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Matching Element Sensitivity Analysis for the Operation of a Dual-band Power Amplifier with CRLH Transmission Lines

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Abstract

In this paper, we analyzed the sensitivity of matching elements for the dual-band operation of a power amplifier with composite right/left-handed (CRLH) transmission lines. Metamaterial theory enables CRLH transmission to support arbitrary impedance matching at dual frequencies. In general, at sub-GHz range, the CRLH matching networks are commonly implemented with lumped elements, which are prone to manufacturing distribution. In order to reduce the effect from the distribution of element values in design, we suggest a method to analyze the sensitivity of matching elements from the performance aspect of power amplifiers. Based on the analysis, a 40dBm dual-band power amplifier operating at 0.7GHz and 1.5GHz is designed.

Key words: PAPR, Power Amplifier, Efficiency, Envelope Tracking, Supply Modulator

Ⅰ. Introduction

As the demand for wireless devices supporting multiple frequency bands in small packages is increasing, a lot of effort have been focused on multi-frequency technology and package minimization [1], [2]. As such, power amplifiers to support multiple bands are widely adopted, and dual-band operation is an important issue in terms of the miniaturization and the usage of a device [1]. In this regard, based on the CRLH transmission-line theory, arbitrary impedance matching at dual frequencies is a feasible solution [3]. However, when CRLH transmission line (TL) is implemented with lumped elements, its performance may degrade significantly by inaccurate component values from manufacturing distribution [4]. For this reason, the distribution of lumped element values should be taken into account from the design process. Therefore, we propose a method to analyze the sensitivity and identify the most critical component in CRLH TL networks and to find out the optimal values for the operation of the dual-band PA. The matching network was designed for a 10W dual-band PA that supports dual frequencies (0.7GHz for the public safety operation and 1.5GHz for the satellite communication).

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II. Composite Right/Left Handed Transmission Line

CRLH transmission line is an artificial structure showing pseudo-metamaterial characteristic with the conventional passive components. The Right-handed (RH) transmission line (TL) is composed of a shunt capacitance and series inductances, and it has a characteristic of low-pass frequency response. On the other hand, the Left-handed (LH) transmission line is composed of shunt inductors and series capacitors, showing high pass frequency response [5]. Fig. 1 shows the equivalent circuit of RH and LH transmission lines with lumped elements [6], [7].

In fact, it is quite difficult to implement LH TLs because of the parasitic capacitance in the LH TL within the series inductor, L_R, which is a parasitic component due to the current flow. Also, during the inductor implementation of LH TL, the shunt capacitor C_R introduces a parasitic component between the micro-stripline and the ground plate.

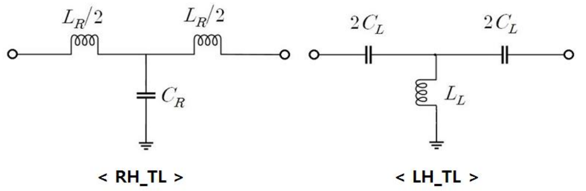

Fig. 1. Equivalent circuit of RH_TL and LH_TL.

At low frequencies, CRLH TL operates as an LH TL because the immittances (impedance and admittance) of L_R and C_R are negligible. At higher frequencies, CRLH TL operates as an RH TL because this time immittances of C_L and L_L are negligible. Consequently, the CRLH TL has a bandpass characteristic [5]. Fig. 2 shows the equivalent circuit of the CRLH TL by using lumped elements and frequency response of the CRLH TL [7], [8].

Dual band matching can be realized from the characteristic of the CRLH TL, assuming that the load impedance is defined as $Z_{1} = R_1 + jX_1 = 1/(G_{L1} + jB_{L1})$ at f_1. The first step is to transform Z_{L1} into $R+jX$ with the feeding transmission line of Z_0 and the phase shift, Φ_{feed} as shown in Fig. 3. The impedance $Z_{feed}(R+jX)$ and the phase shift, Φ_{feed}, Φ_{stub} at the input of the feeding line can be calculated as follows [6]:

$$R = \frac{G_L(1+\tan^2(\Phi_{feed}))}{G_L^2 + (B_{L+}\tan(\Phi_{feed})/Z_0)^2} \tag{1}$$

$$X = \frac{{G_L}^2\tan(\Phi_{feed}) - (Y_{0-}B_L\tan(\Phi_{feed}))(Y_{0+}B_L)}{Y_0[{G_L}^2 + (B_L + \tan(\Phi_{feed})Y_0)^2]},$$

$$where \quad Y_0 = \frac{1}{Z_0} \tag{2}$$

$$\Phi_{feed} = \tan^{-1}\left(\frac{B_L \pm \sqrt{\dfrac{G_L[(Y_{0-}G_L)^2 + {B_L}^2]}{Y_0}}}{G_L - Y_0}\right),$$

$$\text{for} \quad G_L \neq Y_0 \tag{3}$$

$$\mathit{\Phi}_{stub} = -\tan^{-1}\left(\frac{X}{Z_0}\right) \tag{4}$$

Similarly, for the design at f_2, two more phase shifts are calculated to match to 50 ohm [6].

