Concurrent Dual-Band Class-E Power Amplifier Using Composite Right/Left-Handed Transmission Lines

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

***Abstract*—A concurrent dual-band class-E power amplifier using composite right/left-handed transmission lines (CRLH TLs) is proposed. Dual-mode operation is achieved by using the frequency offset and nonlinear phase slope of CRLH TLs for the matching network of power amplifiers. The frequency ratio of two operating frequencies is not necessarily an integer. Two operating frequencies are chosen as 836 MHz and 1.95 GHz for simulation. Three methods for designing a CRLH TL power amplifier are proposed. The measured results based on one method show that output powers of 22.4 and 22.2 dBm were obtained at 800 MHz and 1.70 GHz, respectively. In terms of maximum power-added efficiency, we obtained 42.5% and 42.6% at 800 MHz and 1.70 GHz, respectively.**

***Index Terms*—Class-E power amplifier, composite right/left-handed transmission line (CRLH TL), dual band.**

I. Introduction

RECENTLY, RF equipment is required to operate seamlessly using different wireless communications standards and spectra that are in use around the world. Various efforts have been made to realize multiband operation. Adaptable RF circuits whose performance can be changed without loss of performance according to the wireless environment will be necessary to achieve this concept [1]. Power amplifiers are a key component in mobile terminals and must have high operation efficiency in order to maximize the battery life, and reduce the size and cost. In several power amplifiers, the switched-mode class-E tuned power amplifiers with a shunt capacitor have found widespread application due to their design simplicity and high-efficiency operation. The drain efficiency of the class-E power amplifier theoretically reaches 100% [2].

Concurrent dual-band operation is beneficial to reduce the number of circuit components in modern wireless communication systems requiring two frequency bands. However, dual-band power amplifiers are difficult to design because matching networks of power amplifier are usually made to operate at one specific frequency. The need for good matching networks arises in order to deliver maximum power to a load [3]. Since matching networks are fixed to one operating frequency, concurrent dual-band power amplifiers need a novel matching network. Dual-band power amplifiers using the low-pass Chebyshev-form impedance transformer were presented in [4] and [5]. In this paper, the simple features of metamaterial [6] based on transmission lines are used to implement a matching network for class-E power amplifier for concurrent dual-mode operation. As described in [7], composite right/left-handed transmission lines (CRLH TLs) possess interesting phase characteristics such as antiparallel phase and nonlinear phase slope. Thus far, this novel transmission media have been used in the implementation of passive devices such as couplers, resonators, and antennas [7]–[9]. The use of CRLH TLs allows for the manipulation of phase slope and phase offset at zero frequency [8]. This attribute can be used to specify the phase delay of a CRLH TL at different frequencies to create the necessary impedance for proper matching network. Using this method, a CRLH TL network can be used to design a dual-band class-E power amplifier [10].

Another key point in RF equipment is its size. The size of the power amplifier is an important feature in evaluating its performance. RH TL parts of the proposed CRLH TL in [10] are composed of microstrip lines. Proposed dual-band power amplifier in this study, using only the negative phase response of the CRLH TL, has long electrical length of RH TLs. Elongated RH TLs cause increased size and power loss of the power amplifier. In this paper, the relationship between the left-handed (LH) and right-handed (RH) parts is analyzed. The electrical length of RH TLs can be shortened using the positive phase response of the CRLH TL. The design of the dual-band class-E power amplifier using the CRLH TL was originally introduced in [10]; here, a more shortened CRLH TL and a lumped- element CRLH TL have been considered.

II. Class-E Power Amplifier

In the class-E power amplifier, the transistor operates as an on–off switch and the shapes of the current and voltage waveforms provide a condition that minimizes the power dissipation and maximizes the power amplifier efficiency. The circuit topology for the class-E power amplifier [2] is shown in Fig. 1. It consists of a transistor acting as a switch, a shunt capacitor (C_s) across the switch, and the matching network using microstrip lines. When the switching frequency of the transistor

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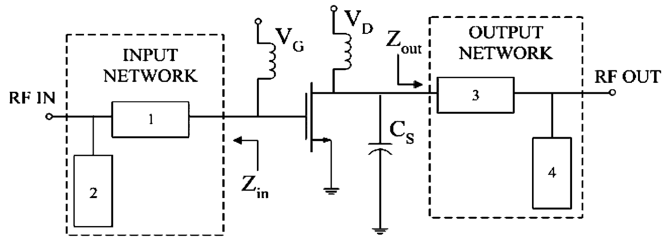


Fig. 1. Class-E power amplifier circuit topology.

