Linearity Improved Doherty Power Amplifier Using Composite Right/Left-Handed Transmission Lines

Seung Hun Ji, Sang Ki Eun, Choon Sik Cho, *Member, IEEE*, Jae W. Lee, *Member, IEEE*, and Jaeheung Kim, *Member, IEEE*

***Abstract*—A Doherty power amplifier using composite right/left-handed transmission lines (CRLH-TL) is proposed for linearity improvement. The $\lambda/4$ transmission line incorporating CRLH-TL is designed to suppress the second harmonic of the output of the main amplifier. The output power of the proposed power amplifier at the fundamental frequency (2.30 GHz) shows 31.0 dBm with 13 dBm input power excited. The Doherty power amplifier using CRLH-TL improves the linearity considerably compared to that without employing CRLH-TL.**

***Index Terms*—Composite right/left-handed transmission line (CRLH-TL), Doherty power amplifier.**

I. Introduction

COMPLEX and bandwidth-efficient digital modulation methods used in modern wireless communication systems have considerably increased the linearity requirements of power amplifiers [1]. The substantial loss of transmitter efficiency due to the stringent linearity requirements has forced the industry to look for alternative solutions to alleviate the tradeoff between efficiency and linearity [2]. In particular, its power efficiency and linearity are two key parameters that must be maximized to optimize the communication system's performance. One of the techniques that have been touted as potential candidates for providing both high linearity and high efficiency is the Doherty power amplifier. In the Doherty system, an input signal is divided into two constant envelope signals having 90° phase difference. The divided signal is amplified after the peaking amplifier turns on. The $\lambda/4$ transmission line is utilized to perform matching, to perform impedance inversion, and to compensate phase delay. After compensating each signal is summed.

In this letter, the $\lambda/4$ transmission line is substituted by a composite right/left-handed transmission lines (CRLH-TL) to suppress the second harmonic of the main amplifier output. Using a CRLH-TL allows for the manipulation of phase slope and phase offset at the specified frequency [3]. This attribute can be used to specify the phase delay of a CRLH-TL at different harmonic frequencies to create the necessary impedance for proper microstrip line. Using this method a CRLH-TL network can be used to suppress the second harmonic [4].

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S. H. Ji, S. K. Eun, C. S. Cho, and J. W. Lee are with the School of Electronics, Telecommunication and Computer Engineering, Korea Aerospace University, Goyang, Korea (e-mail: neonjsh@hau.ac.kr; Snagki@hau.ac.kr; cscho@hau.ac.kr; jwlee1@hau.ac.kr).

J. Kim is with the Department of Electrical and Electronic Engineering, Yonsei University, Seoul, Korea (e-mail: jaeheung@ieee.org).

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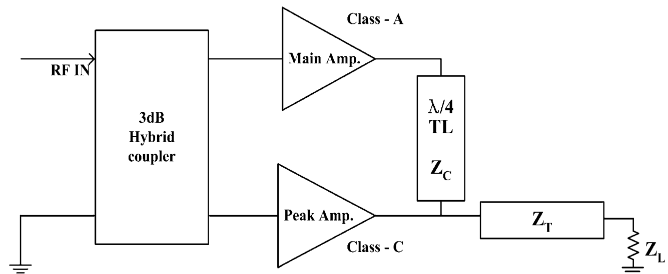

Fig. 1. Doherty power amplifier.

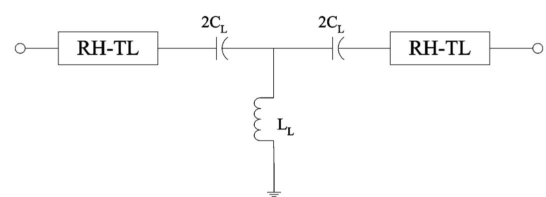

Fig. 2. Lumped elements model for the CRLH-TL when $N = 1$.

II. Design of Doherty Amplifier Using CRLH-TL

Fig. 1 is a block diagram of the Doherty power amplifier. Doherty power amplifier consists of two or more power amplifiers that are operated on Peak-Envelop Power (PEP) level. As in Fig. 1, the carrier (main) power amplifier signal through $\lambda/4$ transmission line is combined with the peak power amplifier signal at the output.

Due to the gain expansion and compression characteristics, the linear operation of the Doherty amplifier can be achieved [5]–[8]. However, this technique improves linearity only a little.

Primary theorem of Doherty power amplifier is load modulation technique using active device changing from load impedance to high value impedance on low power level [8]. Since the conventional Doherty power amplifier concentrates on PAE improvement, it does not always take care of the linearity.

In this work, the second harmonic is suppressed by employing the CRLH-TL shown in Fig. 2 to improve the linearity. The CRLH-TL substitutes for the $\lambda/4$ transmission line. Fig. 2 shows the lumped elements model for the CRLH-TL unit cell ($N = 1$) where the right-handed transmission line (RH-TL) and the left-handed transmission line (LH-TL) composed of capacitors and inductor are incorporated.