When, the CRLH TL are built with the N repetition of the unit cell, the final components can be found as follows [6]:

$$L_R = \frac{Z_t[\Phi_1(\omega_1/\omega_2) - \Phi_2]}{N\omega_2[1-(\omega_1/\omega_2)^2]} \tag{5}$$

$$C_R = \frac{[\Phi_1(\omega_1/\omega_2) - \Phi_2]}{N\omega_2 Z_t[1-(\omega_1/\omega_2)^2]} \tag{6}$$

$$L_L = \frac{NZ_t[1-(\omega_1/\omega_2)^2]}{\omega_1[\Phi_1 - \Phi_2(\omega_1/\omega_2)]} \tag{7}$$

$$C_L = \frac{N[1-(\omega_1/\omega_2)^2]}{\omega_1 Z_t[\Phi_1 - \Phi_2(\omega_1/\omega_2)]} \tag{8}$$

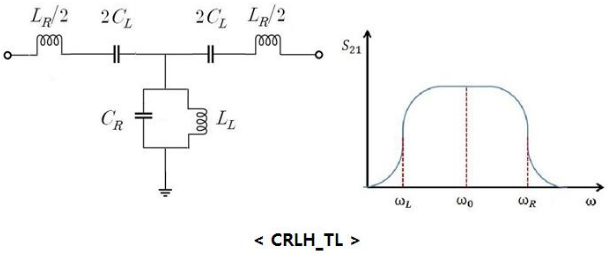

Fig. 2. Equivalent circuit of CRLH TL and its frequency response.

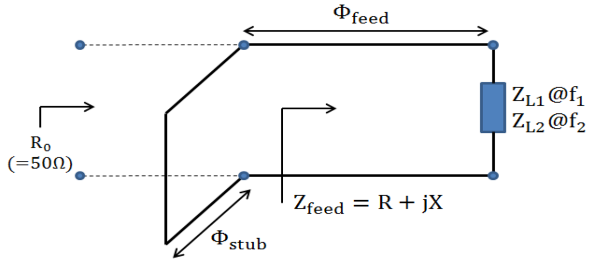

Fig. 3. Matching with the series-shunt stub tuning method.

III. Sensitivity Analysis and Design

In this section, the sensitivity to PA performance from the variation of component values in the output matching network was analyzed by assuming 20% distribution from the mean value of each element. Fig. 4. shows the unit cell of a CRLH TL, where this unit cell is connected in series or shunt to compose matching networks. Fig. 5. shows the schematic of the designed power amplifier based on CRLH TLs, which is composed of two unit cells for each series- and shunt- TL connection. At the first hand, a dualband PA was designed with ideal component values to operate at 0.7GHz and 1.5GHz for 40dBm output power. Then, the variation of the output power of the PA at the desired frequencies was simulated with the distribution of component values in CRLH unit cells. Consequently, the sensitivity of the power to each component was analyzed, from which Table1 shows the effect of critical components in the output matching network (OMN). From the Table, series C_R is identified as the most critical element in terms of the sensitivity of the output power. Then PAE and P_{out} are analyzed over the variation of the series C_R. Fig. 6. and Fig. 7. show PAE and P_{out} over the variation of the series C_R. In Fig. 6., it is shown that the series C_R makes minimum sensitivity around the value of 3.6pF from the perspective of the output power. However, regarding the PAE, 4.2pF is found to be the optimal value. So, the C_R can be chosen to have 3.9pF as a trade-off between the efficiency and the output power. In a similar manner, the second analysis was done on the effect of the series L_{R1}, and contours of performance metrics are found to get the optimal values of C_R and L_{R1}. While the shunt C_{L1} is the most sensitive at 0.7GHz, it is so dominant at the frequency that there is no need for the optimization with other component values. As well, at 1.5GHz, the aforementioned first two components do the most job.