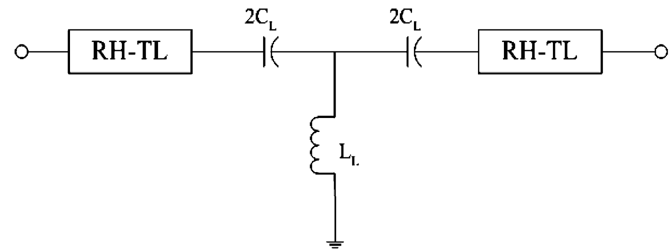


Fig. 2. Lumped elements model for the CRLH TL when $N = 1$.

TABLE I
IMPEDANCES TOWARD SOURCE AND LOAD

Mode	Frequency	Source (Z_{in})	Load (Z_{out})
Single band	836MHz	0.31 - j86.95	0.03 - j11.84
	1.95GHz	0.03 + j20.56	0.03 - j1.64
Dual band	836MHz	0.66 - j112.40	0.12 - j4.251
	1.95GHz	0.23 + j16.94	0.21 - j0.44

is ω_s at the fundamental frequency, the impedance of the output network including the load is found to be [11]

$$Z_{\text{out}} = \frac{1}{C_s \cdot \omega_s} e^{j49^\circ} \tag{1}$$

assuming the impedances of all other harmonics are open. In practice, an open-circuit termination at the second harmonic is sufficient to give class-E operation [11].

In the mean time, the output impedance (Z_{out}) can also be optimized using the load–pull technique [12]. This study obtains the optimized Z_{in} and Z_{out} using the source–pull and load–pull techniques, as shown in Table I. At first, two different class-E power amplifiers are designed individually at two different operating frequencies (f_1, f_2). At this time, dc-bias voltages such as gate bias voltage (V_G) and drain bias voltage (V_D) are set at the same values in two different class-E power amplifiers. The transistor must operate as an on–off switch and the typical duty cycle is 50% [13]. C_s for producing maximum output power takes different values at two frequencies [2].

The input matching circuit is realized by source–pull conjugate matching and output matching circuit by load–pull conjugate matching using (1) as a starting point. The input matching circuit and output matching circuit can be composed of two microstrip lines, respectively. Each matching section has a phase response (ϕ_A, ϕ_B) at two frequencies. CRLH TL matching networks, using ϕ_A and ϕ_B, can be designed. In this paper, three methods for designing a dual-band power amplifier are proposed. The first design method uses the negative phase response of the CRLH TL [10]. The second design method uses the positive phase response of the CRLH TL. Meanwhile, the third design method uses an *LC* (inductor and capacitor) lumped network CRLH TL.

III. DESIGN OF DUAL-BAND POWER AMPLIFIER USING CRLH TL

A. First Method

The CRLH TL, which is the combination of an LH TL and an RH TL, is proposed in [14]. The equivalent lumped element model of the LH TL exhibits positive phase response (phase lead). On the other hand, the RH TL has negative phase response (phase lag). Therefore, the CRLH TL can substitute for the matching network shown in Fig. 1. Fig. 2 shows the lumped element model for the CRLH TL when one unit cell $(N = 1)$ is used [8].

L_R and C_R are inductive and capacitive elements of the RH TL and L_L, C_L are the inductive and capacitive elements of the LH TL. When the series resonance (ω_{se}) and shunt resonance (ω_{sh}) are equal,

$$\omega_{\text{se}} = \omega_{\text{sh}} \tag{2}$$
$$L_R C_L = L_L C_R \tag{3}$$
$$Z_{0L} = Z_{0R} \tag{4}$$

the structure is said to be balanced [14]. Z_{0R} and Z_{0L} are the characteristic impedances defined as

$$Z_{0R} = \sqrt{\frac{L_R}{C_R}} \tag{5}$$
$$Z_{0L} = \sqrt{\frac{L_L}{C_L}} \tag{6}$$
$$Z_0^{\text{CRLH}} = Z_{0R} = Z_{0L}. \tag{7}$$

Z_{0R}, Z_{0L}, and Z_0^{CRLH} are usually fixed as 50 Ω. The phase response can approximately be expressed in the balanced condition

$$\phi_R \approx -N 2\pi f \sqrt{L_R C_R} \tag{8}$$
$$\phi_L \approx \frac{N}{2\pi f} \sqrt{L_L C_L} \tag{9}$$
$$\phi_C = \phi_R + \phi_L. \tag{10}$$

Unlike the ideal case, the CRLH TL has innate LH and RH cutoff frequencies as [15]

$$f_c^{\text{LH}} = \frac{1}{4\pi\sqrt{L_L C_L}} \tag{11}$$
$$f_c^{\text{RH}} = \frac{1}{\pi\sqrt{L_R C_R}}. \tag{12}$$

