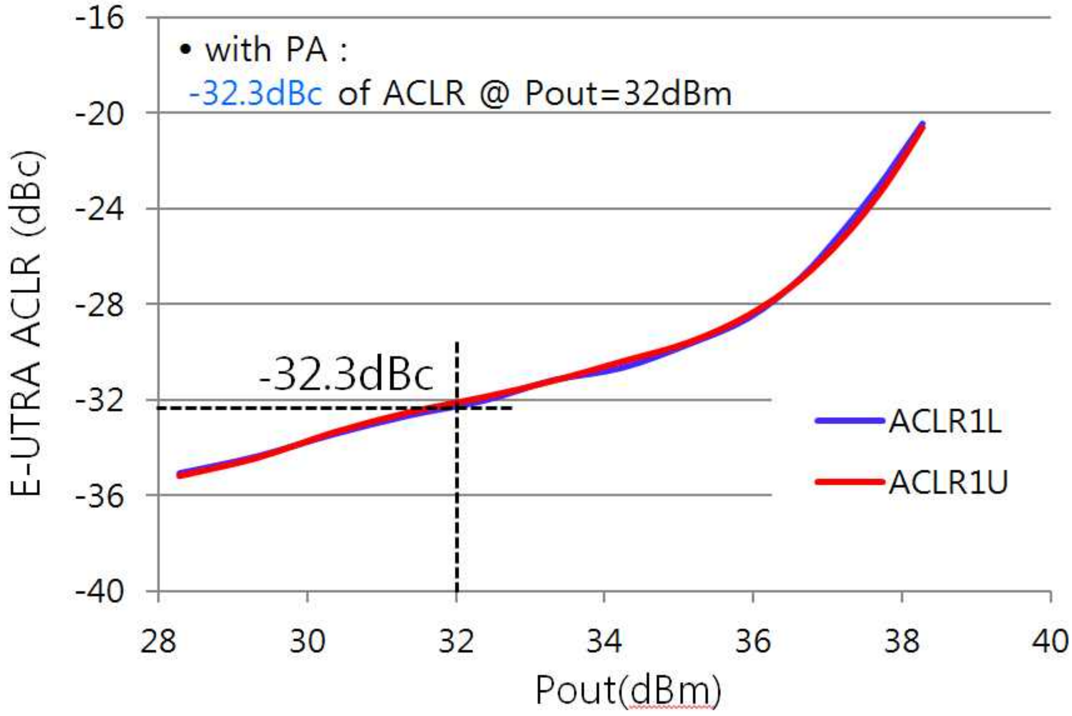
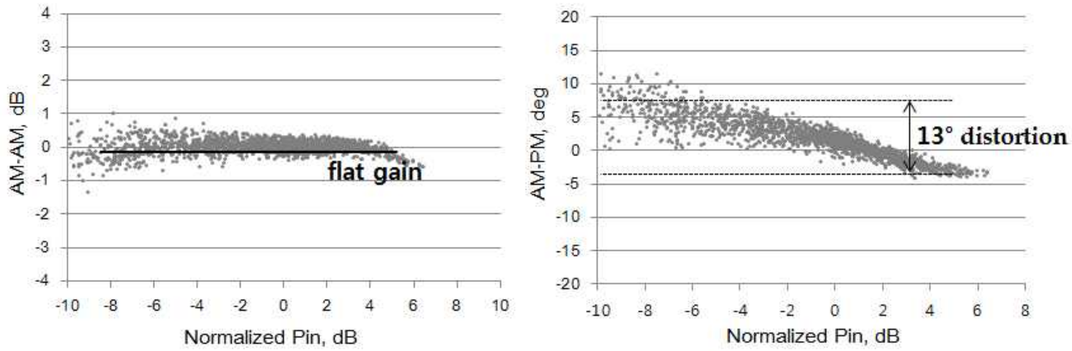


Figure 3.14 Measured ACLRs versus output power at 9.56 GHz.



(a) (b)

Figure 3.15 Measured dynamic AM-AM and AM-PM of PA at Pout = 32 dBm using a 9.56 GHz LTE signal with 20 MHz bandwidth.

Chapter 4

Linearization of transformer-Based Doherty Power Amplifier

4.1 Theory of Linearization

As shown before, the AM-PM distortion of the PA should be compensated while maintaining the good quality of the AM-AM. In this work, AM-PM of the transformer-based Doherty PA has a 13 degrees distortion of declining shape. To solve this problem, an AM-PM which has inclining shape is need to be injected at input or output of the PA. Then the AM-PM of the entire circuit will shows flattened shape. In this work, a varactor based phase linearizer is employed in front of the PA that utilizes the re-shaped envelope signal as a control voltage for the varactor. Figure 4.1 shows a block diagram of this linearization technique.