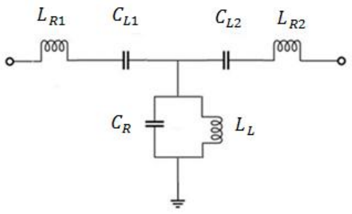

Fig. 4. Unit cell of CRLH.

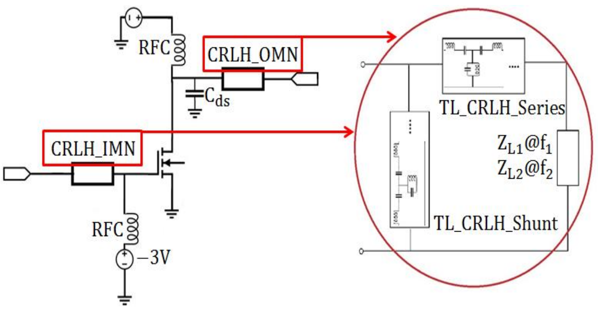

Fig. 5. Schematic of the designed power amplifier based on CRLH.

Table. 1. Sensitivity of elements in OMN composed of CRLH over the distribution of ±20% around the desired values.

Error rate 20%, Sensitivity(dBm/pF, dBm/nH)		
	0.7GHz	1.5GHz
Series CRLH TL branch		
L_{R1} = 7nH	0.071	1.110
L_{R2} = 7nH	0.009	0.494
C_{L1} = 7.5pF	0.124	0.221
C_{L2} = 7.5pF	0.003	0.117
L_L = 9nH	0.161	0.113
C_R = 4pF	0.178	1.714

Shunt CRLH TL branch		
L_{R1} = 2nH	0.002	0.154
L_{R2} = 2nH	0.000	0.002
C_{L1} = 1pF	0.305	1.417
C_{L2} = 1pF	0.014	0.028
L_L = 8nH	0.010	0.001
C_R = 10pF	0.012	0.013

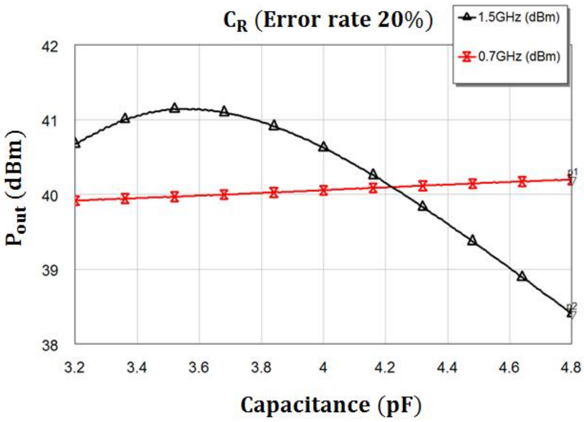

Fig. 6. P_{out} for variance of the series C_R.

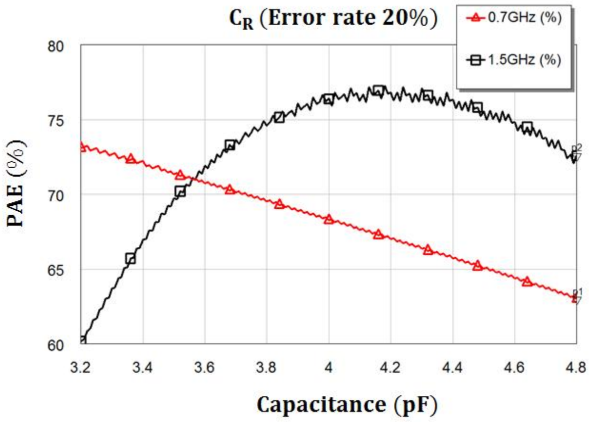

Fig. 7. PAE for variance of the series C_R.

Fig. 8 and Fig. 9 show PAE and P_{out} contour for the variance of the series C_R and L_{R1} at 0.7GHz and 1.5GHz. From the contour, the value of L_{R1} can be chosen based on the value of $C_R(3.9pF)$. The optimal point was chosen from the slope of the contour surface, with the given value of 3.9pF. As a result, $C_R(3.9pF)$ and L_{R1} $(7.1nH)$ are found as the optimal values for PAE and P_{out} at the target frequencies.

Fig. 10, Fig. 11 and Table 2 show the performance of the designed PA.