Since the phase response of the CRLH TL is set to $-\phi_A$ at f_1 and $-\phi_B$ at f_2, the phase response of the CRLH TL at f_1 and f_2 can be written as

$$\phi_C(f_1) = -\phi_A \tag{13}$$
$$\phi_C(f_2) = -(n\pi + \phi_B). \tag{14}$$

In (13) and (14), the negative phase response of the CRLH TL was used, as shown in Fig. 3, where n is a positive number and

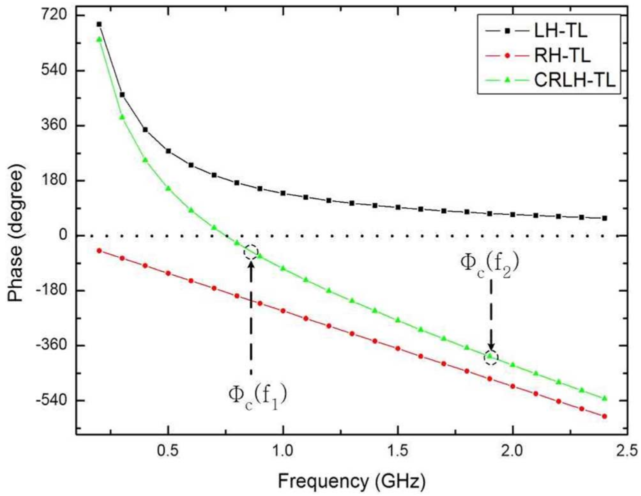


Fig. 3. Phase response of CRLH TL.

can be chosen arbitrarily for minimizing N. From (5)–(10), (13) and (14) can be written as

$$P = 2\pi N\sqrt{L_R C_R} \tag{15}$$

$$Q = \frac{N}{2\pi}\sqrt{L_L C_L} \tag{16}$$

$$-Pf_1 + \frac{Q}{f_1} \approx -\phi_A \tag{17}$$

$$-Pf_2 + \frac{Q}{f_2} \approx -(n\pi + \phi_B). \tag{18}$$

For the given f_1 and f_2, solving for P and Q in (12) and (13) to obtain [8],

$$P \approx \frac{(n\pi + \phi_B)f_2 - \phi_A f_1}{f_2^2 - f_1^2} \tag{19}$$

$$Q \approx \frac{\dfrac{(n\pi + \phi_B)}{f_2} - \dfrac{\phi_A}{f_1}}{\dfrac{1}{f_1^2} - \dfrac{1}{f_2^2}}. \tag{20}$$

If $Q < 0$, P and Q are calculated with a large n. For the next step, f_c^{LH} is calculated from (11). If $f_c^{\mathrm{LH}} < f_1$, the design is completed. Otherwise, the design is performed again with a larger N [8]. P, Q, Z_{0R}, and Z_{0R} are used to determine C_L and L_L from (5) and (15), and the physical length of the RH TL from (6) and (8). Finally, CRLH TLs are substituted for the matching network instead of microstrip lines to realize a dual-band operation. Fig. 4 shows the proposed concurrent dual-band class-E power amplifier using CRLH TLs.

For suitable ϕ_A and ϕ_B of the designed class-E power amplifier proposed here, the value of n needs to be greater than 2. When $n = 2$, the length of RH TLs is almost λ_{f_1}.

B. Second Method

The problem with the first design method is the long physical length of the RH TL. The positive phase response of the CRLH TL can be used in order to decrease the size of the power amplifier in the second design method. Instead of (13), the phase response of the CRLH TL can be set as

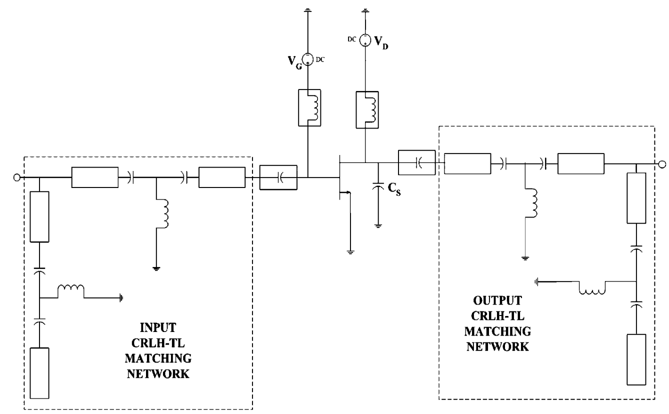


Fig. 4. Proposed concurrent dual-band class-E power amplifier using CRLH TLs.

