Design and Realization Of 2-Way Unequal-Split Power Divider Based On Branchline Coupler For S-Band Radar Applications

Fannush S. Akbar[1], Nilla Rachmaningrum[2]

{ fannush.akbar@ittelkom-sby.ac.id [1]}

Department of Telecommunication Engineering, Institut Teknologi Telkom Surabaya (ITTS),
Surabaya, Indonesia[1,2]

Abstract. In this paper, the design of 2-way power dividers based on a branch line coupler with an unequal splitting ratio is designed and realized. A mathematical formulation is elaborated to calculate the impedance of the transmission lines for such a splitting ratio. Three coupler designs with different power splitting ratios are presented, namely 1:4 (-6 dB), 2:1 (3 dB), and 4:1 (6 dB). The couplers are realized using microstrip-based technology and simulated in the full-wave electromagnetic (EM) simulator. The simulated and measured S-parameter results, magnitude and phase at the frequency of 3 GHz indicate that all designed couplers meet the target requirements.

Keywords: unequal-split, power divider, branchline coupler.

1 Introduction

In a Radar with an array antenna, a low sidelobe level (SLL) is required to avoid missed target detection. This is because the echo signal from the unwanted target is entering the Radar through the high sidelobes. One of the effective solutions to lower the SLL is amplitude tapering, i.e., Taylor amplitude distribution [1-3]. The tapered amplitudes can be realized by using an attenuator located at the input of each element or by using a power divider network that produces unequal output power. Attenuators can lower the power efficiency, so a power divider network is preferred.

There are two types of power dividers, namely resistive and lossless designs. The most commonly used resistive power divider is Wilkinson's design [4-5], while for lossless power dividers, branch-line coupler is the most famous due to its simplicity in planar circuit design [6-7]. The branch-line coupler is then selected to obtain better power efficiency.

A branch-line coupler is a microwave component that distributes or combines microwave signals passively [8]. It has four ports: port 1 is an input, ports 2 and 3 as output, and port 4 is isolation. In the common design, the output power equals 90° phase difference between output

IConVET 2022, October 06, Singaraja, Indonesia
Copyright © 2023 EAI
DOI 10.4108/eai.6-10-2022.2327432

ports 2 and 3. The phase difference is unavoidable due to using different line lengths between those output ports.

A power divider with unequal power distribution is required to achieve this tapered amplitude for SLL reduction. Therefore, this paper presents the mathematical formulation to obtain the transmission line impedance for such a splitting ratio. Three coupler types with different splitting ratios are analyzed. Microstrip-based coupler designs are then realized and validated in simulation and measurement. The realization is considered to operate at S-band frequency, especially at 3 GHz. The measured results show a similarity with the simulation. This indicates that the branch-line coupler design can be used for realizing a power divider with an unequal splitting ratio.

2 Unequal-Split Branchline Coupler

The general design of a branch-line coupler is presented in Fig. 1. It can be seen that it is the input power, output power, and isolation. The horizontal and vertical branches are represented by impedances of and, respectively. Both branches have electrical lengths.

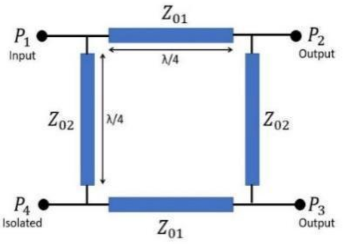


Fig. 1. Unequal-split branchline coupler design.

The mathematical formulations for obtaining the impedance of both branch lines are indicated in Eq. (1) and (2), respectively. This formulation is based on the analysis in [9].

$$Z_{01} = Z_0 \times \sqrt{\frac{\frac{P_2}{P_3}}{1+\frac{P_2}{P_3}}} \tag{1}$$

$$Z_{02} = Z_0 \times \sqrt{\frac{P_2}{P_3}} \tag{2}$$

where Z_0 is the characteristic impedance of the microstrip transmission line. The ratio between P_2 and P_3 is called the splitting ratio and is indicated in Eq. (3) with dB scale.

$$Splitting\ Ratio\ [dB] = 10 \times log_{10}\left(\frac{P_2}{P_3}\right) \quad (3)$$

Fig. 2 shows the impedance values of horizontal and vertical branches as a function of the splitting ratio with $Z_0 = 50\ \Omega$. It can be seen that the blue line represents the Z_{01} while the red line represents the Z_{02}. The splitting ratio is analyzed in the range of -10 dB to 10 dB. Designing an unequal-split coupler can be easily done by using this graphical plot because the precise impedance values are obtained.

