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Design and fabrication of an eight-port binary Wilkinson power splitter

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Abstract: An eight-port X-band power splitter based on binary Wilkinson power splitter topology is presented in this paper. The proposed power splitter consists of three stages, with one, two, and four equal power splitters in the first, second, and third stages, respectively. The input power is divided equally between the eight outputs to provide an equal-split power splitter. Evaluation of the structure is carried out using even- and odd-mode techniques. An epoxy laminate FR4 substrate with thickness of 0.5 mm is chosen, while the designed power splitter is simulated using Keysight Advanced Design System 2019 and ANSYS High Frequency Structure Simulation. As the results indicate, excellent performance is obtained for the power splitter, with a reflection coefficient of –36.5 dB and an insertion loss of –9.32 dB at the 9.65 GHz center frequency. The proposed power splitter has the potential to be employed in radar and microwave systems, specifically in phased-array structures.

Key words: Power splitter, passive circuit, binary, integrated circuit

1. Introduction

Power splitters (also known as power dividers) are microwave circuits employed frequently in the telecommunication industry. These microwave circuits split high-frequency power signals from microwave circuits into different high-frequency circuits [1]. A power splitter is a 3-port circuit containing one input and two outputs, where the two outputs are connected in termination [2]. In addition, each port has a reflection wave with no coupling effect between the output ports (i.e. they are isolated). A number of studies have previously been developed on 3-port T-networks [2, 3]. The theory for equal power dividers in 3-port T-networks (as well as in n-way networks) was developed by Wilkinson in 1960 [4]. One useful application for power splitters is feeding array antennas [5]. Recently, a 1×3 power divider with substrate integrated waveguide (SIW) structure was proposed by Kiris et al. [6], with equal power transmission across all output ports. The measured output power in this power divider is very close to the ideal value of 4.77 dB, with bandwidth of approximately 17.5%, and better reflection coefficient of –18.76 dB at operating frequency of 10 GHz. The SIW structure proposed in this study is interesting, and it can be applied to designing a wide range of power dividers with multiple outputs. One successful technique for multiport structures is $(1 * 2)^n$, where n = 1,2,3, ... K indicates the type of the power interpolation. The 1×3 structure had previously been applied successfully to different designs [7]. Moreover, a SIW microstrip chip has also been added to this power divider with compressed SMA ports. The maximum difference measured in the output ports is approximately 0.5 in the 10.68 GHz band, measured at –8.93 dB. Moreover, in [8], a transition microstrip layer over the SIW structure was proposed using a cone

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microstrip circuit. Plus, its equivalent circuit has also been applied to a transport reflection tapper in [9]. To identify this transition, two microstrip circuits have been added to the SIW transition, which can be employed in the operating band shown in Figure 1. This design is carried out using the CST guidance tool.

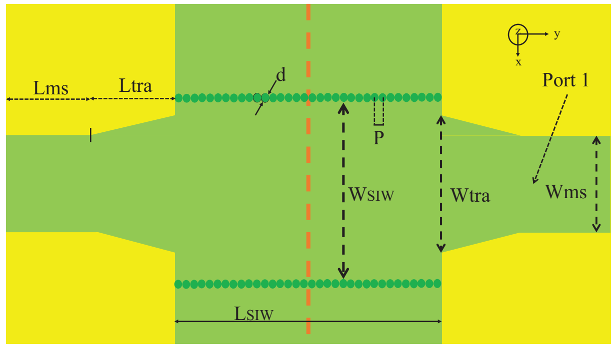

Figure 1. 1×3 power divider with SIW structure [6].

This figure has a complete symmetrical structure separated with a red line. The length of the microstrip cone is increased gradually to reduce the reflection coefficient and insertion loss. This transition is designed with a Rogers 5880 substrate with thickness of 1.575 mm. This substrate has $\varepsilon = 2.2$ and $\tan\delta = 0.0009$ at the 10 GHz frequency.

