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RESEARCH ARTICLE

Compact Load Network Having a Controlled Electrical Length for Doherty Power Amplifier

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ABSTRACT The load network of the carrier amplifier for the conventional Doherty power amplifier (DPA) consists of an impedance matching circuit, an offset line, and a λ/4 transmission line (TL), so that the overall electrical length of the network can easily exceed the minimum value of 90°. Then for appropriate impedance modulation, it should be 270° with an additional 180°. This excessive electrical length of the load matching network limits the bandwidth at either the low-power or peak-power level. In this paper, a compact quasi-lumped λ/4 impedance transformer (ITF) having simultaneous multiple functions of impedance matching and load impedance modulation with a controlled electrical length of 90° is presented. The proposed load network includes the internal components of the transistor, the simplest high-pass network using a shunt inductor, and a low-pass L-C network. Using the optimized value of the shunt inductor, the electrical length of the load network can be adjusted to 90°, while other components are accordingly changed to match the optimum load impedance. To verify the proposed load network, a DPA was designed and implemented using 10 W GaN-HEMTs for both carrier and peaking amplifiers. Using a 5G New Radio (NR) signal with signal bandwidth of 100 MHz and peak-to-average power ratio (PAPR) of 7.8 dB, a drain efficiency (DE) of 47 - 54.2%, and adjacent channel leakage power ratio (ACLR) of -27.9 - -23 dBc were achieved at an average output power level of 35.8 - 36.3 dBm for the frequency band of 3.4 - 3.8 GHz.

INDEX TERMS Doherty power amplifier, compact load network, controlled electrical length, 5G New Radio, GaN-HEMT.

I. INTRODUCTION

Power amplifiers for the recent wireless communication systems are required to have high efficiency at large output power back-off (OBO) due to the high PAPR of the modulated signals. DPAs have been used in the base transceiver systems, because of the simple structure and high efficiency in the large OBO condition [1]–[25].

Two power states, such as low-power and peak-power levels, should be simultaneously considered for the bandwidth of the DPAs. The bandwidths for the two power states are generally in strong trade-off with each other. For the carrier amplifier of the conventional DPAs, the load network generally has an electrical length of 270° or more, since an impedance matching network, an offset line, and a λ/4 TL for a load modulation should be included. A large electrical length of the load network makes this trade-off worse and limits the overall bandwidth of the DPAs.

Transformer-less load modulation (TLLM) techniques have been reported to extend the bandwidth of the DPAs, and to reduce the size of the load network [11]–[13]. Akbarpour *et al.* [11] proposed a DPA that can be designed

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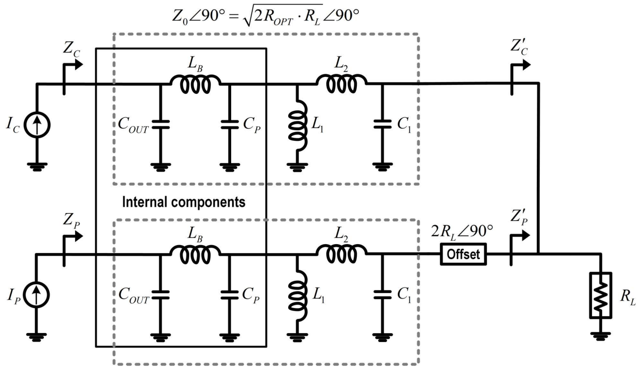


FIGURE 1. Simplified load network of the proposed DPA.

using a two-point impedance matching technique, without a λ/4 TL and an offset line at the load network. However, the design method is very complex, and the synthesized circuit was composed of multiple sections, using many lumped components for both the carrier and peaking amplifiers. Watanabe *et al.* [12] implemented a DPA using an output combining balun to remove an additional λ/4 TL and an offset line. The impedance matching network was still needed, since the output combining balun could not match the optimum impedance. Shao *et al.* [13] reported a DPA that was designed without an additional λ/4 TL and a post-matching network. However, the impedance matching network was complex and an additional offset line for electrical length control was still required.