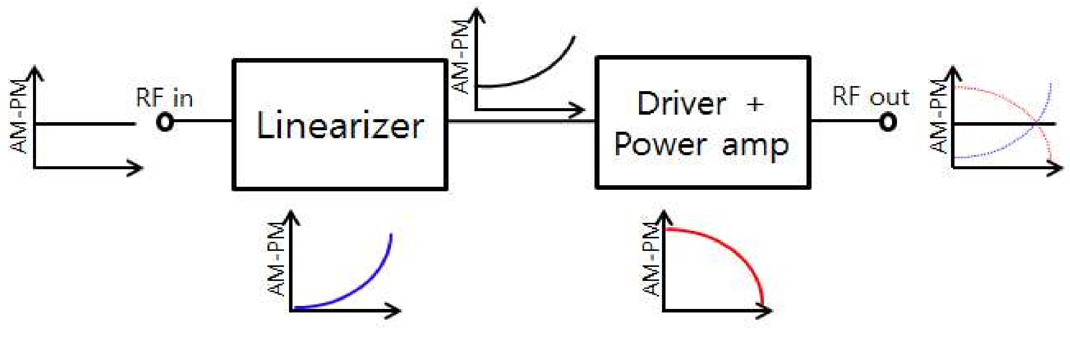


Figure 4.1 The block diagram of AM-PM linearization technique.

4.2 Design of Linearizer

A schematic of the varactor based phase linearizer is shown in Figure 4.2. An envelope signal is re-shaped by the waveform generator and supplied to a cathode of the varactor. Capacitance of the varactor diode varies by the value of reverse biased voltage.

In this design, required capacitance of the varactor is from 1 pF at low power region to 0.1 pF at peak power.

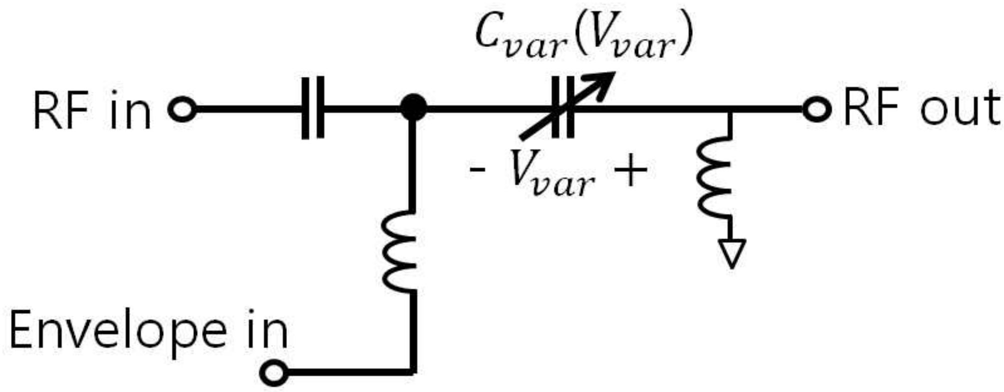


Figure 4.2 The schematic of the linearizer.

4.3 Measurement results of linearizer

Measurement setup for this experiment is shown in Figure 4.3. An AWG is used to supply envelope to the linearizer and an oscilloscope is used to detect waveform of a RF signal and an envelope. Figure 4.4 is a module photograph of the phase linearizer. The varactor diode used in the linearizer provides 0.1 to 1 pF for 1 to 12 V reverse bias voltage [7].