A previous study [10] proposed a novel power divider/mixer that employed a three-port waveguide with left-handed overlap. The left-handed power divider is fashioned using a left-handed T-junction, with a very high bandwidth (roughly 2.5 times higher than the operating frequency bandwidth and 50% smaller than the central frequency). In comparison with the existing T-junction, the advantage of this power divider is evident. There are some fascinating discussions in literature on metamaterials and RF, including photonic band gaps, negative permittivity, negative permeability, and left-handed (LH) structures [11]. In LH structures, the metamaterial is based on split ring resonators (SRRs) with an array that has a transition line for load and SRR (CSRR)/capacitive gap pair complements [12, 13]. A loaded line with serial capacitors and shunt inductance is still capable of demonstrating the left-handed property [14, 15]. The layouts for the right- and left-handed power divider are depicted in Figures 2 and 3.

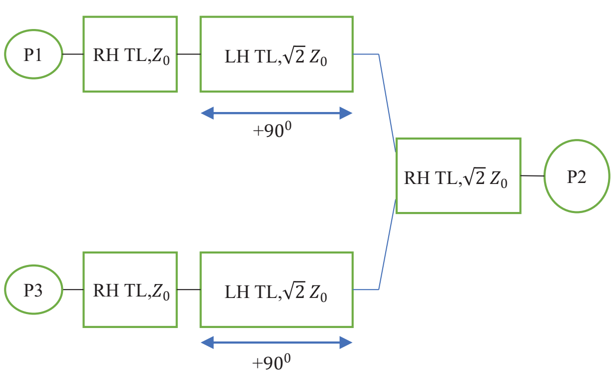

Figure 2. The layout diagram for the LH T-junction power divider [10].

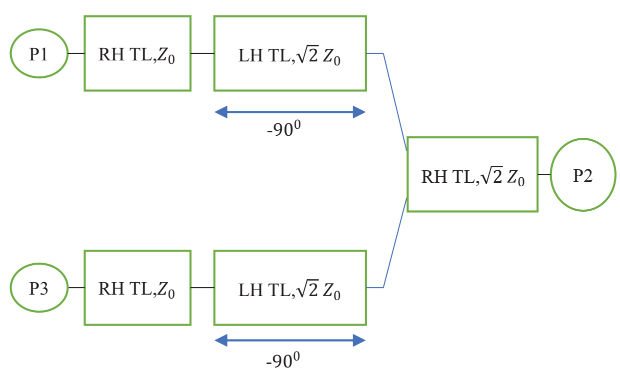

Figure 3. The layout diagram for the RH T-junction power divider [10].

The broadband equipment with SIW technology was proposed in [16]. The proposed structure design includes a grounded coplanar waveguide (GCPW) transition with a transfer power of approximately 0.4 dB. In addition, T-junctions and Y-junctions were developed with bandwidths of approximately 63% and 40%, respectively, and a transmission power of approximately 0.6 dB. Designing the Wilkinson power divider in the X-band is an advantage, since it includes an 8-port structure. The SIW structure possesses a low profile that is practical and suitable in integrated circuits. Typically, transferring GCPW to SIW includes two distinct sections, a coupling gap section and a transformer section. Following the transformer section, a broadband is embedded using a coupling gap, and impedance is also embedded in a cone connection slot from the transformer [17]. In this manner, not only is feeding a part of the waveguide wall improved, but the coupling along the gap will also be located in a triangular and cone-shaped gap, similar to the direction of the electric field in the coupling gap. The coupling gap is strictly perpendicular to the structure of the SIW. The broadband power splitter designed using the SIW technology is demonstrated in Figure 4.