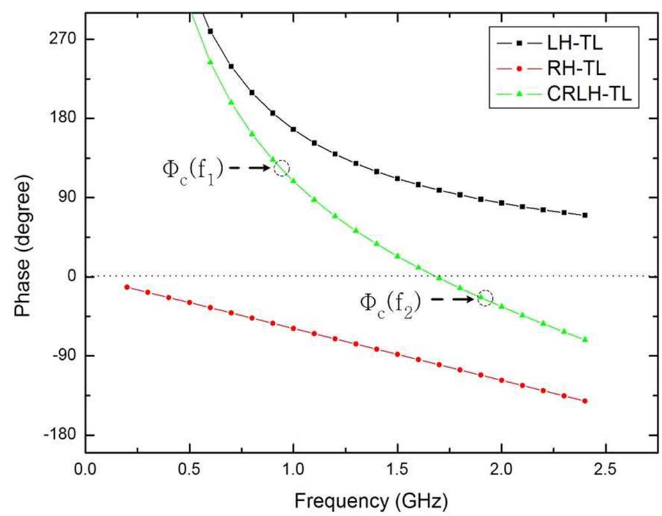


Fig. 5. Phase response of CRLH TL using the second method.

$$\phi_C(f_1) = \pi - \phi_A \tag{21}$$

$$\phi_C(f_2) = -(n\pi + \phi_B) \tag{22}$$

where $\phi_C(f_1)$ has a positive value because $\phi_A \leq \pi$ and n is a positive number. Fig. 5 shows the phase response of the CRLH TL using the second method. The next steps are the same as the first method.

Fig. 6 shows the difference between the phase responses of the first and second methods.

In Fig. 6, the phase slope of the CRLH TL simulated using the first method is steeper than that using the second method because the difference between $\phi_C(f_1)$ and $\phi_C(f_2)$ is larger in the first method. Such difference increases the phase slope of the CRLH TL. As the phase slope of the CRLH TL increases, the phase slope of the RH TL also increases. The electrical length of the RH TL increases in proportion to the phase slope of the RH TL. Therefore, electrical length of the RH TL, using the first method, is longer than that using the second method. However, since the electrical length of the RH TL is not proportional to

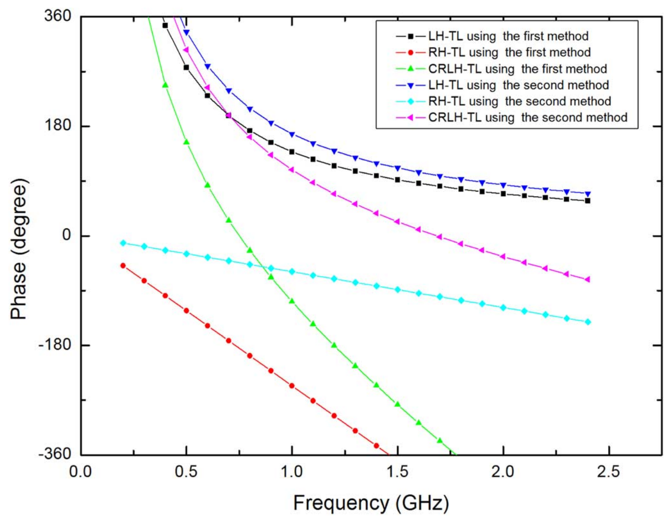


Fig. 6. Phase responses of CRLH TL using the first and second methods.

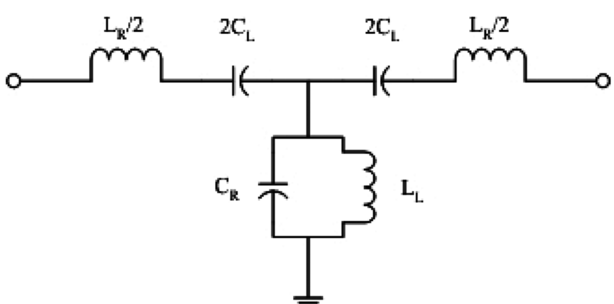


Fig. 7. Unit cell of *LC* CRLH TL.

N, the number of unit cell increases. As the phase slope of the CRLH TL increases, the phase slope of the LH TL increases. As ϕ_R increases, f_c^{LH} decreases in (9) and (11). As the value of f_c^{LH} becomes smaller, the number of unit cells in the CRLH TL is lowered.

C. Third Method

The *LC* CRLH TL was proposed in [14]. Fig. 7 shows the *LC* CRLH TL composed of lumped elements only. The third design method of a dual-mode power amplifier uses the *LC* CRLH TL. The third method can make the size of the CRLH TL as small as possible. The third method is similar to the second method in that $\phi_C(f_1)$ and $\phi_C(f_2)$ can be set as in (21) and (22). Rest of the steps are the same as the first method and cutoff frequency condition is added as $f_c^{\mathrm{RH}} > f_2$ to obtain the same results from the first method and value of L_L and C_L. Therefore, the dual-band power amplifier can also be designed using the *LC* CRLH TL.