In this paper, a quasi-lumped λ/4 ITF having simultaneous multiple functions of impedance matching and load impedance modulation with a controlled electrical length of only 90° is proposed for the load network of the DPAs. The proposed load network of the carrier amplifier has a quasi-lumped λ/4 ITF including the internal components of the transistor, the simplest high-pass network using only a shunt inductor, and a low-pass L-C network. The value of the shunt inductor can be adjusted to have an electrical length of the load network of 90°, while the L-section low-pass network should be accordingly tuned to match the optimum load impedance. Since the overall load network even including the internal components of the transistor has an electrical length of only 90°, the bandwidth for the load impedance modulation can be extended in the trade-off between the low-power and peak-power bandwidth. The proposed DPA was designed and implemented using GaN-HEMTs for the frequency band of 3.4 - 3.8 GHz. Experimental results using a CW signal and a 5G NR signal are presented.

II. DESIGN OF THE LOAD NETWORK

A. PROPOSED LOAD NETWORK

The electrical length of the load network affects the size of the load network and the load modulation bandwidth of the DPA. Fig. 1 shows a simplified schematic of the proposed load network of the DPA. Since the electrical length of the load network should be 90°+n×180° for a desired load modulation, where n is an integer, including the internal components such as the output capacitance (C_{OUT}), bond-wire inductance (L_B), and packaging capacitance (C_P) of the transistor, the internal components should be extracted first [14]. When the proposed quasi-lumped λ/4 ITF has a characteristic impedance of $\sqrt{2R_{OPT}\cdot R_L}$ and an electrical length of 90°, the load impedance at the low power level of the carrier amplifier at the current source plane, Z_C, becomes $2R_{OPT}$. Then, Z_C, at the peak power level, is converted to R_{OPT}. The load impedance toward the combining node, Z'_C, is converted from R_L at the low power level, to $2R_L$ at the peak power level. For the peaking amplifier, the load impedance at the current source plane, Z_P, becomes R_{OPT} at the peak power level. The load impedance toward the combining node, Z'_P, is converted from infinity at the low power level, to $2R_L$ at the peak power level.

TABLE 1. Component values and the electrical lengths of the proposed load network for three cases.

	L_1	L_2	C_1	Electrical length
Case I	0.37 nH	0.22 nH	2.37 pF	40°
Case II	1.13 nH	0.76 nH	1.74 pF	90°
Case III	∞	0.83 nH	2.66 pF	125°

The proposed load network of the carrier amplifier is composed of a high-pass network using a shunt inductor and a L-section low-pass network. This network is one of the π-type transformers which have been used for impedance matching [15]. In general, when only a L-section low-pass network is used for the impedance matching, the electrical length of the matching network cannot be controlled. However, a shunt inductor before the L-section low-pass network is deployed, which allows the electrical length to be controlled while having an optimum load impedance matching condition by adjusting the other components, L_2 and C_1.

B. QUASI-LUMPED λ/4 ITF USING AN OPTIMIZED SHUNT INDUCTOR

For the low power level, the load impedance of the carrier amplifier, Z_C, should be $2R_{OPT}$. From this condition, the component values of L_2 and C_1 of the matching network can be derived as a function of L_1 as given in (1) and (2), as shown at the bottom of the next page, where, ω_0 is the center frequency. The electrical length of the load network of the carrier amplifier can be calculated according to the value of L_1 using the corresponding component values of L_2 and C_1. Fig. 2 presents the calculated electrical length. For L_1 of 1.13 nH, the electrical length becomes 90° at ω_0.