When the series and shunt resonances are equal, the structure is said to be balanced [9]. Z_{0R}, Z_{0L} and Z_0^{CRLH} are fixed as Z_C. The characteristic impedance Z_C of the $\lambda/4$ transmission line

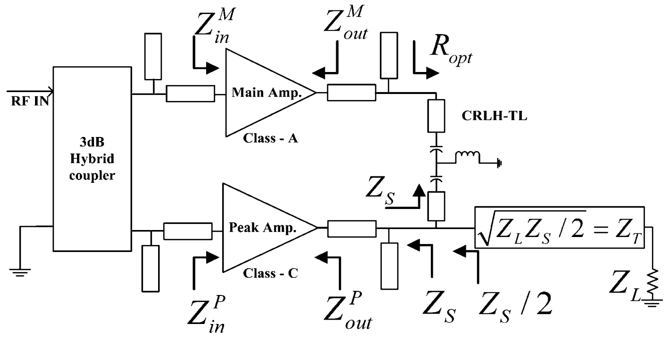

Fig. 3. Proposed Doherty power amplifier using CRLH-TL.

TABLE I
COMPONENT VALUES OF CRLH-TL

	Z_{0R}	Z_{0L}	C_L	L_L	RH-TL(ϕ)
Calculated value	50 Ω	50 Ω	1.26 pF	3.16 nH	−210°
Real value	50.2 Ω	46.9 Ω	1.50 pF	3.30 nH	−188°

can be obtained by load modulation technique [8]. According to the desired phases for two different frequencies, the phase response of CRLH-TL will be $-\pi/2$ at f_1 (fundamental frequency) and -2π at f_2 (second harmonic). Therefore, a large portion of the second harmonics generated from the main and peaking amplifiers will be canceled at the summing load. The phase responses of CRLH-TL at f_1 and f_2 can be written as

$$\phi_C(f_1) = -\pi/2 \tag{1}$$
$$\phi_C(f_2) = -2\pi. \tag{2}$$

The CRLH-TL can be designed using (3) and (4), and the method described in [9]

$$P \approx \frac{2\pi f_2 - (\pi/2) f_1}{f_2^2 - f_1^2} \tag{3}$$
$$Q \approx \frac{\frac{2\pi}{f_2} - \frac{\pi/2}{f_1}}{\frac{1}{f_1^2} - \frac{1}{f_2^2}} \tag{4}$$

P, Q, Z_{0R}, and Z_{0L} are altogether used to determine C_L, L_L, and physical length of RH-TL [9], [10]. Finally, the CRLH-TL is substituted for the $\lambda/4$ transmission line to realize a second harmonic suppression. Fig. 3 shows the proposed Doherty power amplifier using CRLH-TL where class-A and class-C amplifiers are used for the main and peak amplifiers, respectively. Using the design procedure proposed, the CRLH-TL was designed and standard values were used for C_L and L_L, resulting in deviation of the phase response as shown in Table I.

III. MEASUREMENT RESULT

The proposed Doherty power amplifier was designed and simulated using Agilent ADS at 2.4 GHz. The transistor model used is Mitsubishi MGF2430. At first, two different class (Main amplifier: class-A, Peaking amplifier: class-C) power amplifiers are combined, then the $\lambda/4$ transmission line is converted by CRLH-TL as shown in Fig. 3. The input and output impedances are optimized based on the source and load-pull simulation. The input matching networks are designed by the conjugate matching. The output matching networks are also designed by the conjugate matching where $R_{\rm opt}$ and Z_S are used for the load impedances of main and peak amplifiers, respectively. The $R_{\rm opt}$ is selected as 100 Ω when the peak amplifier turns off, and 50 Ω when it turns on. The characteristic impedances of the CRLH-TL and $\lambda/4$ impedance transformer (Z_C) are 50 Ω and Z_T in Fig. 3 is calculated by using Z_S and Z_L as shown in Table II.

TABLE II
DESIGN PARAMETERS FOR THE PROPOSED DOHERTY AMPLIFIER

Z_{in}^{M}	Z_{out}^{M}	$Z_S/2$
32.4 + j77.9 Ω	26.5 + j18.2 Ω	23.9 Ω
Z_{in}^{P}	Z_{out}^{P}	Z_T
16.1 + j82.4 Ω	24.9 - j7.8 Ω	35.7 Ω

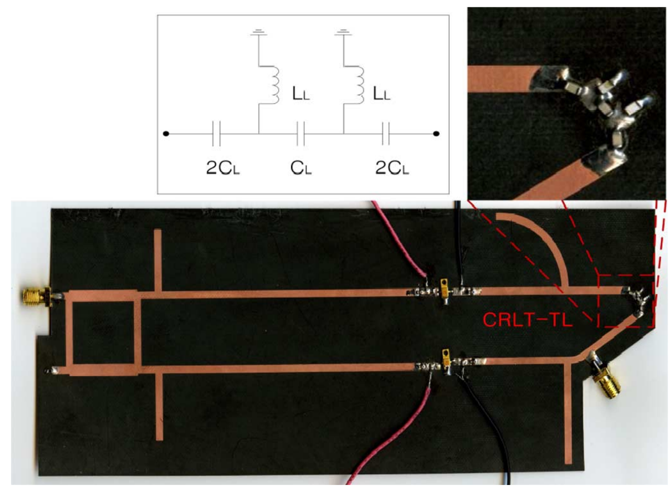

Fig. 4. Layout of the fabricated Doherty power amplifier using CRLH-TL.

