Miniaturized Multi-Section Power Divider with Parallel RC Isolation Circuit

Young-Chul Yoon¹ · Young Kim^{2,*}

Abstract

This paper proposes a miniaturized multi-section power divider with parallel resistor and capacitor isolation circuits. Each of the section transmission lines constituting the proposed multi-section power divider has a length less than a quarter wavelength and the impedance of the transmission lines can be controlled within a certain range while avoiding high impedance. In addition, each circuit connected between the transmission lines consists of a parallel resistor and capacitor to satisfy the matching and isolation characteristics between output ports. To validate the proposed power divider, two circuits at a frequency of 2 GHz were designed with two- and three-section dividers. In comparison to a conventional power divider, the proposed divider showed broadband performances with a small structure.

Key Words: Miniaturization, Multi-Section, Parallel Resistor and Capacitor Isolation Circuit, Power Divider.

I. INTRODUCTION

The power divider is a vital element in communication systems such as power amplifiers, mixers, and transceivers, owing to its simple design and superior performance. The conventional power divider has good matching of input and output, isolation performance, and low loss in narrow band operation. Due to its narrow band characteristics, its application has been limited in the current large-capacity communication systems of WCDMA, LTE, and 5G.

To address this limitation, a multi-section divider [1–5] has been proposed. Although the multi-section divider has broadband characteristics with an achievable bandwidth greater than 100%, it has the disadvantages of a large circuit and increased insertion loss.

Recently, various designs to reduce the circuit size of power

dividers have been researched, such as a structure using short uniform transmission line [6, 7], an isolation circuit positioned in a quarter-wavelength transformer [8, 9], and artificial transmission lines built up with lumped elements [10].

However, since these dividers use a $\lambda/4$ transformer between the input and output or between the input or output and 50 Ω termination, they cannot achieve an overall reduction in size. In addition, the bandwidth is reduced due to the impedance transformer, and the parasitic uncertainty of lumped elements is not desirable.

The power divider proposed in this paper has a multi-section structure to realize broadband characteristics, with the electrical length of each power splitting section less than a quarter wavelength to reduce the circuit size. The characteristic impedance of each power-splitting section can be controlled within a certain range while avoiding high impedance. All input and output ports are designed with 50 Ω termination, so there is no need

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for an impedance transformer. In addition, a parallel resistor-capacitor circuit structure is adopted to obtain the broadband output matching and isolation characteristics of the proposed power divider.

II. THEORY AND DESIGN

The structure of the proposed N-section power divider is shown in Fig. 1. It consists of transmission lines with electrical lengths $(\theta_1, \theta_2, \dots, \theta_N)$ less than 90° and isolation circuits with parallel resistors $(R_1, R_2, \dots, R_N)$ and capacitors $(C_1, C_2, \dots, C_N)$. The proposed power divider is analyzed using the even- and odd-mode analysis methods; Fig. 2(a) and (b) show the even- and odd-mode equivalent circuits, respectively.

To obtain the electrical lengths and characteristic impedances of the transmission lines, the matching mechanism of the cascade transmission lines [11] is presented in Fig. 3. As seen in Fig. 3(a) and (b), it is possible to convert a part of the impedance transformer with Z_a and 90° to another impedance Z_b and electrical length θ_b . To match the conversion portion of the impedance transformer, the admittance values of $Y_{in,a}$ and $Y_{in,b}$ must be the same. By solving the equation for the real and imaginary parts of the admittance ($Y_{in,a}, Y_{in,b}$), the impedance Z_b and termi-

Fig. 1. Schematic of the proposed power divider.

Fig. 2. Equivalent circuits of even-mode (a) and odd-mode (b).