3 Microstrip-Based Coupler Design Analysis and Realization

In this section, the In this section, the microstrip-based coupler designs are realized and analyzed. Rogers RO4003C with a dielectric constant (ε_r) of 3.35 and thickness (h) of 1.524 is used as the substrate material. The realized designs are then measured using Vector Network Analyzer (VNA) to obtain the magnitude and phase of the S-parameters.

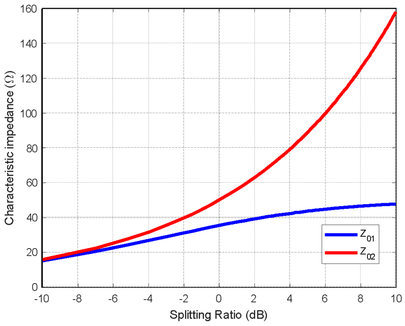


Fig. 2. Characteristic impedance of Z_{01} and Z_{02} according to the splitting ratio.

Using the mathematical formulation presented in the previous section, the line impedance of each branch of all couplers can be obtained. Then, the dimensions (length and width) of the microstrip line can be obtained with the formulation in [10]. The general design of the microstrip-based branchline coupler is shown in Fig. 3. It can be seen that W_{Z0}, W_{Z1}, and W_{Z2} represent the width of the lines with impedances of Z_0, Z_{01}, and Z_{02}, respectively. Meanwhile, the length of the lines with impedances of Z_{01} and Z_{02} are indicated with L_{Z1}, and L_{Z2}, respectively.

There are three microstrip couplers designed, and each design has its microstrip line dimensions for each branch, except the characteristic impedance Z_0 of 50 Ω, where the line width is equal to 3.41 mm for all couplers. The detailed design and dimensions of all couplers are discussed in the following subsections. All performance analyses are conducted at the frequency of 3 GHz due to the design target.

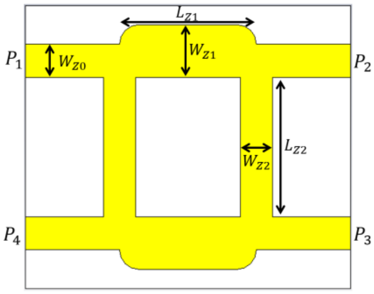


Fig. 3. General design of microstrip-based branchline coupler.

3.1 -6 dB Coupler

A -6 dB splitting ratio means that the output power ratio between output ports P_2 and P_3 is ¼. According to Eq. (1) and (2), Z_{01} and Z_{02} values are then equal to $22.36\,\Omega$ and $25\,\Omega$, respectively. The detailed dimension (length and width) of this coupler design corresponds to the impedance of the line is described in Table 1, while this design is realized and presented in Fig. 4. It can be seen that all four ports are connected with SMA connectors.

Table 1. Microstrip line dimensions of coupler with -6 dB splitting ratio

Impedance	Parameter	Dimension
Z_{01}	W_{Z1}	6 mm
$(22.36\,\Omega)$	L_{Z1}	14.33 mm
Z_{02}	W_{Z2}	5.72 mm
$(25\,\Omega)$	L_{Z2}	14.41 mm

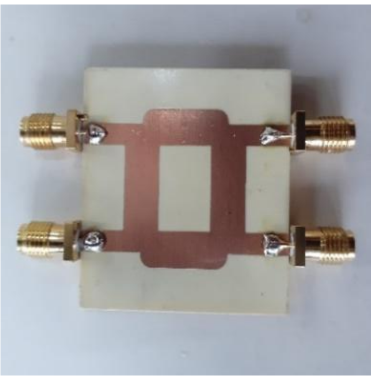
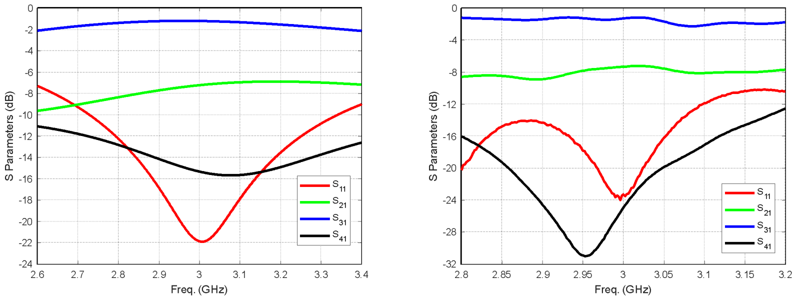


Fig. 4. Realized microstrip branchline coupler with -6 dB splitting ratio.

