High Efficiency Class-E tuned Doherty Amplifier using GaN HEMT

Gil Wong Choi[1], Hyoung Jong Kim[1], Woong Jae Hwang[1], Suk Woo Shin[1], Jin Joo Choi[1], and Sung Jae Ha[2]

[1] Kwangwoon University , 447-1, Wolgye-dong, Nowon-gu, Seoul, Korea, 139-701

[2] Samsung Thales Co., Ltd , 304, Chang-Li, Namsa Myun, Cheoin-Gu, Yongin, Korea, 449-885

***Abstract* — This paper describes the design and fabrication of a highly efficient switching-mode Class-E Doherty power amplifier using gallium nitride (GaN) high-electron mobility transistor (HEMT) for S-band radar applications. Measured results of the Doherty amplifier show power-added efficiency (PAE) and drain efficiency of 62.6% and 73.1% at 37 dBm of 6 dB output back-off point from saturated output power at 2.85 GHz, compared with PAE and drain efficiency of 42.9% and 44.7% for the case of balanced amplifier. It was found that PAE was improved by 19.7% by adopting the Doherty efficiency enhancement technique.**

***Index Terms* — GaN HEMT, efficiency, switching-mode Class-E amplifier, Doherty amplifier.**

I. INTRODUCTION

The capacity and tasks of commercial and military radar applications are increasingly growing and becoming more complicated. The current trend in radar specifications focuses on efficiency of the power amplifier for the reduction of the power dissipation and multi-function radar (MFR). The MFR is based on solid-state device and active phased array radar technology that will provide search, detect, track, and weapon control function. To obtain these objectives, it is necessary that RF signal should be capable of steerable transmitter output power [1]. However, it is difficult to control the output power of amplifier without the reduction of amplifier efficiency. Therefore, there is a strong interest to pursue development of power amplifiers with a high efficiency over a wide range of transmitting power.

The technology of high efficiency amplifier, the switching-mode Class-E configuration has found wide-spread application due to design simplicity and high efficiency operation [2]-[4]. Moreover, a merit of the efficiency improvement decreases DC power consumption, weight, and volume. In this respect, switching-mode Class-E amplifier is suitable for the radar systems [5]. The other method of the improving amplifier efficiency is Doherty amplifier [6]-[8]. In general, a power amplifier in the communication systems operates satisfactorily below the saturation level in order to solve the linearity problem. However, this results in a low efficiency power amplifier. In order to boost low efficiency, the Doherty amplifier configuration is becoming widely adopted. The Doherty amplifier circuit is more complex than a balanced amplifier. But, Doherty circuit operation can be set by adjusting the transition point to trade-off efficiency, gain and linearity.

Generally, the efficiency of power amplifier is limited by the transistors drain-source capacitance (C_{ds}), and its on-state resistance (R_{on}), or knee voltage. In this respect, gallium nitride (GaN) high-electron mobility transistor (HEMT) is a good candidate for Class E amplifiers. GaN transistors have significantly higher power density than GaAs and Si transistor. GaN HEMTs have several inherent characteristics, such as higher breakdown voltage, higher saturation velocity, high thermal conductivity, and good carrier mobility. Consequently, these advantages make GaN HEMT suitable for high efficiency microwave applications [9].

In this paper, we designed and fabricated high efficiency switching-mode Class-E Doherty amplifier. The characteristics of proposed Doherty amplifier were compared with those of a switching-mode balanced amplifier.

II. SINGLE-ENDED SWITCHING-MODE CLASS-E AMPLIFIER

The characteristics of a Class-E amplifier can be determined by finding its steady-state drain voltage and current waveforms. The simplified equivalent circuit of a Class-E power amplifier with a shunt capacitance is shown in Fig. 1(a) where the load network consists of a capacitor C shunting the transistor, a series fundamentally tuned $L_0 C_0$ circuit and a load resistor R. In a common case, a shunt capacitance C can represent the intrinsic device output capacitance and external circuit capacitance added by the load network. This capacitance will minimize the overlap between the current and the voltage waveforms. Fig. 1(b) shows the voltage and current waveforms of the ideal Class-E amplifier. To achieve these waveforms, it is required to match the fundamental and harmonic impedances. The all harmonics have to be an open circuit for the fundamental component to obtain ideal Class-E operation [1]-[3]. The Class-E power amplifier was implemented using the CREE CGH40010F, 10 W GaN HEMT. The device minimum breakdown voltage is about 100 V which is much higher than other devices such as GaAs HBT, Si LDMOS and BJT indicating that the GaN HEMT is ideal for class E-operation.