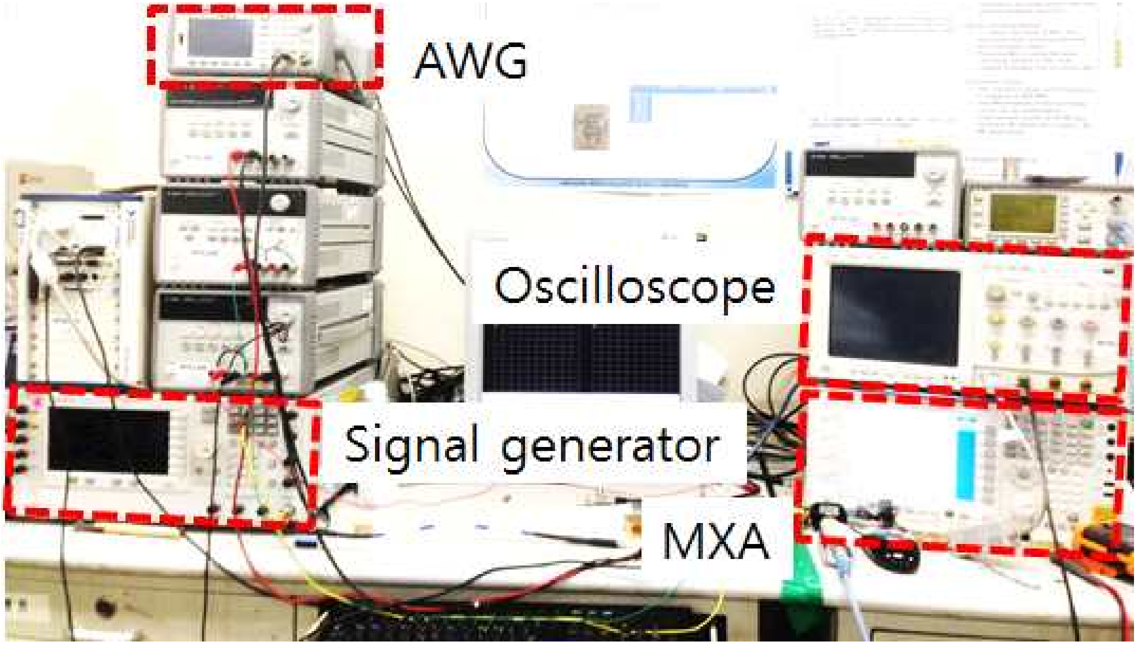


Figure 4.3 Photograph of the measurement setup.

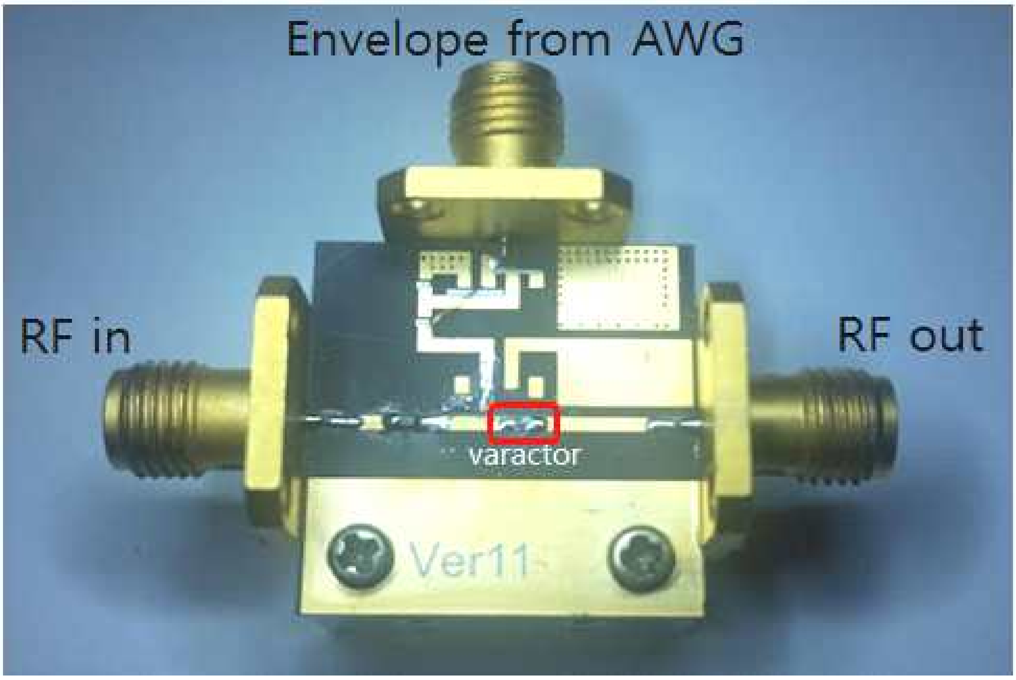


Figure 4.4 Module photograph of the linearizer.

Input impedance variation by the envelope voltage variation is measured using PNA as shown in Figure 4.5. Dynamic characteristics are measured with 20 MHz LTE signal and the measurement results are plotted in Figure 4.6. AM-AM is quite linear but it is below zero due to an input mis-match by large capacitance of the varactor at low power region and goes up to zero by the capacitance decreases when the input power increases. AM-PM variation shows enough value and shape to linearize the PA as expected.