The static rods employed in this structure are made of iron, with two rows close to the GCPW to prevent resonance at the operating frequencies. Moreover, they are placed distant from one another to prevent formation of other modes at the operating frequency. The following equation is employed to obtain the results [18]:

$$W + 2S + 2D < \frac{c}{f_{max}\sqrt{\varepsilon_r}}. \tag{1}$$

In this equation, W, S, and D are the width of the microstrip lines, the gaps, and the distance between the lines, respectively. f_{max} is the highest frequency for TE_{10} in the rectangular waveguide, which resulted in an 8-port power divider after development. Fabrication of a broadband power splitter using SIW technology is demonstrated in Figure 5. In [19], a dividing and power-mixing structure is proposed from Korea Maritime University with several binary transmission lines, which can be applied to bands X and C. The size of this divider is approximately 1.21 m^3. This 4-port power divider has the best frequency response with 4 input and output ports. The proposed power divider has excellent performance and is suitable for solid state power amplifiers. However, one of the most critical applications that this structure is applied to is marine communication, due to its excellent performance, where it is a crucial device in radar systems. In recent years, small power dividers have emerged, known as MMICs or monolithic microwave integrated circuits, which are designed on a GaAs layer. The basic schematics of this divider are as follows.

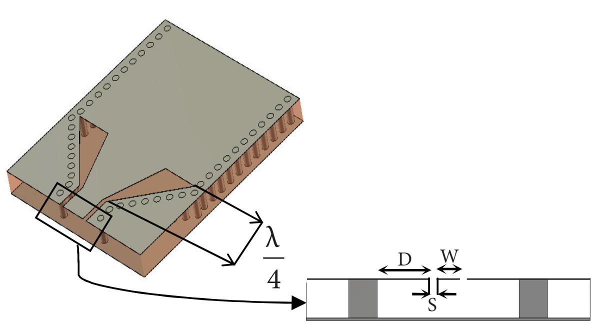

Figure 4. The broadband power splitter using SIW technology [16].

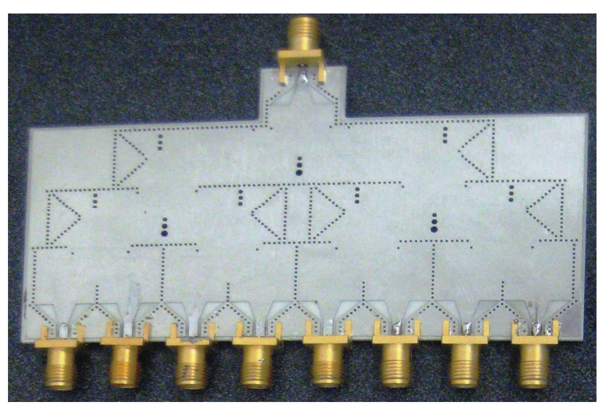

Figure 5. Fabrication of the broadband power splitter using SIW technology [16].

As can be seen in Figure 6, a marine radar with a Wilkinson power divider is employed. Fabrication of a 4-way power splitter is demonstrated in Figure 7.

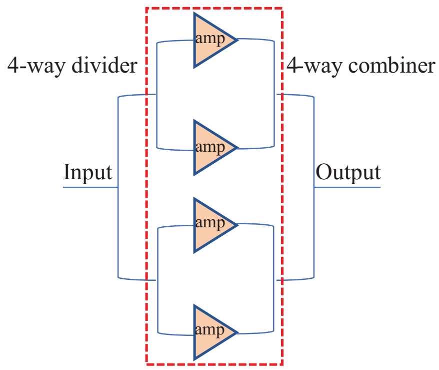

Figure 6. A block diagram of a power divider and a combiner [19].

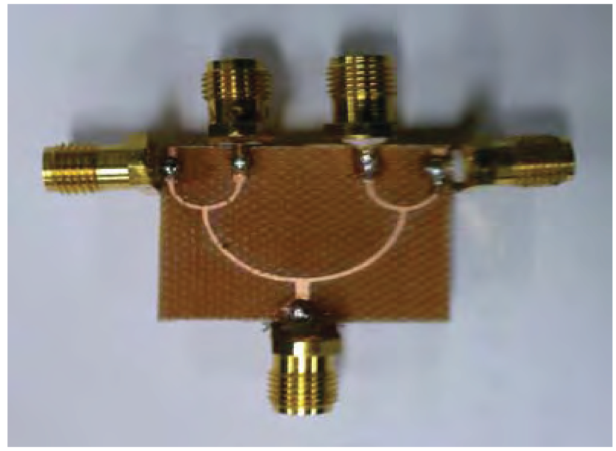

Figure 7. Fabrication of a 4-way power splitter[19].