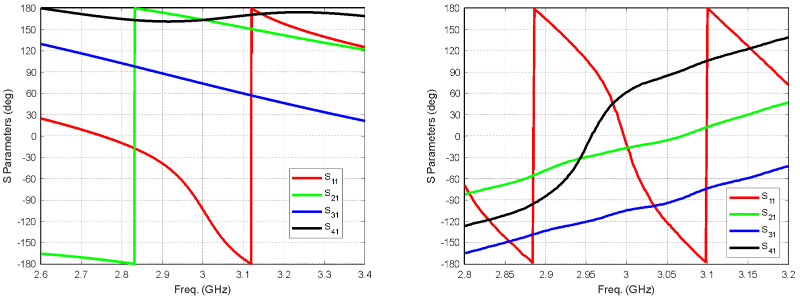
The simulation and measurement results of magnitude of S-parameters are shown in Fig. 5a and Fig. 5b, respectively. Meanwhile, the simulation and measurement results of phase of S-parameters are shown in Fig. 6a and Fig. 6b, respectively. The exact value of these results is presented in Table 4. It can be seen that this design is well matched at the frequency of 3 GHz, indicated with S_{11} value below -10 dB, -21.9 dB and -23.3 dB from simulation and measurement, respectively.

The splitting ratio is obtained by differentiating between the value of S_{21} and S_{31}. A result of -6 dB splitting ratio is obtained from both simulation and measurement results. In addition, the obtained S_{41} indicates that the isolation of this design is good because the values are below -10 dB, -15.3 dB and -24.9 dB from simulation and measurement, respectively. The phase analysis is focused on the output phase at ports 2 and 3, it can be seen that the phase difference between these ports are 89.8° and 87.8°, from simulation and measurement results, respectively. These results are the same with theoretical design, which is 90°. This phase difference is unavoidable since there is a $\lambda/4$ line length difference between P_2 and P_3. An extra delay line at one of the outputs can be used to produce an equal phase.



(a) (b)

Fig. 5. Magnitude S-Parameters results of microstrip-based coupler with -6 dB splitting ratio. (a) Simulation, (b) Measurement.



(a) (b)

Fig. 6. Phase S-Parameters results of microstrip-based coupler with -6 dB splitting ratio. (a) Simulation, (b) Measurement.

3.2 3 dB Coupler

A 3 dB splitting ratio means that the power ratio between output ports P_2 and P_3 is 2. From the formulation, $Z_{01} = 40.82\ \Omega$ and $Z_{02} = 70.71\ \Omega$ are obtained. Then the microstrip line dimension can be calculated and the results are presented in Table 2. This design is realized and presented in Fig. 7. It can be seen that all four ports are connected with SMA connectors.

Table 2. Microstrip line dimensions of coupler with 3 dB splitting ratio.

Impedance	Parameter	Dimension
Z_{01}	W_{Z1}	4.5 mm
$(40.82\ \Omega)$	L_{Z1}	14.81 mm
Z_{02}	W_{Z2}	1.85 mm
$(70.71\ \Omega)$	L_{Z2}	15.32 mm

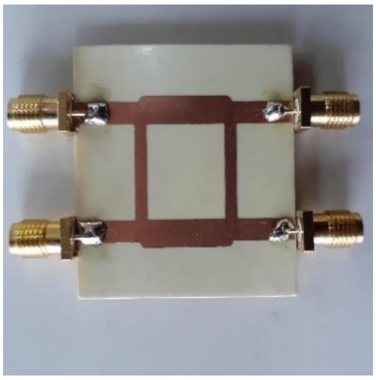
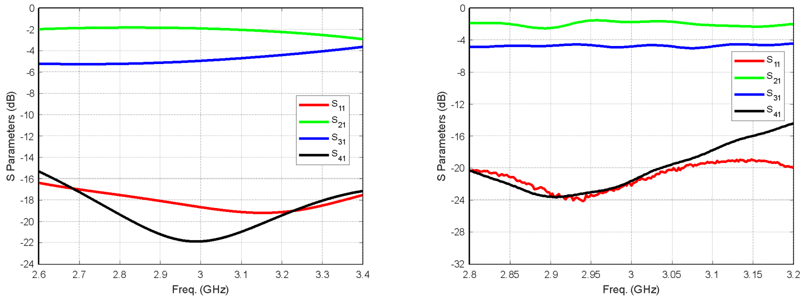


Fig. 7. Realized microstrip branchline coupler with 3 dB splitting ratio.