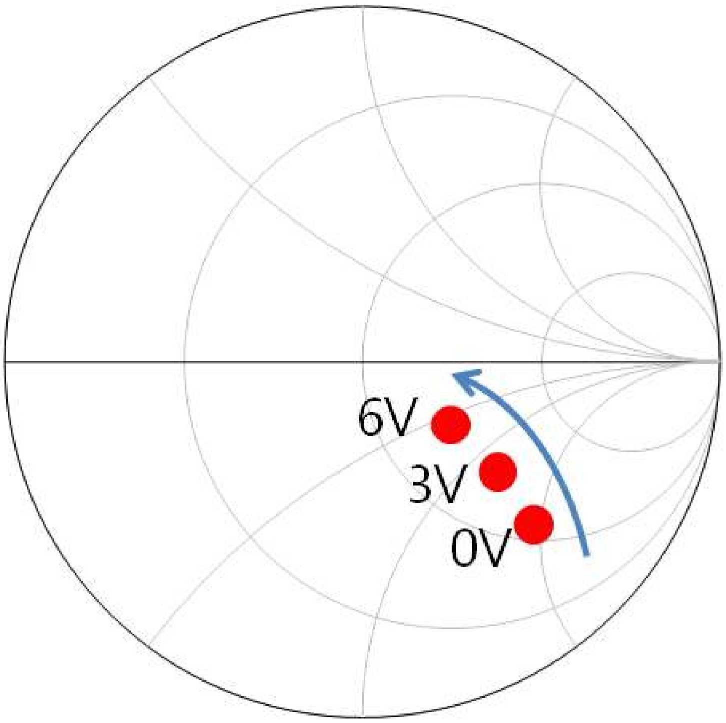


Figure 4.5 Impedance variation of the linearizer by varying the envelope voltage at 9.56 GHz.