Employing a Wilkinson power divider in this system increases its size and thus is a problem. Therefore, to overcome this problem, the n-type structure is employed for the coupled transmission lines. The reduced shape for the 4-port power divider is shown in Figure 8.

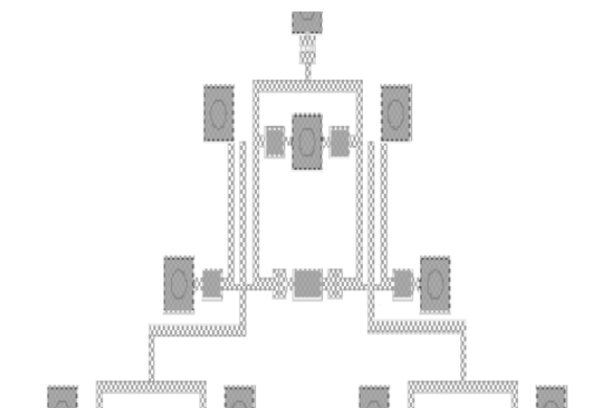

Figure 8. The reduced shape for the 4-port power divider [12].

The Wilkinson power divider is employed as a power supply circuit in phase array transmitters in the frequency range of 8–12 GHz, fabricated with the 4350b Rogers substrate and designed to provide power splitting for eight ports. This power divider provides excellent impedance matching between the output ports. Another advantage of this structure is an isolation of –15 dB and VSWR of less than 2. Phased arrays are utilized in aerial and ground radar applications. The size and output power of this system are compatible with millimeter waves [20]. A phased array system has space-power compatibility technology, with a yield of

80%–90% compared to the previous ones that had a loss in signal composition [21]. Several power splitters have already been proposed to swiftly increase bandwidth for hybrid system applications that require proper coherence of the appropriate phase [22]. An n-way power splitter is in high-power transmission mode, since it employs high-power obstruction, a characteristic that has high performance in the design of such systems. In this paper, an eight-port equal power splitter for X-band applications is proposed. Three stages of –3 dB three-port Wilkinson power splitters are considered to obtain the final outputs. The first, second, and third stages contain one, two, and four Wilkinson power splitters, respectively. The design of the power splitter is spread on a hydrocarbon ceramic laminate (FR-4) dielectric substrate, with relation permittivity of 3.38 and thickness of 0.5 mm. Simulation of our proposed structure in ANSYS HFSS 2017 and ADS 2019 demonstrates acceptable values for the reflection coefficient, insertion loss, and isolation at the 9.65 GHz center frequency. The proposed power splitter can be applied to radar and microwave systems applications, specifically in phased-array structures.

2. Materials and methods

2.1. Brief overview of the Wilkinson power splitter

The Wilkinson power splitter is a 3-port network microwave circuit, which yields no loss as long as the two output ports are matched. The input signal is split into two signals with similar power and phase. A three-port Wilkinson power splitter has two $\frac{\lambda}{4}$ transformers with a characteristic impedance of $2\sqrt{Z_0}$. Moreover, it has a $2Z_0$ resistor to provide isolation between the two ports, obtained according to [6]. The Wilkinson power splitter is often made in microstrip form. The basic topology and its transmission line models are illustrated in Figure 9 and Figure 10.

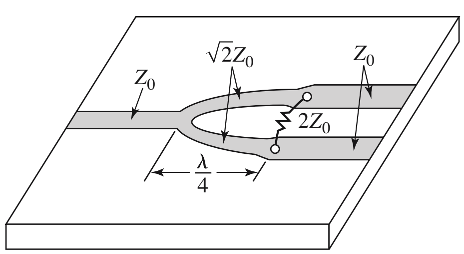

Figure 9. Microstrip circuit [1].