IV. Simulation and Measurement

The proposed concurrent dual-band class-E power amplifiers were simulated using Agilent ADS at cellular (836 MHz) and 3G (1.95 GHz) frequencies. The transistor model used is Mitsubishi MGF2415. At first, two different single-band class-E power amplifiers at the two frequencies are designed individually as shown. The value of C_s is chosen as 3 pF. Practically, the method depicted in [12] was used for matching in two different single-band class-E power amplifiers at the two frequencies. The output impedance was optimized using the load–pull technique to produce class-E operation, as shown in Table I. Thereafter, each microstrip lines in the matching network are substituted for the CRLH TL.

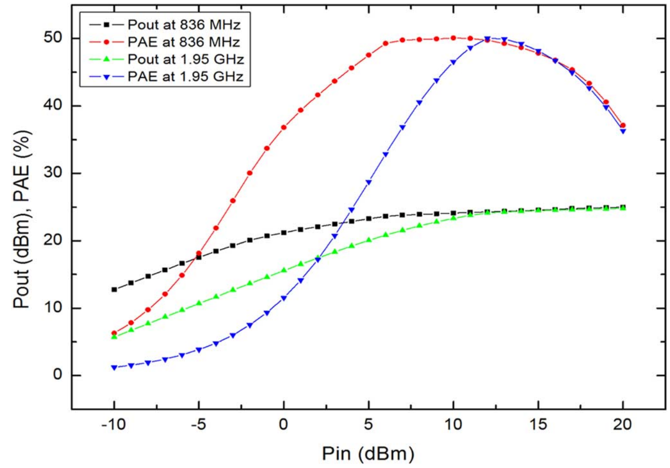


Fig. 8. Performances of proposed single-band class-E power amplifiers at the two operating frequencies.

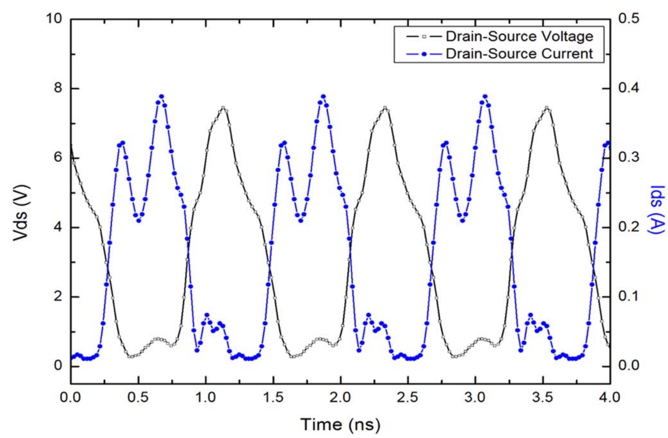


Fig. 9. Voltage and current waveforms of dual-band class-E power amplifier using the first method at 836 MHz.

Fig. 8 shows the simulated output power and power-added efficiency (PAE) of a single-band class-E power amplifier designed individually at 836 MHz and 1.95 GHz. In this case, maximum output powers of 24.9 and 24.8 dBm, and PAEs of 50.07% and 50.04% at 836 MHz and 1.95 GHz were obtained, respectively. Using this configuration, dual-band class-E power amplifiers are designed. Each Z_{in} and Z_{out} is obtained using source–pull and load–pull at 836 MHz and 1.95 GHz, as shown in Table I. Suitable CRLH TLs are designed for the input and output matching networks. The CRLH TLs are optimized to produce a Z_{in} and Z_{out} phase response closer to those for single-band matching networks.

Fig. 9 shows the voltage and current waveform of the simulated power amplifier of a dual-band class-E power amplifier using the first method at 836 MHz. As the voltage and current hardly overlap each other, this is sufficiently operating as class-E operation. In Fig. 9, the transistor operate as an on-off

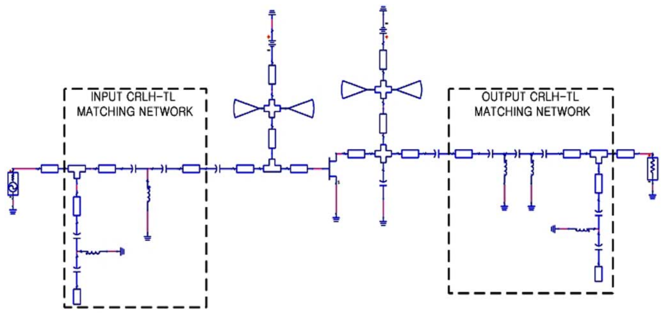


Fig. 10. Simulation layout of proposed dual-band class-E power amplifier using the first method.