The simulation and measurement results of magnitude of S-parameters are shown in Fig. 8a and Fig. 8b, respectively. Meanwhile, the simulation and measurement results of phase of S-parameters are shown in Fig. 9a and Fig. 9b, respectively. The exact value of these results are presented in Table 4. This design also meets the design target. The design is worked well at 3 GHz, indicated with -18.7 dB and -22.2 dB values of S_{11} magnitude from simulation and measurement, respectively.

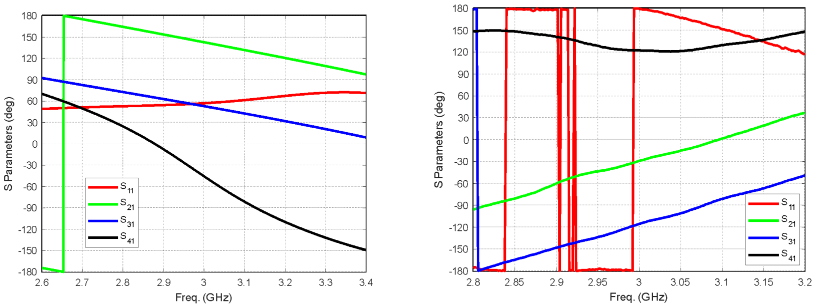
The obtained splitting ratio from both simulation and measurement are 3 dB, indicated by the output power at P_2 is 3 dB higher than the output power at P_3. Good isolation is obtained at port P_4, where the magnitude value of S_{41} is below -10 dB. The phase analysis at Ports 2 and 3 indicates that the phase difference between these ports are 89.8° and 87.2°, from simulation and measurement results, respectively. The use of a $\lambda/4$ line length difference between P_2 and

P_3 produces a 90° phase difference. In case when equal output phase is needed, the use of a delay line can be an effective solution.



(a) (b)

Fig. 8. Magnitude S-Parameters results of microstrip-based coupler with 3 dB splitting ratio. (a) Simulation, (b) Measurement.



(a) (b)

Fig. 9. Phase S-Parameters results of microstrip-based coupler with 3 dB splitting ratio. (a) Simulation, (b) Measurement.

3.2 6 dB Coupler

A coupler design with 6 dB splitting ratio means that the power ratio between output ports P_2 and P_3 is 4. The obtained Z_{01} and Z_{02} for this design are $44.72\ \Omega$ and $100\ \Omega$, respectively. The calculation results of the microstrip line dimensions, including the width and length, are indicated in Table 3. Meanwhile, the realized design is shown in Fig. 10.

Fig. 11a and Fig. 12a show the simulation results of the S-parameters for magnitude and phase, respectively. Meanwhile, Fig. 11b and Fig. 12b show the measurement results. These results are summarized in Table 4. From the simulated and measured magnitude of S_{11} at 3 GHz, values of -17.1 dB and -19.1 dB are obtained, respectively. It means that this design is well-matched at the frequency of 3 GHz.

Table 3. Microstrip line dimensions of coupler with 6 dB splitting ratio

Impedance	**Parameter**	**Dimension**

Z_{01}	W_{Z1}	4.7 mm
$(44.72\ \Omega)$	L_{Z1}	14.89 mm
Z_{02}	W_{Z2}	0.86 mm
$(100\ \Omega)$	L_{Z2}	15.67 mm