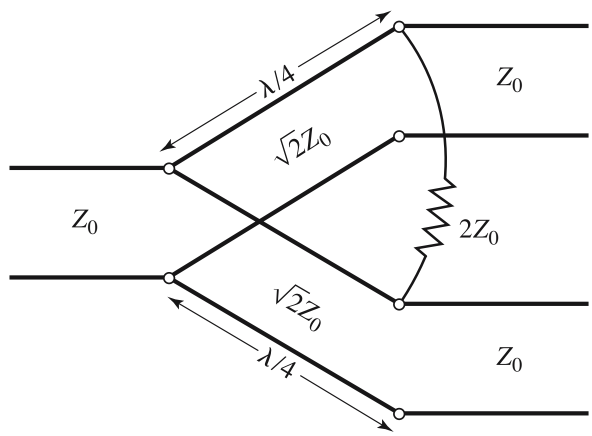

Figure 10. Equivalent circuit [1].

2.2. Scattering parameters

The scattering parameters matrix for a Wilkinson power splitter are determined using even-mode and odd-mode analysis [7], according to the equivalent circuit shown in Figure 11 and Figure 12. Moreover, the reflection coefficient and the input impedance are obtained in [7] considering proper voltages for the input ports in even- and odd-mode analysis.

In summary, the following S parameter matrix can be established [1]:

$$S = -\frac{1}{\sqrt{2}}\begin{bmatrix} 0 & j & j \\ j & 0 & 0 \\ j & 0 & 0 \end{bmatrix} \tag{2}$$

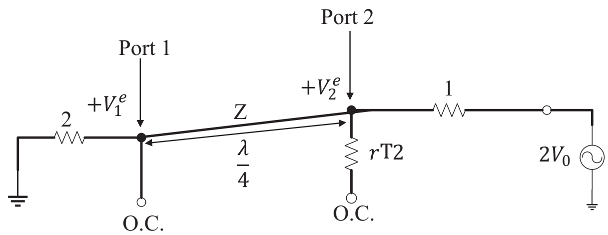

Figure 11. Even mode [1].

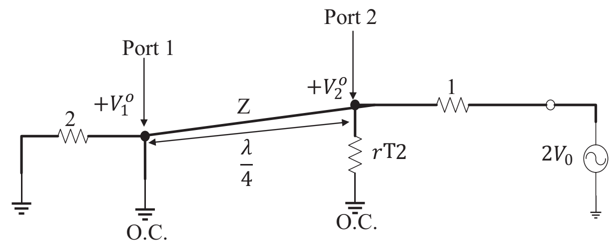

Figure 12. Odd mode [1].

$$RL_1[dB] = -20log|S_{11}| \tag{3}$$

$$RL_1[dB] = -20log|S_{22}| \tag{4}$$

$$CP_{12}[dB] = -20log|S_{12}|. \tag{5}$$

$$IL_{23}[dB] = -20log|S_{23}|. \tag{6}$$

Here, RL indicates the return loss for each port, while CP is the insertion loss from input to output and IL is the isolation between outputs. In addition, if the transmission power ratio in the output ports is K= $\frac{P_3}{P_2}$, we have the following equations [4, 23, 24]:

$$Z_{03} = Z_0 \frac{\sqrt{(1+K^2)}}{K^3}, \tag{7}$$

$$Z_{02} = K^2 Z_{03} = Z_0 \sqrt{K(1+K^2)}, \tag{8}$$

$$R = Z_0(k + \frac{1}{K}). \tag{9}$$

2.3. Design procedure

In binary form, an eight-port equal Wilkinson power splitter has three stages (the power splitter is considered in a binary and cascade form). The essential element of the structure is a two-port, –3 dB Wilkinson power splitter. All ports of the Wilkinson power splitter are matched so that fundamental elements can be repeated in each stage of the final topology. The stages contain one, two, and four power splitters in order to obtain the final eight outputs. The final structure should be of a unique size. The center frequency is set to 9.65 GHz, and an epoxy laminate FR4 substrate (from NEMA Company) with a thickness of 0.5 mm is chosen. The length and the width of the essential elements are determined according to the design procedure described in previous sections. Simulations are carried out in ADS 2019, where a two-port power divider is fabricated as an essential part of the 8-port equal power divider. This power divider is then developed into 4-way and 8-way equal power splitters. The schematics for the eight-way equal Wilkinson power splitter are demonstrated in Figure 13.