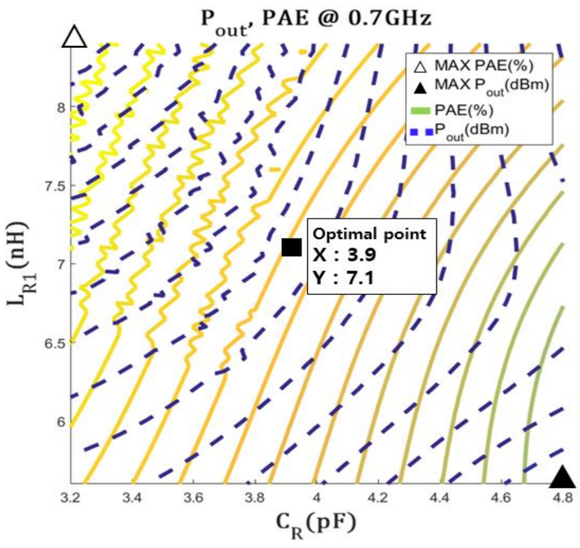

Fig. 8. PAE and P_{out} contour for variance of the series C_R and L_{R1} at the 0.7GHz.

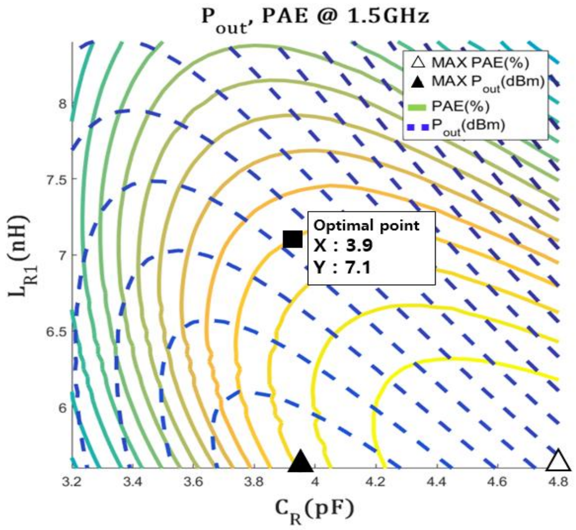

Fig. 9. PAE and P_{out} contour for variance of the series C_R and L_{R1} at the 1.5GHz.

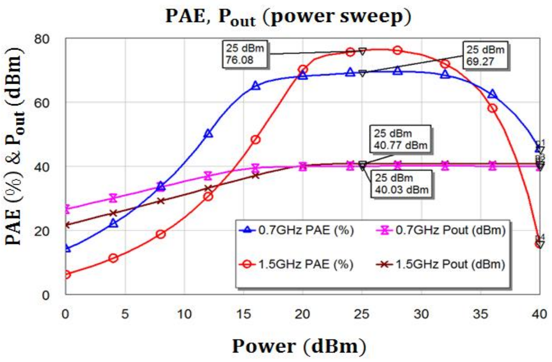

Fig. 10. PAE and P_{out} over the input power.

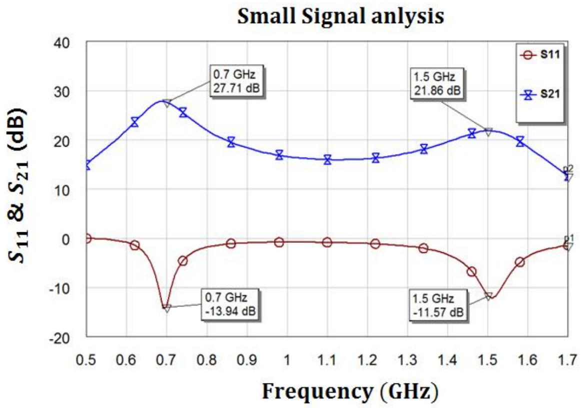

Fig. 11. Small signal result of the designed PA.

Table. 2. Specification of the designed circuit.

	0.7GHz	1.5GHz
PAE	69.27%	76.08%
P_{out}	40.03 dBm	40.77 dBm
S_{11}	−13.94 dB	−11.57 dB
S_{21}	27.71 dB	21.86 dB

Ⅳ. Conclusion

This paper suggests a design approach for a dualband PA based on CRLH transmission lines. With the identification of the critical elements from its manufacturing distribution, we chose the optimal value of identified element with its given variation. The optimal values are used to design a 10W, dualband class-J PA. The designed PA showed outstanding performance of 76% and 69%, for the 40dBm output. This approach enables us to establish a process to mitigate the performance degradation from the manufacturing variation in component values, as well as to control the material cost with the given performance specification for a cost-effective product.

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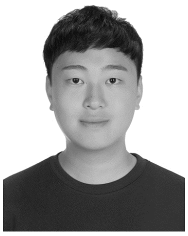

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