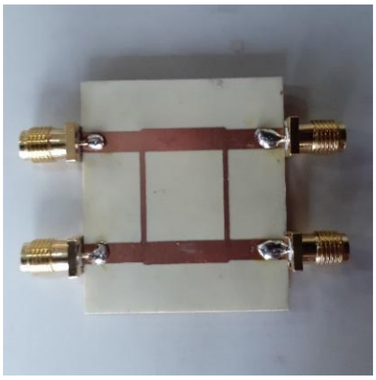


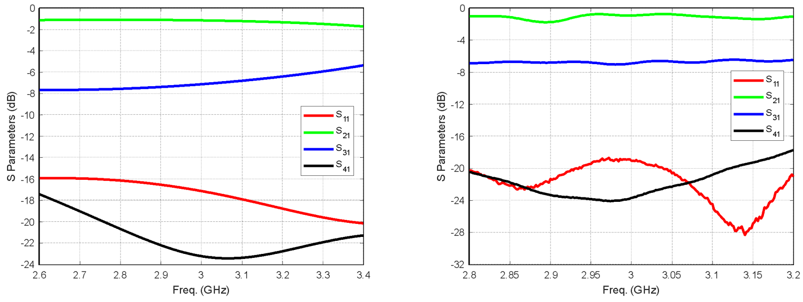
Fig. 10. Realized microstrip branchline coupler with 6 dB splitting ratio.

The obtained splitting ratio from simulation and measurement (difference between S_{21} and S_{31}) are 6 dB, respectively. It means that the output power at P_2 is 6 dB higher than the output power at P_3. This result meets the target splitting ratio. Moreover, the magnitude of S_{41} gives a good isolation condition with -23.2 dB and -23.7 dB from simulation and measurement, respectively. Around 90° phase difference is obtained between S_{21} and S_{31}. The use of a $\lambda/4$ line length difference between P_2 and P_3 is the cause of this phase difference. For realizing an equal output phase, the use of an additional delay line is recommended.

Table 4. S-parameters results (magnitude and phase) for all couplers at 3 GHz.

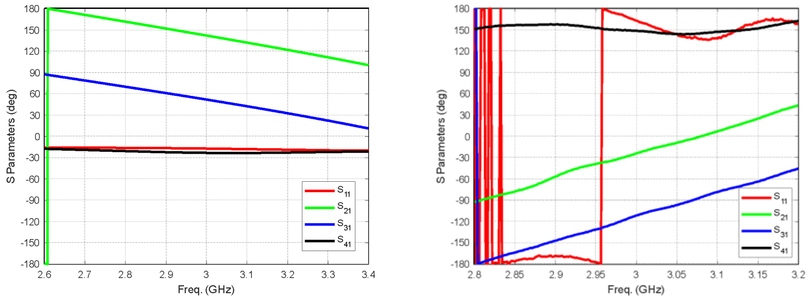
S-parameters	**-6 dB Coupler**				**3 dB Coupler**				**6 dB Coupler**			
	Magnitude		**Phase**		**Magnitude**		**Phase**		**Magnitude**		**Phase**	
	Sim. (dB)	**Meas. (dB)**	**Sim. (°)**	**Meas. (°)**	**Sim. (dB)**	**Meas. (dB)**	**Sim. (°)**	**Meas. (°)**	**Sim. (dB)**	**Meas. (dB)**	**Sim. (°)**	**Meas. (°)**
S_{11}	-21.9	-23.3	-103.3	-11.2	-18.7	-22.2	57.0	179.3	-17.1	-19.1	-16.7	163.1
S_{21}	-7.20	-7.31	163.7	-16.8	-1.90	-1.74	142.7	-29.2	-1.10	-0.91	-1.1	-24.1

S_{31}	-1.20	-1.27	73.9	-104.6	-4.90	-4.78	52.9	-115.3	-7.10	-6.91	-7.3	-111.7
S_{41}	-15.3	-24.9	163.5	61.74	-21.9	-21.6	-45.7	122.4	-23.2	-23.7	-22.6	148.7



(a) (b)

Fig. 11. Magnitude S-Parameters results of microstrip-based coupler with 6 dB splitting ratio. (a) Simulation, (b) Measurement.



(a) (b)

Fig. 12. Phase S-Parameters results of microstrip-based coupler with 6 dB splitting ratio. (a) Simulation, (b) Measurement. microstrip-based coupler designs are realized and analyzed. Rogers RO4003C with a dielectric constant (ε_r) of 3.35 and thickness (h) of 1.524 is used as the substrate material. The realized designs are then measured using Vector Network Analyzer (VNA) to obtain the magnitude and phase of the S-parameters.