Table 1 shows the values of L_2, C_1, and the electrical length of the load network of the carrier amplifier for three values of L_1. For case II using an optimum L_1 of 1.13 nH, the electrical length of the load network can be adjusted exactly to 90°. For case I using an L_1 of 0.37 nH, an additional

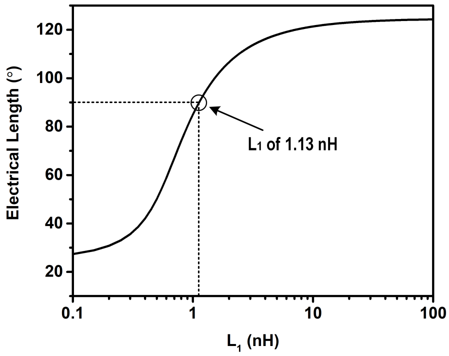


FIGURE 2. Calculated electrical length of the proposed load network for the various values of the shunt inductor, L_1.

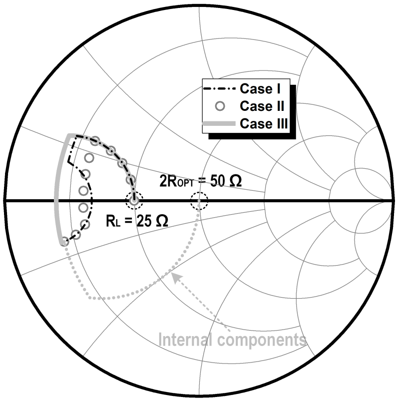
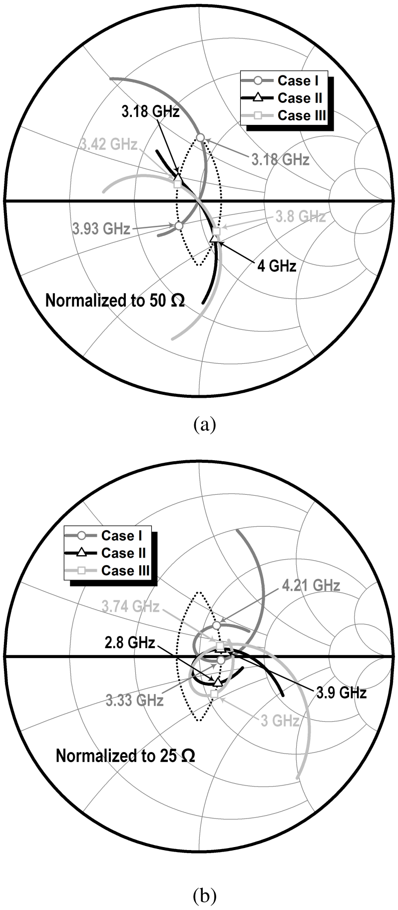


FIGURE 3. Load impedance trajectories of the proposed load network for the low power level.



(a)

(b)

FIGURE 4. Simulated load impedances on an ideal 1 dB power contour for three cases at the frequency band of 2.5 - 4.5 GHz: (a) Z_C for the low power level, and (b) Z_C for the peak power level.

offset line with an electrical length of 50° is needed to have the overall electrical length of 90°. For case III using no shunt inductor (conventional case), an additional offset line to make the overall electrical length of 270° is still needed since the electrical length of the network is already more than 90°. Fig. 3 shows the load impedance trajectories at the low power level for the three cases. For all three cases, the load impedance can be transformed from R_L of 25 Ω to $2R_{OPT}$ of 50 Ω through different trajectories using different component values.

Fig. 4 shows the simulated load impedances of the carrier amplifier on an ideal 1 dB power contour for the three cases at the frequency band of 2.5 - 4.5 GHz. For cases I and II, a little difference in the load modulation bandwidths (600 vs. 720 MHz for the intersection between the low-power and peak-power bandwidths) can be found. However, these cases have a considerably extended load modulation bandwidth, compared to case III (320 MHz) with a total electrical length of 270° including an additional offset line. Case II has a more compact load network compared to case I, because of the absence of an additional offset line.