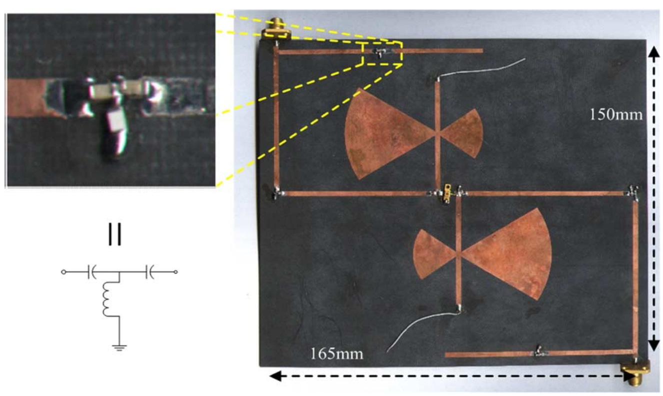
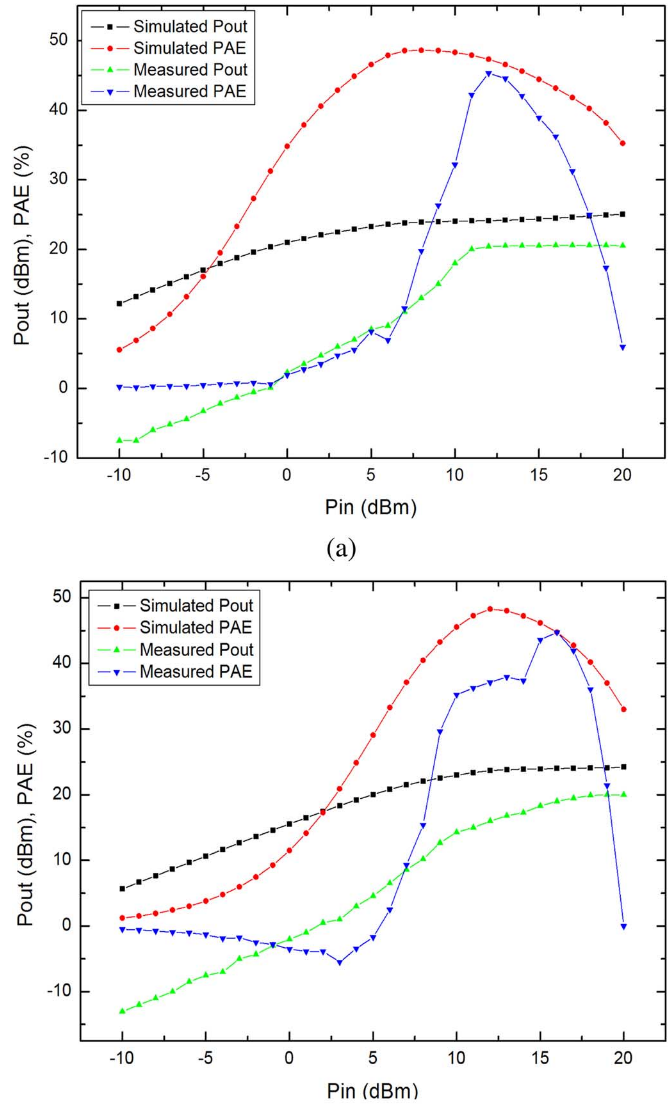


Fig. 11. Fabricated layout of proposed dual-band class-E power amplifier using the first method.

switch and the duty cycle is approximately 50%, enabling the simulated power amplifier to operate well for class-E operation. Fig. 10 shows the simulation layout of the proposed dual-band class-E power amplifier using the first method at the two operating frequencies. In the simulation layout, a different microstrip radial stub size for biasing is used to operate at 836 MHz and 1.95 GHz. The device is biased with a drain voltage of 2.8 V and a gate voltage of -1.9 V. Fig. 11 shows the fabricated layout of the proposed dual-band class-E power amplifier using the first method. Its size is 165 mm $\times$ 150 mm.

Fig. 12 shows the output power and PAE of simulated and measured dual-band class-E power amplifier at the two operating frequencies using the first method. In this case, maximum PAE of 45.3% and 44.7% were obtained at 830 MHz and 1.80 GHz for measured results, respectively. The output powers of 20.6 and 19.5 dBm were obtained at 830 MHz and 1.80 GHz. Since the operating frequencies are chosen for the maximum output power, a gap between simulation and measurement is observed for some input powers. This error can be mitigated if a post-tuning for the matching section is carried out.

Fig. 13 shows the fabricated layout of proposed class-E power amplifier using the second method at the two operating frequencies. Its size is 90 mm $\times$ 110 mm. Fig. 14 shows measured results using the second method. Maximum output powers of 22.4 and 22.2 dBm were obtained and maximum PAEs of 42.5% and 42.6% at 800 MHz and 1.70 GHz, respectively. With input power less than 12 dBm, performance obtained is not satisfactory due to the occurrence of frequency shift. The reason it operates in an unexpected manner is also caused from the shifted operating frequency, which was chosen for maximum output



(a)

(b)

Fig. 12. Output powers and PAEs of dual-band class-E power amplifier using the first method at the two operating frequencies. (a) 836 MHz for simulation, 830 MHz for measurement. (b) 1.95 GHz for simulation, 1.80 GHz for measurement.

