Unequal Wilkinson Power Dividers with In-/Reverse-Phase Using Lumped-Element Circuits

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Introduction

For microwave and millimeter-wave circuit systems, power dividers/combiners are one of the key components. Wilkinson power dividers are practically used because of easy construction and design [1], [2]. In recent years, with the rapid expansion of wireless communication systems, various microwave devices with high performance have been required. Therefore, reduced-size [3], [4], dual-band [5], and unequal split Wilkinson power dividers [6] have been developed by many researchers. Authors have also reported lumped-element Wilkinson power dividers consisting of LC-ladder circuits [7].

In this paper, we propose in-/reverse-phase Wilkinson power dividers with unequal power-split ratio using lumped-element circuits. Although unequal Wilkinson power dividers using the defected ground structure (DGS) have been reported [6], impedance mismatch between DGS lines and conventional microstrip lines, and radiation may become problems. The proposed divider consists of parallel Π/T-networks and LC-ladder circuits. The designed reversed-phase divider with a power-split ratio of 4 has a practical property of a relative bandwidth of about 14 %. The validity of this design procedure is also shown by EM-simulations and experiments.

Design Method

A. Conventional unequal power divider

A circuit construction of a conventional unequal Wilkinson power divider which has a power-split ratio of K : 1, based on the distributed circuit theory is shown in Fig. 1(a). In this case, circuit parameters are given by following equations:

$$R_2 = Z_C / K^{1/2} \ , \ R_3 = K^{1/2} Z_C \ , \ R_{\mathrm{int}} = K^{-1/2}(K+1)Z_c \qquad (1), (2), (3)$$

$$Z_2 = K^{-3/4}(K+1)^{1/2} Z_C \qquad , \ Z_3 = K^{1/4}(K+1)^{1/2} Z_C \qquad (4), (5)$$

As seen from (1) and (2), terminal impedances of output ports are different values because of no current through the resistor R_{int}. Since terminal impedances of ports are actually selected 50 Ω, the impedance transformers connected output ports have been required as shown in Fig. 1(b). To realize a reversed-phase divider, we have only to move the reference plane of an either output port outward to half-wavelength. Fig. 2 shows the frequency characteristics of scattering parameters for the reversed-phase power divider with K = 4. For -20 dB return loss and ±3 degrees of phase unbalance, the relative bandwidth is about 10 %.

B. Lumped-element circuits

Microwave lumped-element circuits have been constructed by means of transforming from transmission line into Π/T-networks at design frequency. As

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an impedance transformer, LC-/CL-ladder circuits as shown in Fig. 3 are used in this paper. The selection of two transformers depends on magnitude relation of terminal impedance. In order that the impedance transformer shown in Fig. 3(a) converts the terminal impedance, R (R<1) into 1, the following condition is required:

$$1 = \frac{1}{jL} + \frac{1}{R + 1/jC} \qquad (6)$$

From above equation, we can obtain the next equations.

$$C = \frac{1}{\sqrt{R(1-R)}},\ L = \sqrt{\frac{R}{1-R}} \quad (7), (8)$$

In the same manner, the condition of a LC-ladder type shown in Fig. 3(b) can be obtained. In the in-phase unequal power divider shown in Fig. 1, by replacing parallel transmission lines with Π -networks and adding the impedance transformers consisting of LC-ladder circuits, the in-phase lumped-element power divider with an unequal power-split ratio can be constructed as shown in Fig. 4. Fig. 5 exhibits the s-matrix of the in-phase power divider with K=4.

Next, we treat reversed-phase unequal power dividers. Here, impedance transformers are constructed by Π/T-networks to accomplish both impedance and phase transformation. Circuit construction of a reversed-phase unequal power divider is shown in Fig. 6, and Fig. 7 exhibits the s-matrix of this divider. As shown in this figure, very flat phase difference can be obtained over a relative bandwidth of 14 %.