Fig. 3. Matching mechanism of the cascade transmission lines: (a) conventional $\lambda/4$ transformer, (b) proposed transformer with two sections, and (c) proposed transformer with three sections.

nating impedance Z_{Lb} of the proposed two-section transformer for θ_b change can be obtained as:

$$Z_b = Z_{Lb} \cdot \frac{\sqrt{(B - BZ_a^2/Z_{La}^2)^2 + 4Z_a^2/Z_{La}^2 - B(1 - Z_a^2/Z_{La}^2)}}{2Z_a/Z_{La}} \quad (1)$$

$$Z_{Lb} = \frac{(1 + (Z_a^2/Z_{La}^2)\tan^2\theta_a)(1 + \tan^2\theta_b)}{(1 + \tan^2\theta_a)(1 + (Z_b/Z_{Lb})^2\tan^2\theta_b)/Z_{La}} \quad (2)$$

where

$$B = \frac{\tan\theta_a(1 + \tan^2\theta_b)}{\tan\theta_b(1 + \tan^2\theta_a)}.$$

Ahn [12] confirmed that when the electrical length $(\theta_a < \theta_b < 90^\circ)$ and termination conditions $(Z_{La} < Z_{oS})$ are satisfied, Z_b and Z_{Lb} should satisfy $Z_b < Z_a$ and $Z_{Lb} < Z_{La}$. Using the above conditions, the impedance Z_c and electrical length θ_d of the three-section transformer can be obtained in the same way, as seen in Fig. 3(c). Using this method, all the electrical lengths of the multi-section transmission line, which is the proposed divider with each section length less than $\lambda/4$ wavelength, can be obtained.

In addition, for the odd-mode equivalent circuit shown in Fig. 2(b), the following equations can be obtained:

$$Y_{in,N} = G_N + jB_N - j \frac{Y_N}{\tan\theta_N} \quad (3)$$

$$Y_{in,N-1} = G_{N-1} + jB_{N-1} + Y_{N-1} \frac{Y_{in,N} + jY_{N-1}\tan\theta_{N-1}}{Y_{N-1} + jY_{in,N}\tan\theta_{N-1}} \quad (4)$$

$$\Gamma_{ii} = \frac{Y_o - Y_{in,1}}{Y_o + Y_{in,1}} \quad (5)$$

Fig. 4. Equivalent circuit of the entire schematic.

where $G_N = \frac{2}{R_N}$, $B_N = 2\omega C_N$, $Y_N = \frac{1}{Z_N}$, and Γ_{ii} is the reflection coefficient at port 2 ($i = 2$) and port 3 ($i = 3$).

The conductance ($G_1, G_2, \dots, G_N$) and susceptance ($B_1, B_2, \dots, B_N$) values can be obtained to satisfy the condition that the reflection coefficient of Eq. (5) becomes zero.

To achieve isolation performance between ports 2 and 3, the S -parameter S_{32} should be minimized as shown in Fig. 4. To calculate the isolation characteristic of the divider network, ABCD and admittance parameters are used. The ABCD matrix of the circuit Net_N , which is composed of two transmission lines (Z_N, θ_N) and a shunt resistor Z_0 , can be expressed as:

$$\begin{pmatrix} A_{Net_N} & B_{Net_N} \\ C_{Net_N} & D_{Net_N} \end{pmatrix} = \begin{pmatrix} \cos \theta_N & jZ_N \sin \theta_N \\ jY_N \sin \theta_N & \cos \theta_N \end{pmatrix} \begin{pmatrix} 1 & 0 \\ Y_0 & 1 \end{pmatrix} \begin{pmatrix} \cos \theta_N & jZ_N \sin \theta_N \\ jY_N \sin \theta_N & \cos \theta_N \end{pmatrix} \quad (6)$$

The admittance matrix of the composite network Net_{RCN} resistor-capacitor can be represented by:

$$\begin{pmatrix} y_{11}'' & y_{12}'' \\ y_{21}'' & y_{22}'' \end{pmatrix}_{Net_{RCN}} = \begin{pmatrix} \frac{1}{R_N} & -\frac{1}{R_N} \\ -\frac{1}{R_N} & \frac{1}{R_N} \end{pmatrix} + \begin{pmatrix} j\omega C_N & -j\omega C_N \\ -j\omega C_N & j\omega C_N \end{pmatrix}_{C_N} \quad (7)$$