$$C_1=\frac{1}{\omega_0 R_L}\sqrt{\frac{R_L-\mathrm{Re}\{(2R_{OPT}\parallel\frac{1}{j\omega_0 C_{OUT}}+j\omega_0 L_B)\parallel(\frac{1}{j\omega_0 C_P}\parallel j\omega_0 L_1)\}}{\mathrm{Re}\{(2R_{OPT}\parallel\frac{1}{j\omega_0 C_{OUT}}+j\omega_0 L_B)\parallel(\frac{1}{j\omega_0 C_P}\parallel j\omega_0 L_1)\}}},\tag{1}$$

$$L_2=\frac{\omega_0 C_1 {R_L}^2-(1+{\omega_0}^2{C_1}^2{R_L}^2)\,\mathrm{Im}\{(2R_{OPT}\parallel\frac{1}{j\omega_0 C_{OUT}}+j\omega_0 L_B)\parallel(\frac{1}{j\omega_0 C_P}\parallel j\omega_0 L_1)\}}{\omega_0(1+{\omega_0}^2{C_1}^2{R_L}^2)},\tag{2}$$

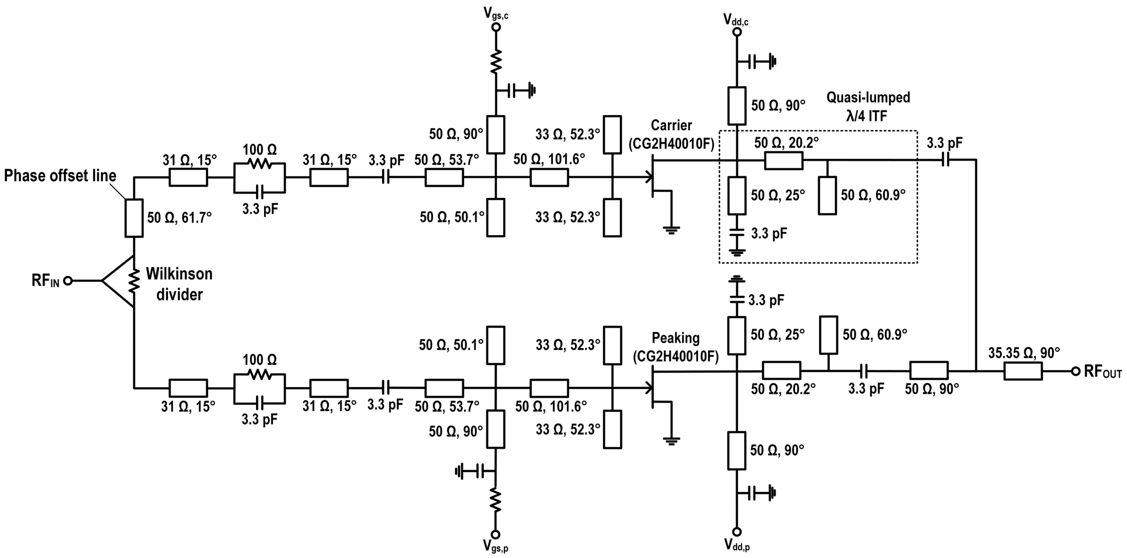


FIGURE 5. **Schematic of the designed DPA.**

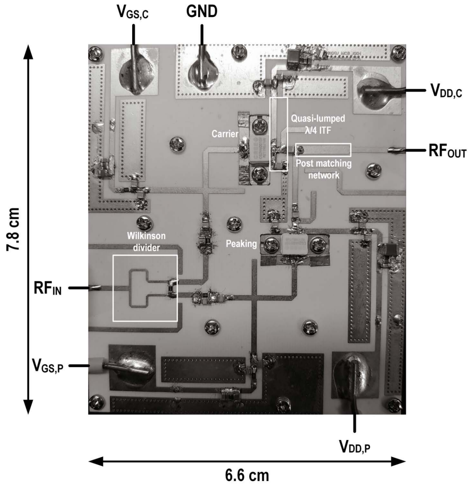
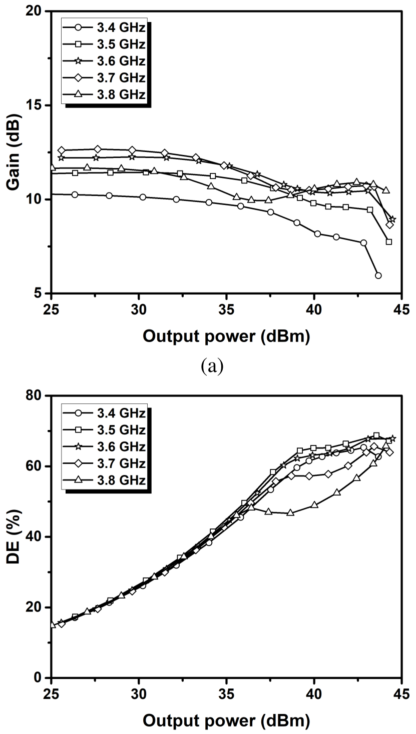