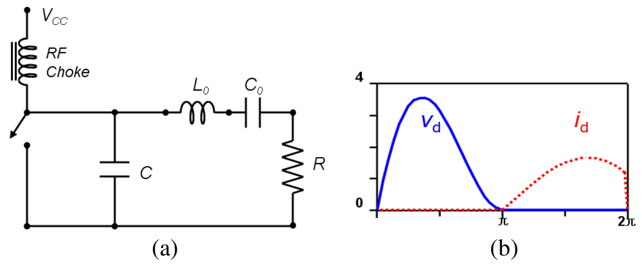

Fig. 1. Ideal switching-mode Class-E amplifier; (a) Basic circuit of Class-E amplifier, (b) Normalized voltage and current waveform of ideal Class-E amplifier.

Fig. 2 shows the simulated output load impedance of the GaN HEMT Class-E power amplifier at 2.9 GHz. Simulations are performed with the Agilent Advanced Design System (ADS) simulation code [10]. The simulation bias conditions of Class E amplifier are set at drain voltage of 28 V and gate voltage of -2.42 V. The input matching network is configured with single-open-stub matching with a conjugate matching for maximum power transfer. The simulated output load network for Class-E amplifier is shown in Fig. 2. The optimum load impedances of fundamental and 2[nd] harmonic and 3[rd] harmonic frequency are 11.613 + *j*7.253 and 7.68 + *j*61.669 and 15.02 + *j*60.49, respectively. The 2[nd] and 3[rd] harmonic impedances are not exactly infinite impedance (open circuit). However, these impedances are high enough for open circuit compared with the very low impedance of the fundamental frequency. The Class-E amplifier is fabricated using Teflon substrate (manufactured by Taconic Inc.) with a dielectric constant of 2.6 and a thickness of 0.504 mm.

Fig. 4 shows measured output power, gain and efficiency characteristics of the GaN HEMT Class-E power amplifier at 2.7 ~ 3.1 GHz. The test conditions of drain and gate bias voltage are 28 V and -2.9 V, respectively. This circuit achieved power added efficiency (PAE) of 58% ~ 76%, output power of 39.6 ~ 41.2 dBm, and gain of 8.3 ~ 14.3 dB across 2.7 ~ 3.1 GHz, respectively.

III. Switching-Mode Balanced Power Amplifier and Switching Doherty Amplifier

1. Switching-mode balanced power amplifier

To compare with the proposed Doherty power amplifier technique, we conducted a switching-mode balanced power amplifier using Class-E GaN HEMT amplifier. The amplifier consists of the switching-mode Class-E amplifiers and broadband Wilkinson power combiner/divider. In order to minimize the effect of Class-E load impedance, the broadband wilkinson combiner/divider was designed up to the 3[rd] harmonic frequency [11]. Measurement results of broadband Wilkinson divider is under the return loss of -15 dB and insertion loss of 0.2 ~ 0.9 dB across 2.7 ~ 9.3 GHz, respectively. Fig. 5 is a photograph of the switching-mode balanced amplifier.

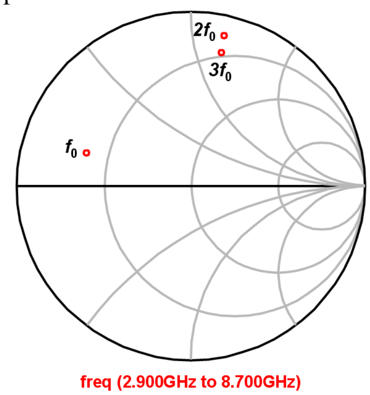

Fig. 2. The simulated output load impedance (f_0: fundamental, $2f_0$: 2[nd] harmonic, $3f_0$: 3[rd] harmonic).