Since the network Net_N is connected in parallel with network Net_{RCN} , we needed to transform Eq. (6) from an ABCD matrix to an admittance matrix. Finally, the composite admittance matrix of Net_N and Net_{RCN} can be obtained as follows:

$$\begin{pmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{pmatrix}_{Net_N + Net_{RCN}} = \begin{pmatrix} y_{11}' & y_{12}' \\ y_{21}' & y_{22}' \end{pmatrix}_{Net_N} + \begin{pmatrix} y_{11}'' & y_{12}'' \\ y_{21}'' & y_{22}'' \end{pmatrix}_{Net_{RCN}} \quad (8)$$

To obtain the equation of the networks, which are connected by two cascade transmission lines (Z_{N-1}, θ_{N-1}) and the composite network of Net_N and Net_{RCN} , the composite network parameters are needed to convert the ABCD matrix. We can compute the ABCD parameters of the networks Net_{N-1} and Net_{RCN-1} as previously calculated. Through this process, the admittance parameters of the entire network can be obtained. The S -parameter

value of isolation, S_{32} , is finally obtained by parameter conversion, and the isolation circuit values of the resistor and capacitor are selected to satisfy the S_{32} parameter condition of $|S_{32}| \leq -25$ dB at the same time among the values satisfying Eq. (5).

III. SIMULATION AND EXPERIMENTAL RESULTS

To confirm the validation of the design rule, we designed two- and three-section power dividers operating at a frequency of 2 GHz and implemented on the substrate of Rogers RO4350B PCB ($\epsilon_r = 3.48$ and $h = 0.762$ mm). The simulation was performed using the Microwave Office software developed by National Instruments.

The two-section power divider configuration process is summarized as follows. First $\lambda/4$ impedance transformer of $Z_{oT} = 50 \Omega$, $Z_{LT} = 35.35 \Omega$, $Z_T = 42.04 \Omega$ and $\theta_T = 90^\circ$ is chosen as shown in Fig. 5(a).

Based on the decomposition theory of a single transmission line [13], the impedance transformer can be divided into two transmission lines of $Z_{oTD} = 100 \Omega$, $Z_{LTD} = 70.7 \Omega$, $Z_{TD} = 84.08 \Omega$, and $\theta_{TD} = 90^\circ$, as shown in Fig. 5(b). To constitute the two-section transmission line of the divider, the following parameters are set: $Z_a = 84.1 \Omega$ and $\theta_a = 60^\circ$. The parameters of $Z_b = 69.56 \Omega$, $Z_{Lb} = 50 \Omega$, and $\theta_b = 76^\circ$ can be calculated using Eqs. (1) and (2). To obtain the parameter values for the three-section lines, we used a similar method as follows:

The following parameters are set: $Z_a = 84.1 \Omega$ and $\theta_a = 50^\circ$. The three-section parameters of $Z_b = 74.44 \Omega$, $Z_{Lb} = 59.22 \Omega$, $\theta_b = 66^\circ$, $Z_c = 67.60 \Omega$, $Z_{Lc} = 50 \Omega$, and $\theta_d = 73^\circ$ can be calculated as described previously. Finally, the resistor-capacitor values satisfying the reflection and isolation characteristics of the output ports are obtained using MATLAB and summarized as follows: In the case of the two-section divider, $R_1 = 120 \Omega$, $C_1 =$

 Fig. 5. Decomposition of transmission lines: (a) $\lambda/4$ transformer and (b) decomposition of single $\lambda/4$ transformer.

0.02 pF, $R_2 = 110 \Omega$, and $C_2 = 0.18$ pF. In the case of the three-section divider, $R_1 = 820 \Omega$, $C_1 = 0.01$ pF, $R_2 = 180 \Omega$, $C_2 = 0.02$ pF, $R_3 = 150 \Omega$, and $C_3 = 0.17$ pF.