FIGURE 6. **Photograph of the implemented DPA.**

III. IMPLEMENTATION AND MEASUREMENT RESULTS

Fig. 5 shows a schematic of the designed DPA using the proposed load network. The shunt inductor was realized using a short-circuited stub with an electrical length of 25°. The series inductor, L_2, was also replaced with a transmission line whose electrical length is 20.2°. The shunt capacitor, C_1, was replaced with an open-circuited stub with an electrical length of 60.9°. The same load network was used for the peaking amplifier with an additional offset line to have the overall electrical length of 180° at ω_0. Both the carrier and peaking amplifiers were designed using 10 W GaN-HEMT, Cree's CG2H40010F. Fig. 6 shows a photograph of the implemented DPA on a PCB using Rogers' RO4350B with a dielectric constant of 3.66. The overall circuit size is 6.6 cm × 7.8 cm.

Fig. 7 shows the measured results of the implemented DPA using a continuous wave (CW) signal. Fig. 7(a) & (b) show the power gain and DE of the DPA, respectively. For the frequency band of 3.4 - 3.8 GHz, the implemented DPA exhibited the DE of 62 - 70% at the peak output power level of 43.6 - 44.4 dBm and the DE of 46 - 60% at the 6 dB OBO levels.



(a)

(b)

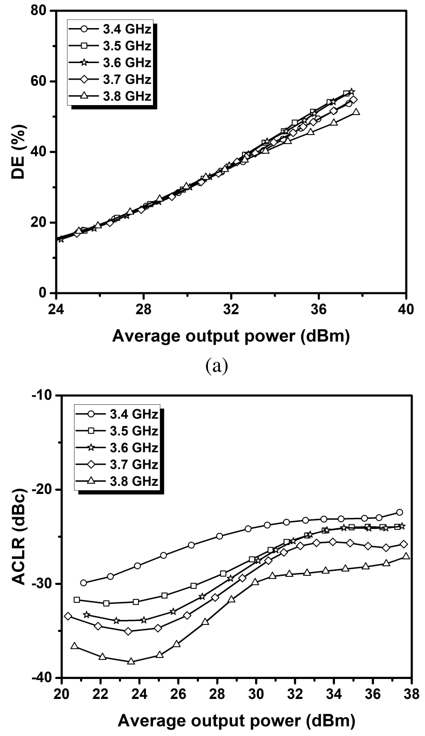
FIGURE 7. **Measured performances using a CW signal: (a) Gain, and (b) DE.**

Fig. 8 shows the measured results of the implemented DPA using a 5G NR signal with signal bandwidth of 100 MHz and

TABLE 2. Performance comparison to the previous works.