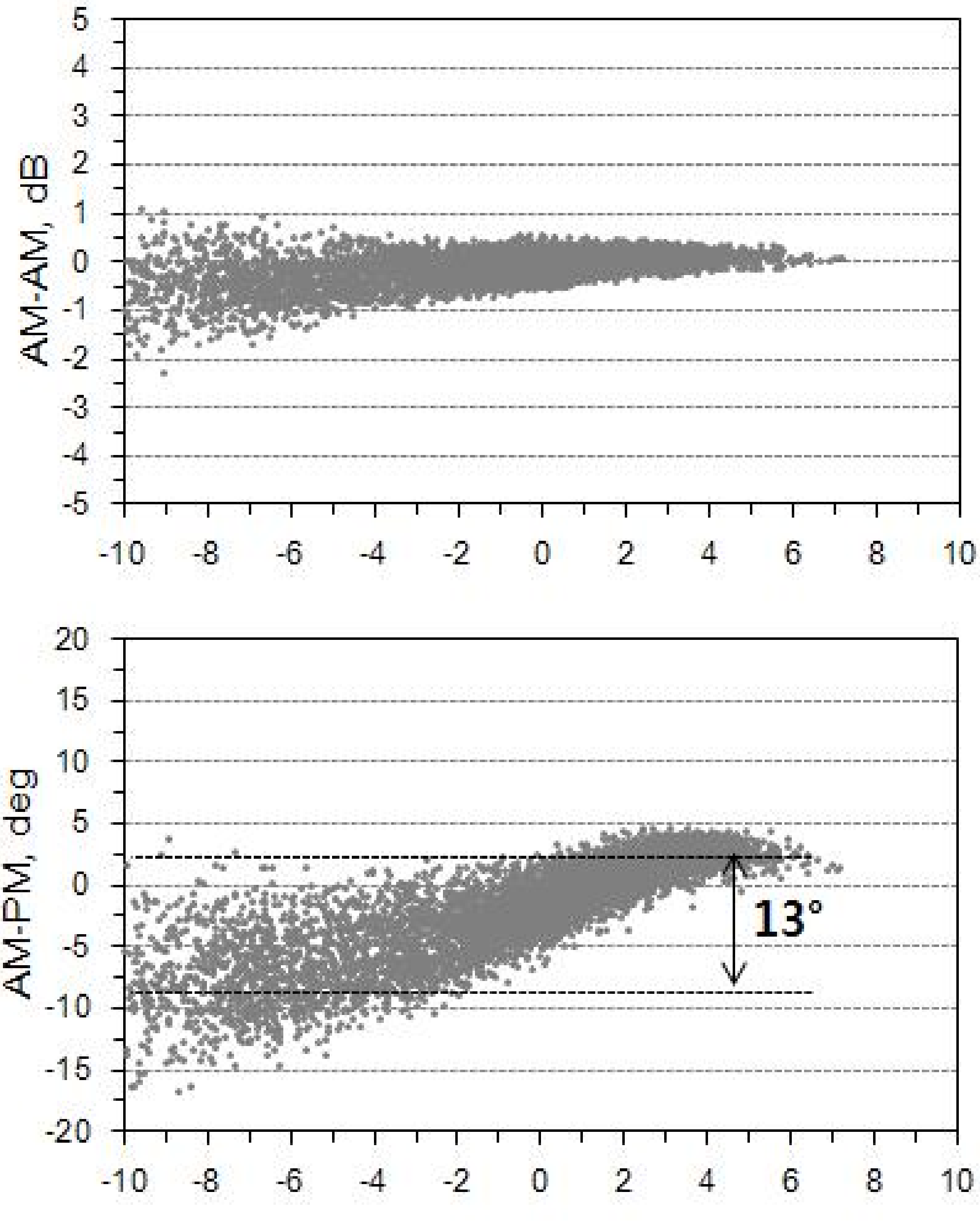


Figure 4.6 Measured dynamic AM-AM and AM-PM of linearizer at 9.56 GHz using a 20 MHz LTE signal.

4.4 Measurement results of PA with linearizer

The measurement setup of whole circuit, PA with linearizer, is shown in Figure 4.3. In this measurement, 20 MHz BW, 7.36 dB PAPR, LTE signal and 40 MHz BW, 9.66 dB PAPR, two carriers aggregated LTE-A signal are used. The gate and drain bias conditions are same with the biases at the CW measurement. To synchronize the envelope from the AWG with the RF signal from the RF signal generator, the time delay of the envelope signal was digitally controlled by detecting waveforms of signals with oscilloscope. And the high and low level of the envelope was controled by the AWG.

20 MHz LTE signal measurement results of dynamic AM-AM and dynamic AM-PM at the output power of 32 dBm are plotted in Figure 4.7. And 40 MHz LTE-A signal measurement results of dynamic AM-AM and dynamic AM-PM at the output power of 31dBm are plotted in Figure 4.8. Both results show that the AM-PM distortion of the PA is completely compensated with the phase linearizer maintaining a linear AM-AM.

Figure. 4.9 shows modulation signal characteristics in terms of gain, DE, PAE and ACLR versus output power of the entire circuit, Doherty PA with linearizer. With 20 MHz BW LTE signal, obtained 24.6% of PAE and obtained -40 dBc of E-UTRA ACLR at 32 dBm output power. With 40 MHz BW LTE-A signal, obtained 23% of PAE and -34.5 dBc of CA E-UTRA ACLR at 31 dBm output power. As shown in Figure. 4.9(c) and 4.9(d), the linearizer improved ACLR by 7.6 dB and 7 dB for each signal.