Simulation Results

In order to verify the above design procedure, we draw circuit patterns of the reverse-phase unequal Wilkinson power divider corresponding to Fig. 7 as a microstrip circuit, and calculated the scattering parameters of these circuit patterns by using a commercial electromagnetic simulator (Sonnet em). Fig. 8 shows the circuit pattern of the unequal Wilkinson power divider with K=4. Input/output ports are terminated with 50 Ω microstrip transmission lines. Lumped elements such as R, L, and C are constructed by a chip resistor, a rectangular spiral inductor, and a Metal-Insulate-Metal (MIM) capacitor, respectively. We assume the dielectric substrate with a relative permittivity of 4.5 and a thickness of 0.508 mm, and a center frequency (f_0) is chosen as 1.0 GHz. Fig. 9 exhibits the simulation results of scattering parameters for the unequal Wilkinson power divider corresponding to Fig. 7. These results show good agreement with the theoretical results.

Experiments

Unequal Wilkinson power dividers designed in section III have been fabricated on a 0.508-mm-thick Rogers TMM4 substrate, which has a relative permittivity of 4.5 and a conductor thickness of 18 μm. Fig. 10 exhibits the photograph of the fabricated reverse-phase power divider with K=4, which has an area of 21.7 × 21.7 mm^2. Lumped-element components such as R, C are implemented in chip components. Although the return loss of output port is slightly shifted from center frequency, nearly agreement with simulation results can be obtained as shown in Fig. 11. These differences between simulation and experimental results may arise from solder to connect chip components and the physical length of the soldering pad for those.

Conclusion

In this paper, we have presented a design method of in-/reverse-phase Wilkinson power divider with an unequal power-split ratio using lumped-element circuits. Using this design method, the in-/reversed-phase Wilkinson power dividers with a power split ratio of 4 have successfully designed, and practical property of a relative bandwidth of 14 % can be obtained for the reversed-phase one. Furthermore, good agreement between the theoretical and simulation results is obtained for both dividers.

References

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Figures

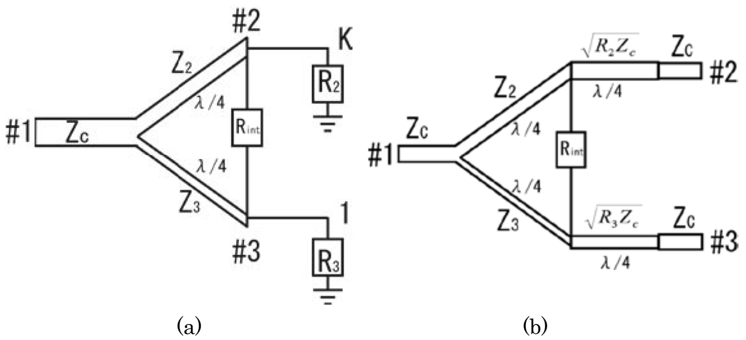

Figure 1. Schematic diagram of an unequal Wilkinson power divider based on distributed circuit theory. (a) Without impedance transformer, (b) with impedance transformer.

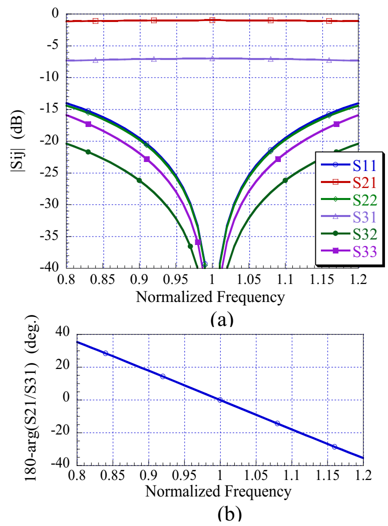

Figure 2. Theoretical frequency dependences of scattering parameters for the reversed-phase Wilkinson power divider with $K = 4$.

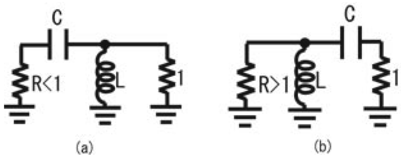

Figure 3. Circuit construction of impedance transformers. (a) CL-ladder circuit and (b) LC-ladder circuit.

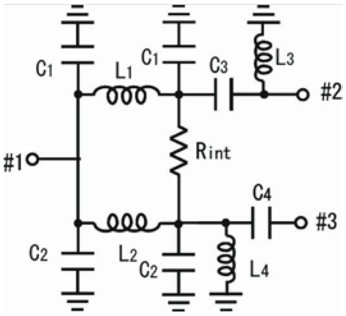

Figure 4. Schematic diagram of an in-phase unequal Wilkinson power divider using lumped-element circuits.