Ref.	Frequency (GHz)	P_{sat} (dBm)	P_{avg} (dBm)	DE$_{avg}$ (%)	ACLR** (dBc)	PAPR (dB)	Signal BW (MHz)	Signal	Device
[11]	1.96-2.46	39.8-41.7	34.4	40*	-34/NA†	7.3	20	WiMAX	CGH40010F
[12]	1.63-1.98	31-34	25-28‡	20-49*	-25/NA†	9	5	WCDMA	NA
[13]	0.8-1.2	40.2-42.9	34.2-36.9‡	30.3-40.1*	NA	NA	NA	NA	CGH40010F
[16]	3.4-3.6	43	35	43*	-24/-50†	LTE	20	7.2	GaN MMIC
[17]	3.3-3.55	47.5	39	50.6*	-26/-46.7†	7.5	20	LTE	CGH40025 CGH40035
[18]	3.45-3.75	41.8-43.5	34.6-36.8	38.5-50.2	-24.6/NA	7.8	100	5G NR	CGH40006P CG2H40010F
[19]	3.3-4.3	43.2-44.5	37.2	48	-27/-48.9†	7.2	20	LTE	CGH60015D
[20]	2.8-3.55	43-45	38.4	56.7	-32.3/-53.7†	6.5	40	OFDM	CGH40010F
[21]	3.3-3.75	48-48.8	40.7	53	-30/NA	8	40	LTE	CGHV27030S
This work	3.4-3.8	43.6-44.4	35.8-36.6	47-54.2	-23/-42	7.8	100	5G NR	CG2H40010F

*: Power-added efficiency (PAE), **: Before DPD / After DPD,
†: Adjacent channel power ratio (ACPR), ‡: 6 dB OBO, NA: Not available



(a)

(b)

FIGURE 8. Measured performances using a 5G NR signal: (a) DE, and (b) ACLR.

PAPR of 7.8 dB. Fig. 8(a) & (b) show the DE and ACLR, respectively. The implemented DPA exhibited the DE of 47 - 54.2% at an average output power level of 35.8 - 36.3 dBm with ACLR of –27.9 - –23 dBc. Fig. 9 shows the measured power spectral densities(PSDs) using a 5G NR signal before and after linearization using a digital pre-distortion (DPD) at an average power. Table 2 summarizes the measurement results. Compared to the previous works, the proposed DPA using a very compact load network shows high efficiency at relatively broad bandwidth.

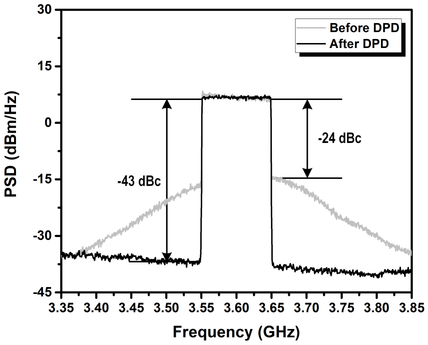


FIGURE 9. Measured PSDs using a 5G NR signal before and after DPD at the frequency of 3.6 GHz.

IV. CONCLUSION

In this paper, a compact quasi-lumped λ/4 ITF for both impedance matching and load impedance modulation with a controlled electrical length of only 90° is proposed for the load network of the DPAs. The proposed load network includes the simplest high-pass network using only a shunt inductor and a L-section low-pass network. The optimum value of the shunt inductor was selected to have an electrical length of the load network of 90° while the L-section low-pass network was accordingly matched to the optimum load impedance. The proposed DPA was designed and implemented using 10 W GaN-HEMTs for both the carrier and peaking amplifiers. Using a 5G NR signal with signal bandwidth of 100 MHz and PAPR of 7.8 dB, DE of 47 - 54.2% and ACLR of –27.9 - –23 dBc were achieved at an average output power level of 35.8 - 36.3 dBm for the broad frequency band of 3.4 - 3.8 GHz. Compared to the previous works, this work exhibited high efficiency at relatively broad bandwidth.

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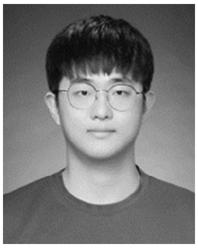

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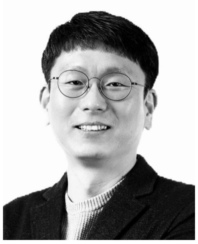

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