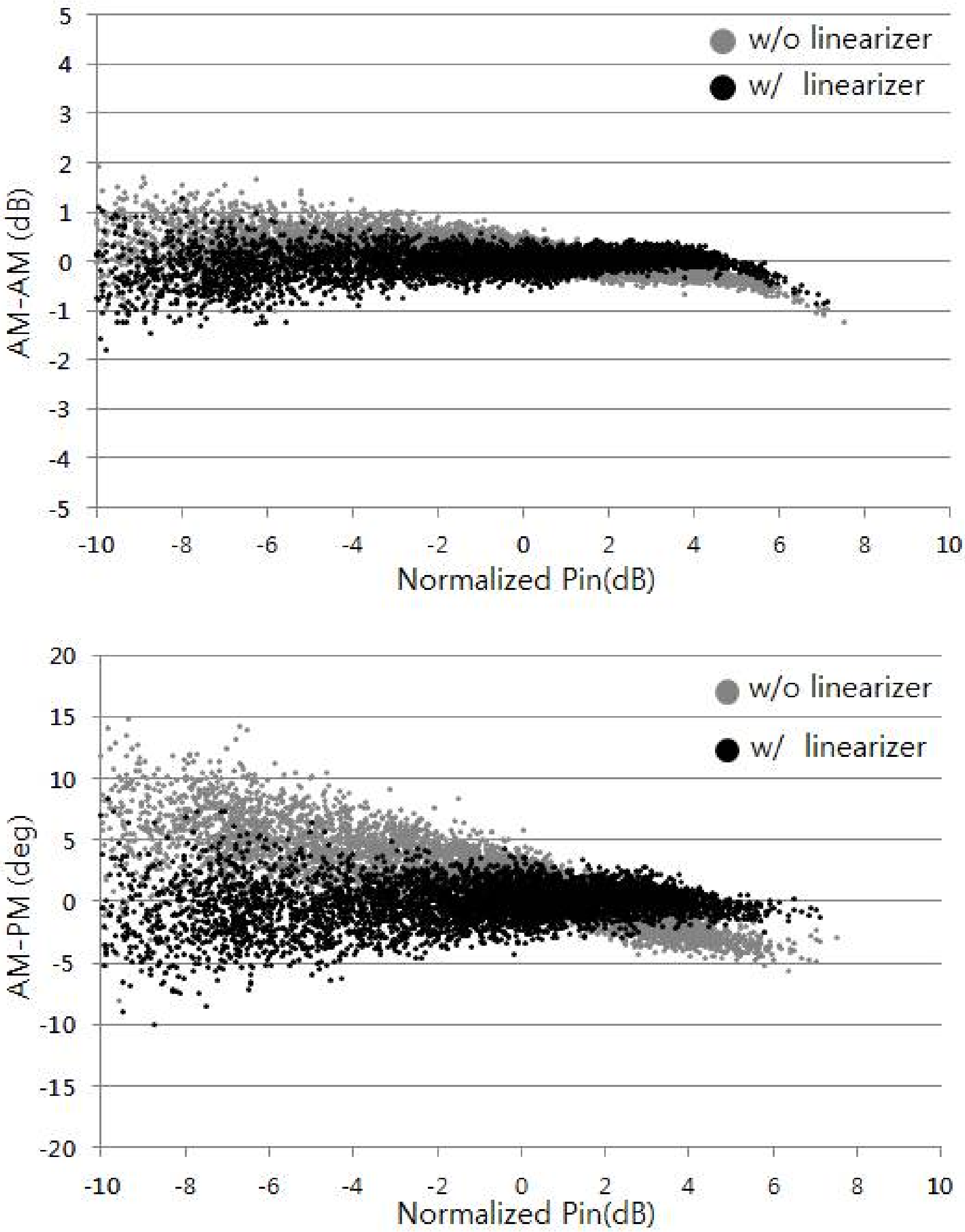


Figure 4.7 Measured dynamic AM-AM and AM-PM of PA at 9.56 GHz when Pout=32 dBm using 20 MHz LTE signal with and without linearizer.