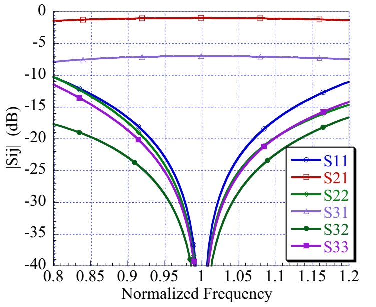

Figure 5. Scattering parameters of the in-phase Wilkinson power divider with $K = 4$.

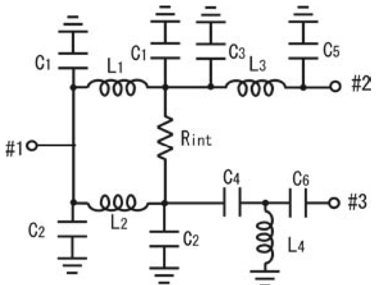

Figure 6. Schematic diagram of a reverse-phase unequal Wilkinson power divider using lumped-element circuits.

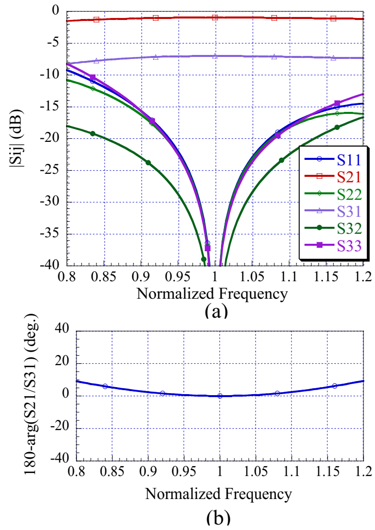

Figure 7. Scattering parameters of the reverse-phase Wilkinson power divider with $K = 4$.

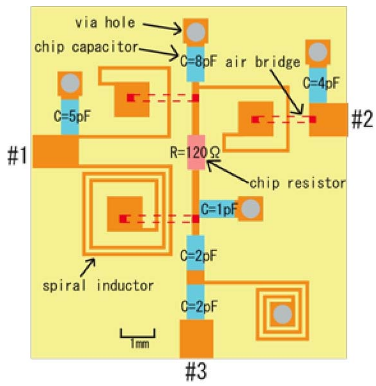

Figure 8. Simulation pattern of the designed divider.

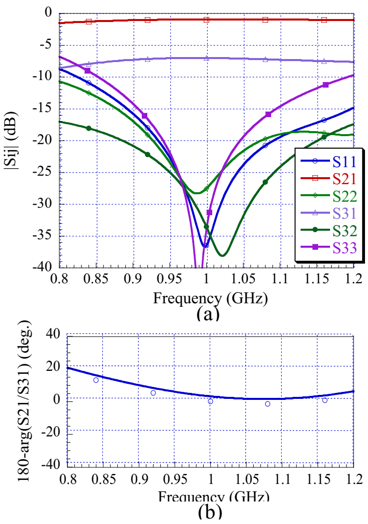

Figure 9. Simulation results.

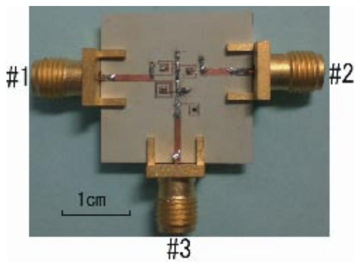

Figure 10. Photograph of the trial reversed-phase power divider with $K = 4$.

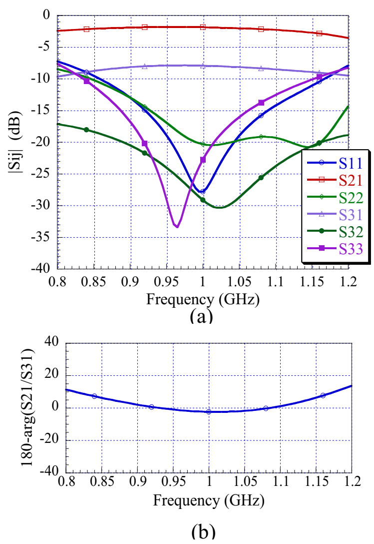

Figure 11. Measured scattering parameters of the trial power divider.