Fig. 6(a) and (b) show photographs of the two- and three-section proposed power dividers. The total length of the two-section divider is 106° , and that of the three-section divider is 179° . Fig. 7(a) and (b) show the measured and simulated S -parameters of the two-section power divider. The insertion losses of $|S_{21}|$ and $|S_{31}|$ were -3.10 dB, and the isolation of $|S_{32}|$ was greater than 25 dB. The input return loss of $|S_{11}|$ was better than -25 dB, and the output return losses of $|S_{22}|$ and $|S_{33}|$ were better than -30 dB at the center frequency of 2 GHz. The measured -15 dB bandwidths of $|S_{11}|$, $|S_{22}|$, $|S_{33}|$, and $|S_{32}|$ were in the ranges of 1.33 – 2.46 GHz, 0.5 – 3.63 GHz, 0.5 – 3.35 GHz, and 1.26 – 2.6 GHz, featuring fractional bandwidths of 56.5% , 156% , 142% , and 67% . In addition, Fig. 8(a) and (b) show the measured and simulated S -parameters of the three-section power divider. The insertion losses of $|S_{21}|$ and $|S_{31}|$ were -3.20 dB, and the isolation of $|S_{32}|$ was greater than 22 dB. The input return loss of $|S_{11}|$ was better than -19 dB, and output return losses of $|S_{22}|$ and $|S_{33}|$ were better than -24 dB at center frequency of 2 GHz. The measured -15 dB bandwidths of $|S_{11}|$, $|S_{22}|$, $|S_{33}|$, and $|S_{32}|$ were in the ranges of 1.1 – 3.42 GHz, 0.54 – 3.76 GHz, 0.52 – 3.76 GHz, and 0.95 – 3.29 GHz, featuring

(a)

(b)

Fig. 6. Photographs of two-section (a) and three-section (b) proposed power dividers.

(a)

(b)

Fig. 7. Measured and simulated S -parameters of the two-section power divider: (a) $|S_{21}|$, $|S_{31}|$, $|S_{32}|$, and (b) $|S_{11}|$, $|S_{22}|$, $|S_{33}|$.

(a)

(b)

Fig. 8. Measured and simulated S -parameters of the three-section power divider: (a) $|S_{21}|$, $|S_{31}|$, $|S_{32}|$, and (b) $|S_{11}|$, $|S_{22}|$, $|S_{33}|$.

Fig. 9. Measured phase difference between the output ports of the two- and three-section power dividers.

Table 1. Comparison of the proposed divider with conventional multi-section divider

Ref.	Center freq. (GHz)	Section no.	Total length ($^{\circ}$)	15 dB BW (%)	Insertion loss (dB)
[2]	30	2	180	100	-5.0
[3]	1	3/4	270 / 360	110	-2.2 / -5.5
[4]	1	3	183	55	-0.5 / -10
[5]	0.8 / 2	2	90	40	-2.06 / -4.88
This work	2	2	106	156 max.	-3.1
		3	179	162 max.	-3.2

fractional bandwidths of 116%, 161%, 162%, and 117%. Fig. 9 shows that the phase difference between the output ports in the two- and three-section power dividers was measured within $\pm 2.5^{\circ}$. Table 1 shows a comparison of the proposed divider with conventional multi-section divider.

IV. CONCLUSION

This paper presents a multi-section power divider with a parallel RC isolation circuit. Because each section of the power divider is less than $\lambda/4$ wavelength, the power divider is implemented in a reduced size. In addition, the bandwidth of the matching and isolation characteristic showed that a fractional bandwidth above 100% is achievable in the three-section divider. By choosing the proper source and load impedance, the power divider can be implemented while avoiding the use of high impedance. By adopting decomposition and the improved transformer, the proposed power divider was demonstrated good performance, and the simulated and measured results were confirmed to be in good agreement.

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