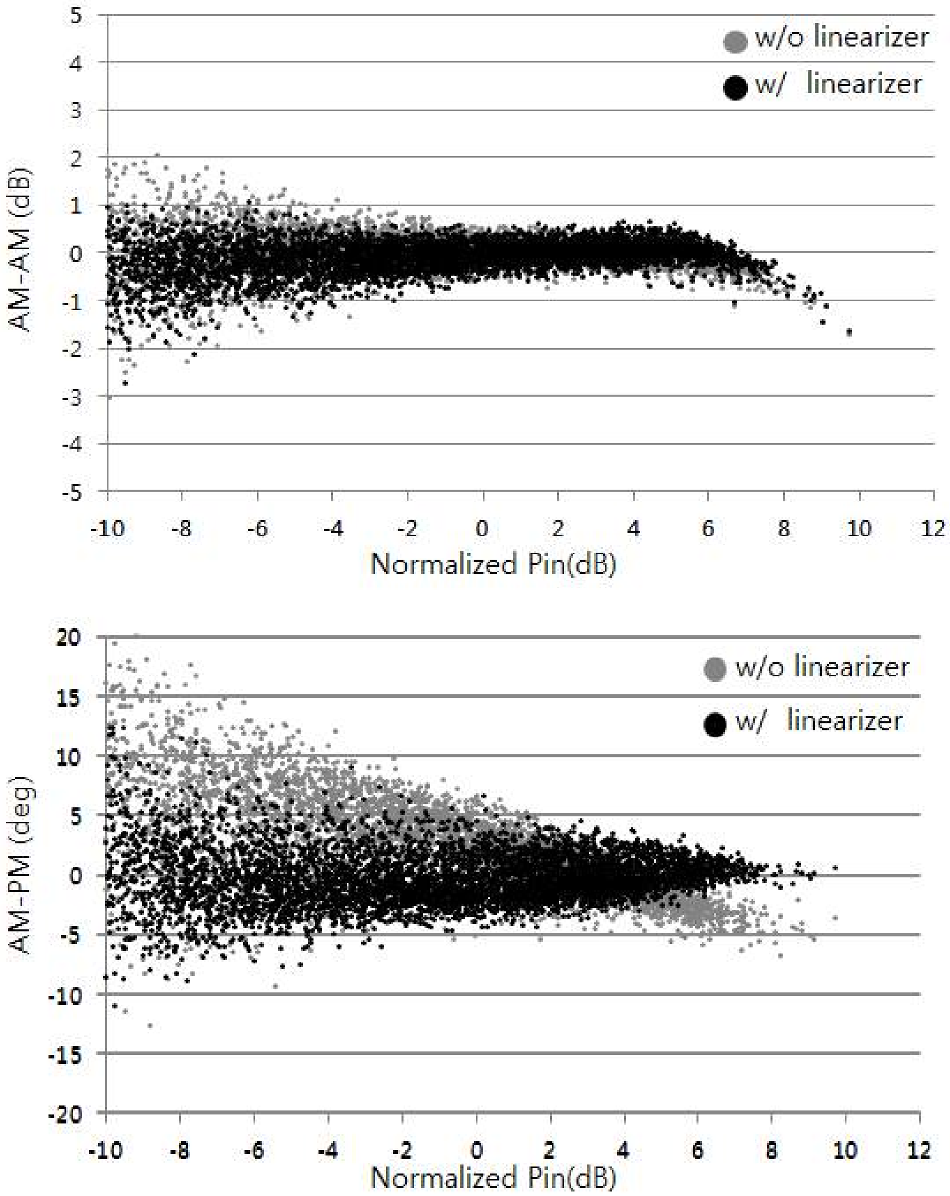


Figure 4.8 Measured dynamic of AM-AM and AM-PM of the PA with the linearizer at 9.56GHz when Pout=31 dBm using 40 MHz LTE-A signal,

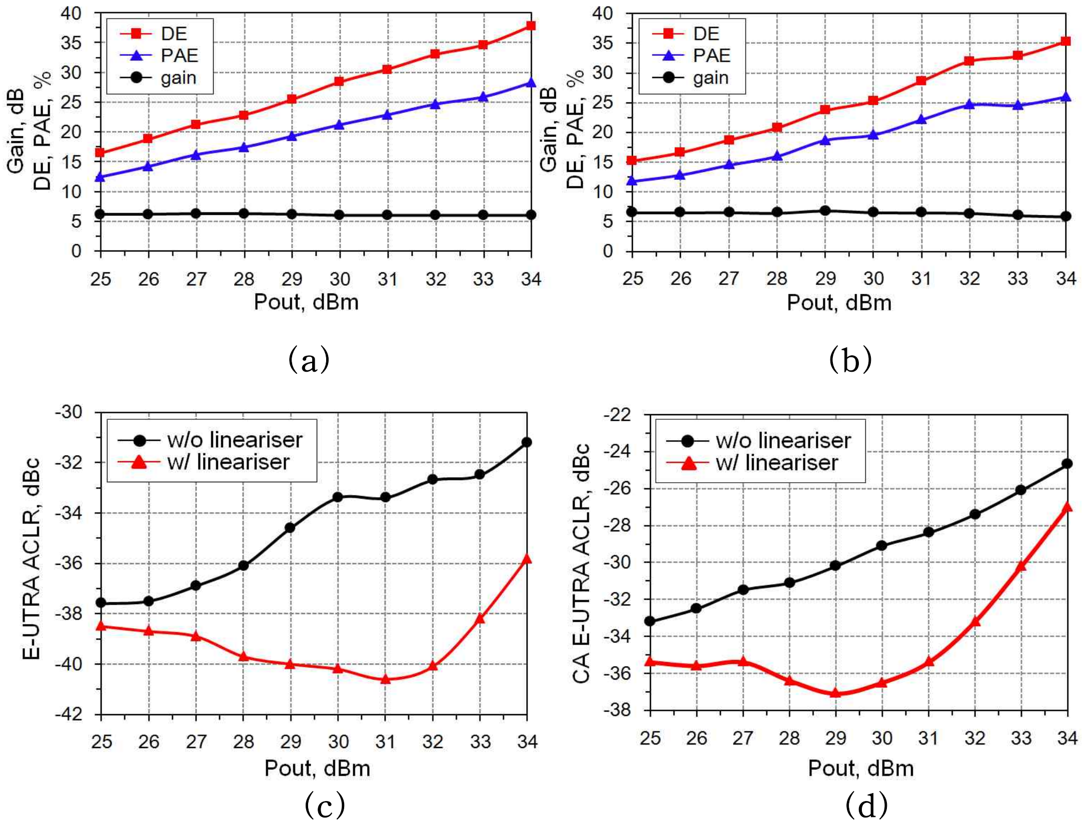


Figure 4.9 Modulation signal characteristics of the PA with linearizer at 9.56 GHz in term of gain, DE, PAE with (a) 20 MHz BW LTE signal and (b) 40 MHz BW LTE-A signal, (c) E-UTRA ACLR with 20 MHz BW LTE signal, and (d) CA E-UTRA ACLR with 40 MHz BW LTE-A signal.