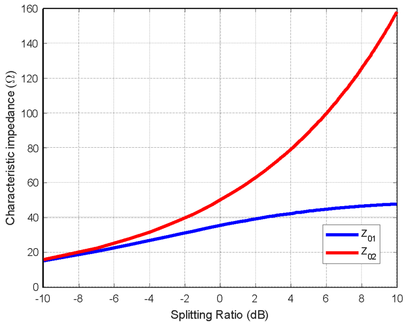


Fig. 2. Characteristic impedance of Z_{01} and Z_{02} according to the splitting ratio.

Using the mathematical formulation presented in the previous section, the line impedance of each branch of all couplers can be obtained. Then, the dimensions (length and width) of the microstrip line can be obtained with the formulation in [10]. The general design of the microstrip-based branchline coupler is shown in Fig. 3. It can be seen that W_{Z0}, W_{Z1}, and W_{Z2} represent the width of the lines with impedances of Z_0, Z_{01}, and Z_{02}, respectively. Meanwhile, the length of the lines with impedances of Z_{01} and Z_{02} are indicated with L_{Z1}, and L_{Z2}, respectively.

There are three microstrip couplers designed, and each design has its microstrip line dimensions for each branch, except the characteristic impedance Z_0 of 50 Ω, where the line width is equal to 3.41 mm for all couplers. The detailed design and dimensions of all couplers are discussed in the following subsections. All performance analyses are conducted at the frequency of 3 GHz due to the design target.

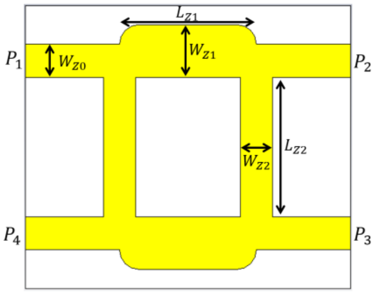


Fig. 3. General design of microstrip-based branchline coupler.

4 Conclusions

The microstrip-based unequal split power dividers based on the branch-line coupler were designed and realized. The mathematical formulation was used to obtain the line impedance value of each branch. There were three coupler designs with different splitting ratios, simulated and realized in this paper, namely -6 dB, 3 dB, and 6 dB. The S-parameters simulation results, magnitude and phase of all microstrip couplers indicate that the design target is achieved at the frequency of 3 GHz. According to the results, it can be concluded that the mathematical formulation is valid and can be used to realize the power divider with an unequal splitting ratio.

References

[1] T. T. Taylor, "Design of Circular Aperatures for Narrow Beamwidth and Low Sidelobes", IRE Trans. Antennas Propag., vol. AP-8, pp. 17-22, January 1960.

[2] Salas-Sanchez, A. A., et al. "Minimization Techniques of Q in Circular Taylor-like Distributions." 2020 14th European Conference on Antennas and Propagation (EuCAP). IEEE, 2020.

[3] Keizer, Will PMN. "Amplitude-only low sidelobe synthesis for large thinned circular array antennas." IEEE Transactions on Antennas and Propagation 60.2 (2011): 1157-1161.

[4] J. Wilkinson, "An n-Way Hybrid Power Divider", IRE Trans. Microwave Theory Tech., vol. 8, pp. 116-118, January 1960.

[5] S. Saleh, A. Alzoubi and M. Bataineh, "Compact UWB Unequal Split Wilkinson Power Divider Using Nonuniform Transmission Lines," 2018 International Conference on Computer, Control, Electrical, and Electronics Engineering (ICCCEEE), 2018, pp. 1-5, doi: 10.1109/ICCCEEE.2018.8515887.

[6] B. Schiek, “Hybrid branchline couplers-Useful new class of directional couplers,” IEEE Trans. Microwave Theory Tech., vol. MTT22, no. 10, pp. 804-869, Oct. 1974.

[7] Soodmand, Soheyl, Mark A. Beach, and Kevin A. Morris. "Hybrid coupler for compact ultra-wideband UHF transceivers." 2021 International Conference on Communication, Control and Information Sciences (ICCISc). Vol. 1. IEEE, 2021.

[8] D. M. Pozar, “Microwave engineering,” John Wiley and Sons, 2009.

[9] Y. B. Kim, H. T. Kim, K. S. Kim, J. S. Lim and D. Ahn, "A branch line hybrid having arbitrary power division ratio and port impedances", Proc. Asia Pacific Microw. Conf., pp. 1-4, 2006.

[10] K. C. Gupta, R. Garg, I. Bahl and P. Bhartia, Microstrip Lines and Slotlines, MA, Norwood:Artech House, 1996.