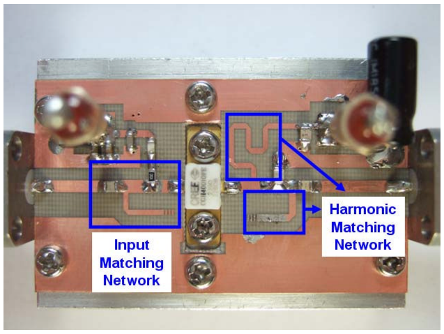

Fig. 3. Photograph of a fabricated single-ended class-E power amplifier using GaN HEMT.

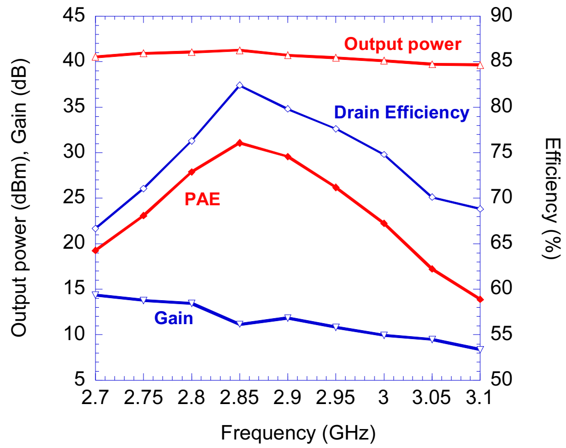

Fig. 4. The measured efficiency and gain characteristics of the Class-E GaN HEMT amplifier.

Fig. 6 shows measured output power, gain and efficiency characteristics of the switching-mode balanced amplifier at 2.7 ~ 3.1 GHz. The test conditions of two GaN HEMT drain and gate bias voltage are 28 V and -2.9 V, respectively. This circuit achieved power added efficiency (PAE) of 51.7% ~ 67.2%, output power of 40.9 ~ 42.3 dBm, and gain of 8.7 ~ 14 dB across 2.7 ~ 3.1 GHz, respectively.

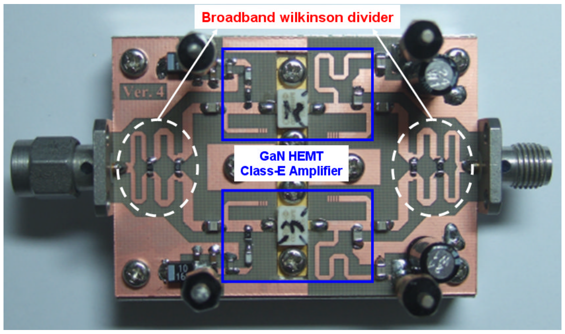

Fig. 5. Photograph of a fabricated switching-mode balanced power amplifier using GaN HEMT.

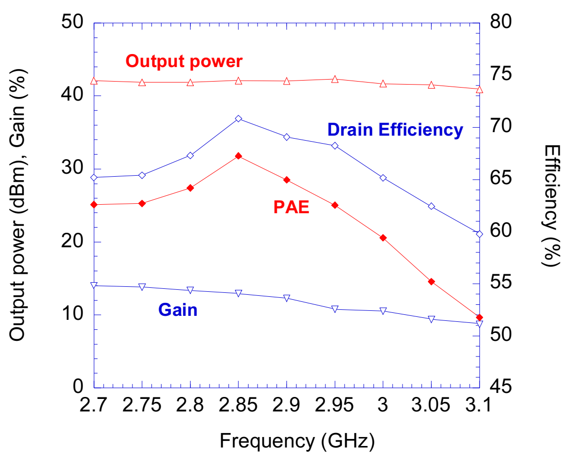

Fig. 6. The measured efficiency and gain characteristics of the switching-mode balanced amplifier.