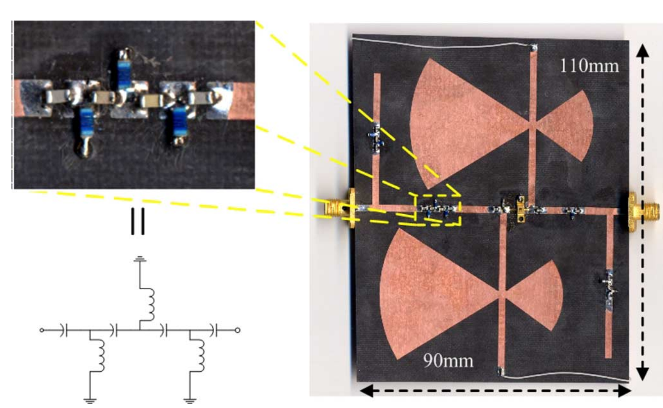


Fig. 13. Fabricated layout of proposed dual-band class-E power amplifier using the second method.

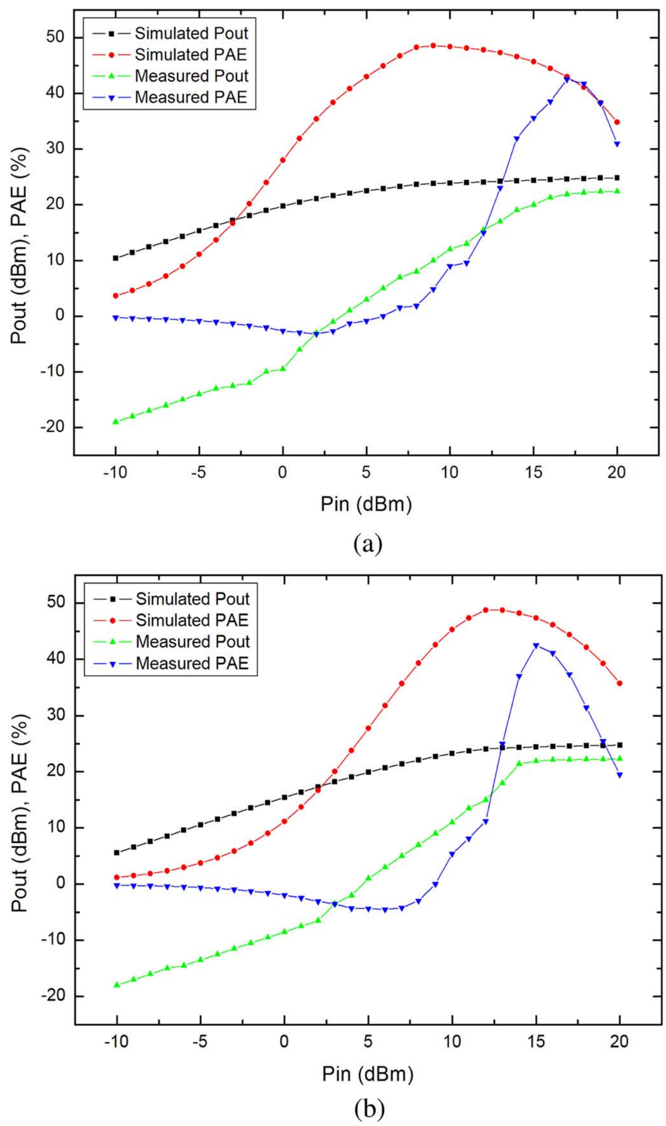


Fig. 14. Output power and PAE of dual-band class-E power amplifier using the second method at the two operating frequencies. (a) 836 MHz for simulation, 800 MHz for measurement. (b) 1.95 GHz for simulation, 1.70 GHz for measurement.

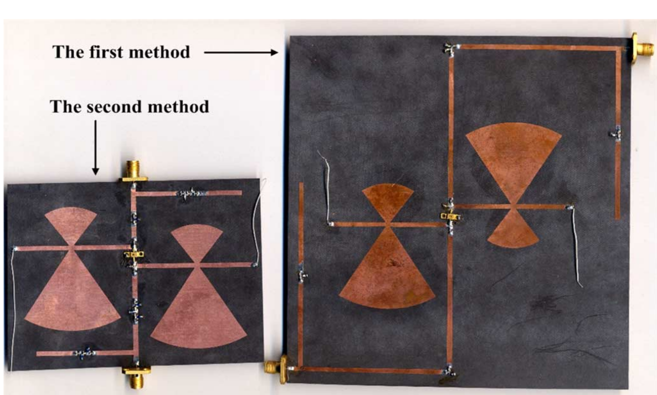


Fig. 15. Dual-band class-E power amplifiers using the first method versus the second method.

power. A post-tuning for the matching section can also ameliorate this error.