Table 1 compares the performance with LTE signal of the reported Linearized X-band Transformer-based Doherty PA with the latest paper has LTE signal measurement data at X-band.

TABLE 1

Performance comparison of the Linearized X-band Transformer-based Doherty PA with other PAs

	[5]	[5]	This work	This work
Techinique	Constant supply	Modulated supply	Doherty PA with Linearizer	Doherty PA with Linearizer
Frequency (GHz)	10	10	9.56	9.56
LTE signal Bandwidth (MHz)	18	18	20	20
Output power (dBm)	40.3	40.3	39.6	39.6
Chnnel power (dBm)	32.5	31.8	32	31
PAE (%)	13.3	23.3	24.6	22.9
ACLR (dBc)	-26.2	-23.1	-40.1	-35.4

Chapter 5

Conclusion

A Transformer-based Doherty PA for X-band application is designed and implemented. The Transformer-based Doherty PA has a peak output power of 39.6 dBm at 9.56 GHz and at 6 dB output power back-off region, DE and PAE of the amplifier is still as high as 40% and 32.5% respectively. The module size of the Transformer-based Doherty PA only takes 7% for the size of the Conventional Doherty PA, and this compactness of module size has considerable advantages in commercial value.

To applicate the PA to the real world communication system, Linearizer has been introduced. By virtue of AM-PM compensation, the AM-PM distortion of the PA was completely solved. The measured ACLRs at 9.56 GHz are －40.1 dBc and －35.4 dBc with 20 HMz LTE and 40 MHz LTE respectively.

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초록

본 논문에서는 Cree사의 6W GaN HEMT bare die 트랜지스터를 사용한 X-band용 트랜스포머 베이스 도허티 전력 증폭기를 설계하였고 7-layer PCB에 회로를 구현하였다. 그리고 추가적인 선형화 회로를 이용하여 선형성을 향상하였다.

성능 비교를 위하여 Cree사의 6W GaN HEMT bare die 트랜지스터를 사용한 X-band용 컨벤셔널 트랜스포머 베이스 토허티 전력 증폭기를 10GHz에서 설계하였고 RT/Duroid 5880 10mil 두께의 기판을 사용하여 제작하였다. CW 측정 결과 40V 드레인 전압에서 40.3dBm의 최대전력을 출력하며 최대 51%의 DE 와 최대 40.3%의 PAE를 가진다. 그리고 최대출력전력 대비 6-dB 낮은 전력에서 DE와 PAE는 각각 41%와 33%의 효율을 가진다.

X-band용 트랜스포머 베이스 도허티 전력증폭기는 9.56GHz에서 측정되었다. CW 측정 결과 40V 드레인 전압에서 최대전력 39.6dBm을 출력하며 최대 50.4%의 DE와 최대 38.5%의 PAE를 가진다. 그리고 최대출력전력 대비 6-dB 낮은 전력에서 DE와 PAE는 각각 40%와 32.5%의 효율을 가진다.

X-band용 트랜스포머 베이스 도허티 전력증폭기의 선형성을 측정하였고 전력증폭기의 선형성을 향상 시키기 위해 선형화회로를 설계하였다. 선형화회로에는 MACOM technologies의 varactor diode를 사용하였다. 선형화회로를 사용한 X-band용 트랜스포머 베이스 도허티 전력증폭기의 선형성을 측정하기위해 9.56GHz에서 20MHz의 대역폭과 40MHz의 대역폭을 가지는 LTE신호를 사용하

였다. 20MHz LTE 신호를 사용한 측정 결과 최대출력전력 대비 7dB 낮은 전력에서 -40dBc의 ACLR을 얻었고 40MHz LTE 신호를 사용한 측정에서는 최대출력전력 대비 9dB 낮은 전력에서 -35.4dBc의 ACLR을 얻었다.

주요단어 : X-band, 도허티 전력 증폭기, 선형성, LTE,
트랜스포머 전력 결합

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