2. Switching Doherty power amplifier

Fig. 7 shows the configuration of the proposed GaN HEMT switching Doherty amplifier employing the switching-mode Class-E topology at 2.9 GHz. The switching Doherty amplifier consists of the carrier amplifier, peaking amplifier, broadband Wilkinson divider, offset line, and output combiner. The drain bias voltage of both carrier and peaking amplifier are set to 28V. The gate bias voltages of carrier and peaking amplifier are -2.9 V and -7 V, respectively. Fig. 8 shows the fabricated photograph of the Doherty amplifier. To minimize the effect of Class-E load condition, input divider used the broadband Wilkinson divider which has a multi-section impedance transformer. Generally, the operation condition of conventional carrier amplifier is Class AB because of the linearity of the amplifier. In this paper, the linearity of amplifier is not a major concern because the radar signal carries only single frequency at a time with either continuous wave (CW) or pulse waveform. Fig. 9 shows measured efficiency and gain of Doherty amplifier. Experimental results show PAE of 62.6% and 73.1% at 6 dB back-off from saturation.

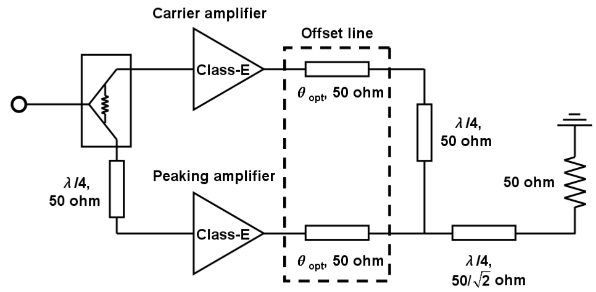

Fig. 7. The configuration of the proposed GaN HEMT switching Doherty amplifier.

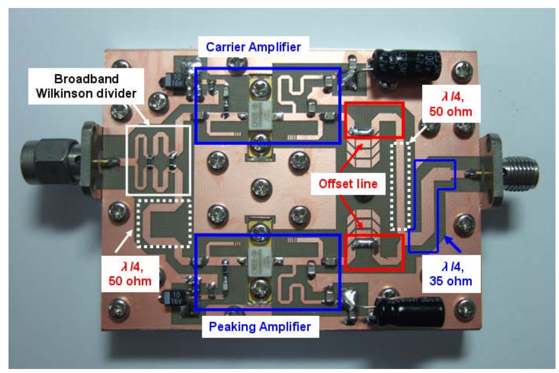

Fig. 8. Photograph of a fabricated switching-mode Doherty power amplifier using GaN HEMT.

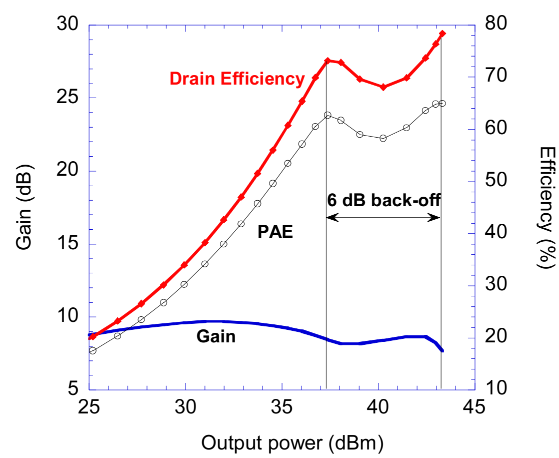

Fig. 9. The measured efficiency and gain characteristics of switching Doherty power amplifier.

Fig. 10 depicts measured drain currents of the carrier and peaking amplifier at 2.85 GHz. As shown in Fig. 10, the current of peaking amplifier starts to flow at 6 dB output back-off point and increases rapidly as output power reaches to saturation. Fig. 11 shows comparison on PAEs of the Doherty amplifier and balanced amplifier. The efficiency of the Doherty amplifier was improved by 19.7% at 6 dB back-off from saturation, compared with the balanced switching amplifier.

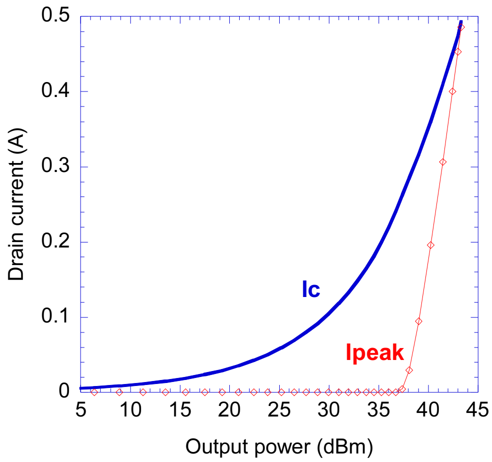

Fig. 10. The measured drain current of carrier and peaking amplifier with Doherty amplifier operation.