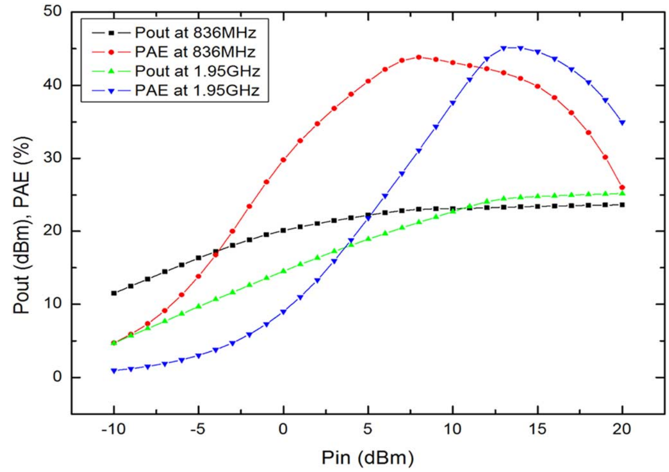


Fig. 16. Simulation result of power amplifier using the third method.

TABLE II
SUMMARY OF DESIGNED MATCHING SECTIONS

matching section (in Fig.1)	1	2	3	4
Physical Length at f_1 (mm)	100.5	50.7	21.0	31.0
Phase delay at f_1 ($-\phi_A$)	$-138°$	$-70°$	$-29°$	$-42°$
Physical Length at f_2 (mm)	11.8	21.8	9.1	15.4
Phase delay at f_2 ($-\phi_B$)	$-38°$	$-69°$	$-28°$	$-50°$
N of the First method	1	1	2	1
RH-TL of the 1st method (mm)	126	84	140	78
N of the Second method	1	2	3	2
RH-TL of the 2nd method (mm)	21	35	33	39
N of the third method	1	2	3	2

TABLE III
PERFORMANCE COMPARISON

Work	Frequency	Max. P_{out}	Max. PAE	Remark
[1]	900 MHz	30 dBm	46%	MEMS
	1.9 GHz	31 dBm	62%	
[4]	7.15 MHz	24 dBm	92%	class-E
	10.1 MHz	23 dBm	87%	
[5]	801 MHz	31 dBm	52%	
	1.5 GHz	28 dBm	52%	
This work (the 1st method)	830 MHz	21 dBm	45%	class-E
	1.8 GHz	19 dBm	45%	
This work (the 2nd method)	800 MHz	22 dBm	43%	class-E
	1.7 GHz	22 dBm	43%	

Using the second method, the physical size of the dual-band power amplifier was reduced as shown in Fig. 15. Dual-band power amplifier using the third method is also designed using simulation only (see Fig. 16). Maximum output power was obtained almost at the same values as those of each single-band class-E power amplifier.

Table II shows the summary of matching sections, which were designed using the electrical and physical lengths for all three cases (in Fig. 1). Table III shows performance comparison with other studies. At high frequencies, the proposed dual-band class-E power amplifiers employing CRLH TLs shows comparable performance.

V. CONCLUSION

A concurrent dual-band class-E power amplifier using CRLH TLs was proposed. Dual-band operation was achieved by the frequency offset and phase slope of the CRLH TL for matching networks. The frequency ratio of two operating frequencies is not necessarily an integer. We can control the phase response of the CRLH TL as needed at two operating frequencies. Two operating frequencies are originally chosen, i.e., 836 MHz and 1.95 GHz, in this study. In the proposed dual-band class-E power amplifier using the first method, the output powers of 20.6 and 19.5 dBm were obtained at 830 MHz and 1.80 GHz. In case of maximum PAE, we obtained 45.3% and 44.7% at two operating frequencies. The measured results of the proposed dual-band class-E power amplifier using the second method showed that output power of 22.4 and 22.2 dBm was obtained at 800 MHz and 1.70 GHz, respectively. In case of maximum PAE, we obtained 42.5% and 42.6% at two operating frequencies. The PAE of proposed dual-band class-E power amplifiers using the first and second methods reaches almost 90% performance of a normal class-E power amplifier at two individual operating frequencies. Therefore, CRLH TLs can be applied to other circuits requiring multiband operation.

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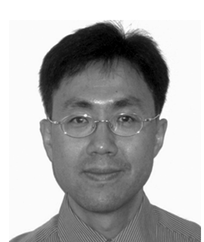

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