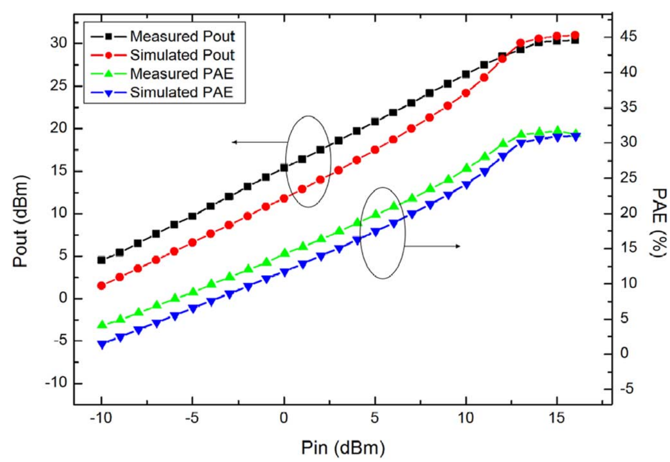

Fig. 5. Measured (2.3 GHz) and simulated results (2.4 GHz) of Doherty power amplifier using CRLH-TL.

Fig. 4 shows the layout of fabrication for the proposed Doherty amplifier where RT Duroid 5880 substrate was used and 2 unit cells were used for CRLH-TL.

Fig. 5 shows the simulated and measured output powers and PAEs of the proposed Doherty power amplifier using CRLH-TL. The maximum measured PAE is 32.1% at 2.30 GHz.

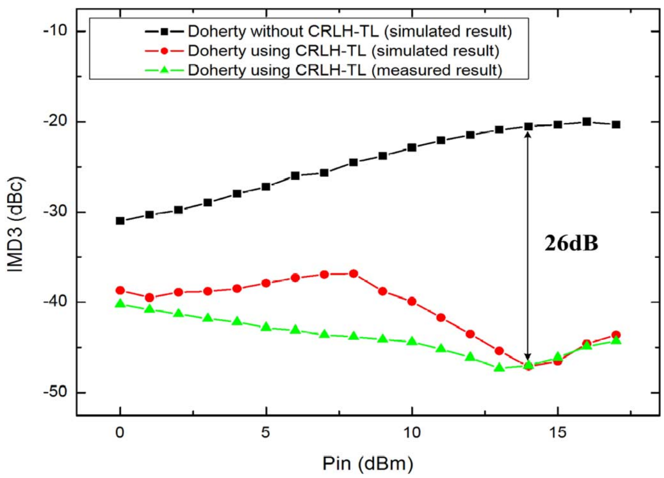

Fig. 6. IMD3 of the proposed Doherty amplifier with CRLH-TL and the Doherty amplifier without CRLH-TL (10 MHz offset).

TABLE III
PERFORMANCE COMPARISON

Work	Frequency	Max. P_{out}	Max. IMD3	Remark
[11]	2.4 GHz	23 dBm	-43 dBc	CMOS
[12]	1.88 GHz	29 dBm	-37 dBc	HBT
[13]	2.14 GHz	55 dBm	-44 dBc	GaAs FET
This work	2.30 GHz	31 dBm	-47 dBc	GaAs FET

This result is in good agreement with simulation except the frequency shift. With the input power of 13 dBm, the output achieved maximum power of 31.0 dBm at 2.30 GHz. Since the post-tuning for various microstrip lines was not performed, the output frequency was a bit deviated. In addition, the lumped element values of inductors and capacitors used for fabrication contribute to the frequency shift.

Fig. 6 shows that the IMD3 of the proposed Doherty amplifier was considerably improved even at low input power region compared to that of the Doherty amplifier without CRLH-TL at 10 MHz offset. It proves the improvement of linearity. It is because the second harmonic was suppressed successfully by incorporating CRLH-TL. The IMD3 is improved even at low input power region because the peaking amplifier is not perfectly shut down at that region, eventually providing the second harmonic to the summing node.

Table III shows performance comparison with other works [11]–[13]. At high frequencies, the proposed Doherty amplifier employing CRLH-TLs shows comparable performance.

IV. CONCLUSION

A Doherty power amplifier using composite right/left-handed transmission line was proposed. Second harmonic suppression was achieved by manipulating the phase slope of CRLH-TL for matching network. We can control the phase response of CRLH-TL as needed at the operating frequency. Operating frequency was chosen at 2.4 GHz for simulation and at 2.3 GHz after fabrication. In the proposed Doherty power amplifier using CRLH-TL, the output power of 31.0 dBm was obtained at 2.3 GHz. In case of maximum PAE, we obtained 32.1% at 2.3 GHz. Simulation and measured results verifies considerable improvement of linearity.

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