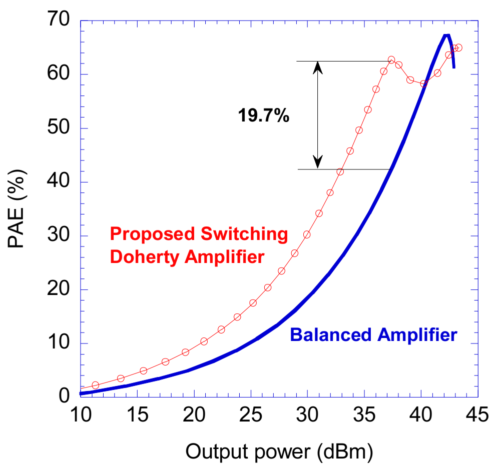

Fig. 11. The measured PAE of the proposed Doherty amplifier and balanced amplifier.

IV. Conclusion

In this paper, we have presented the high efficiency GaN HEMT switching Doherty amplifier using a switching-mode Class-E harmonic matching network for the S-band radar applications. Experimental results of the proposed Doherty amplifier show that the PAE and drain efficiency are 30% ~ 62.6% and 50% ~ 73.1% in the frequency range of 2.7 ~ 3.1 GHz, respectively. The efficiency of the Doherty amplifier was improved by 19.7% at 6 dB back-off from saturation, compared with the balanced switching amplifier. This present amplifier design topology is suitable for multi-function radar (MFR) application such as the variable range detection radar with maintaining high efficiency of transmitter.

Acknowledgement

This work was supported by the Samsung-Thales Co., Ltd.

References

[1] J. van Bezouwen, "System Trends in Ground Based Active Phased Array Radar," *38th European Microwave Conf. Workshop Handouts-WTH-13*, 27-31 Oct. 2008.

[2] H. Zirath and D.B. Rutledge, "An LDMOS VHF class-E power amplifier using a high-Q novel variable inductor," *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 2534-2538, December 1999.

[3] A.J. Wilkinson and J.K.A. Everard, "Transmission-line load-network topology for class-E power amplifiers," *IEEE Trans. Microwave Theory Tech.*, vol. 49, pp. 1202-1210, June 2001.

[4] A.J. Wilkinson and J.K.A. Everard, "Transmission-line load-network topology for class-E power amplifiers," *IEEE Trans. Microwave Theory Tech.*, vol. 49, pp. 1202-1210, June 2001.

[5] T. Quach, et al., "Broadband Class-E Power Amplifier for Space Radar Application," *IEEE GaAs IC Symp. Dig.*, pp. 209-212, 2001.

[6] Y. Yang, J. Yi, Y. Y. Woo, and B. Kim, "Experimental investigation on efficiency and linearity of microwave Doherty amplifier," *2001 IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 2, pp. 1367-1370, 20-25 May 2001.

[7] Y. Yang, J. Yi, Y. Y. Woo, and B. Kim, "Optimum design for linearity and efficiency of microwave Doherty amplifier using a new load matching technique," *Microwave J.*, vol. 44, no. 12, pp. 20–36, Dec. 2001.

[8] N. Srirattana, A. Raghavan, D. Heo, P. E. Allen, and J. Laskar, " A high-efficiency multistage Doherty power amplifier for WCDMA," in *Proc. Radio and Wireless Conf.*, Boston, MA, pp. 397–400, Aug. 2003.

[9] U. K. Mishra, P. Parikh and Y. Wu, "AlGaN/GaN HEMTs-An overview of Device Operation and Applications," *Proc. of the IEEE*, vol. 90, no. 6, pp. 1022-1031, Jun. 2002.

[10] Advanced Design System (ADS), Version 2008, Agilent Technologies USA.

[11] A. Wentzel, V. Subramanian, A. Sayed, G. Boeck, "Novel Broadband Wilkinson Power Combiner," in *Pro. 36th Eur. Microw. Conf.*, pp. 212-215, Sept. 2006.