The final layout and fabrication of the eight-way power splitter (as designed in ANSYS HFSS 2017) are shown in Figure 14 and Figure 15, respectively. An acceptable fabrication solution is obtained through solving the dimensional problem of the design and examining the simulation results at f_c = 9.650 GHz center frequency.

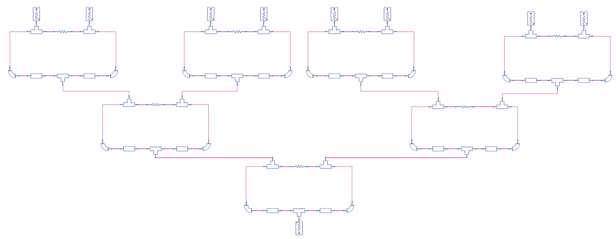

Figure 13. The schematics for the 8-way equal Wilkinson power splitter as designed in ADS 2019.

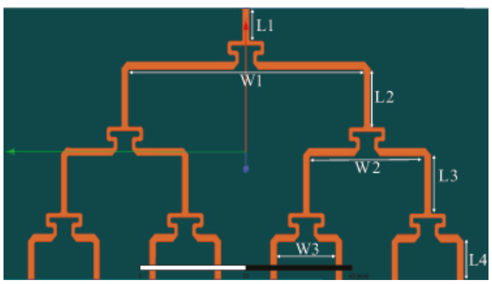

Figure 14. Schematics for the 8-way equal Wilkinson power splitter in ANSYS HFSS 2017.

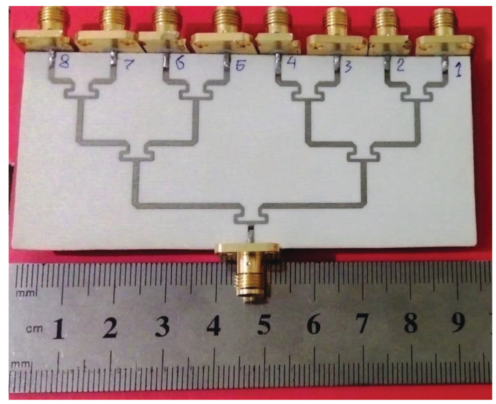

Figure 15. Fabrication of the 8-way equal Wilkinson power splitter in ANSYS HFSS 2017.

As can be seen in Figure 15, the dimensions of the model are L1 = 4 mm, L2 = 9 mm, L3 = 9 mm, L4 = 6 mm, W1 = 45 mm, W2 = 22 mm, and W3 = 12 mm. The overall size of the structure is acceptable in the X-band, which indicates its potential application in microwave systems.

The measurement results for the s-parameters following fabrication and simulation results of the eight-way equal power splitter in ANSYS HFSS 2017 and ADS 2019 are shown in Figure 16, Figure 17, and Figure 18.

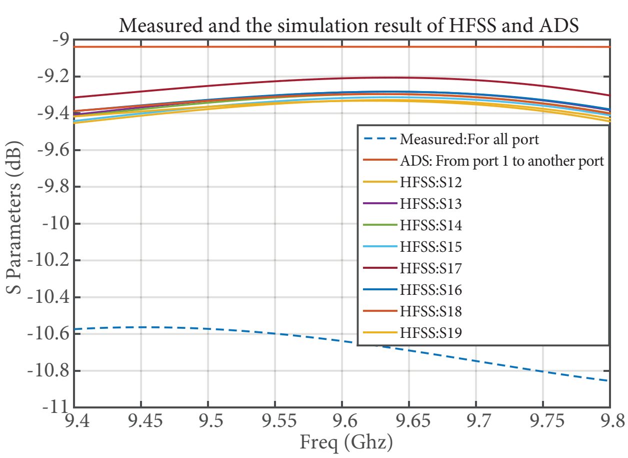

Figure 16. Results for insertion loss.

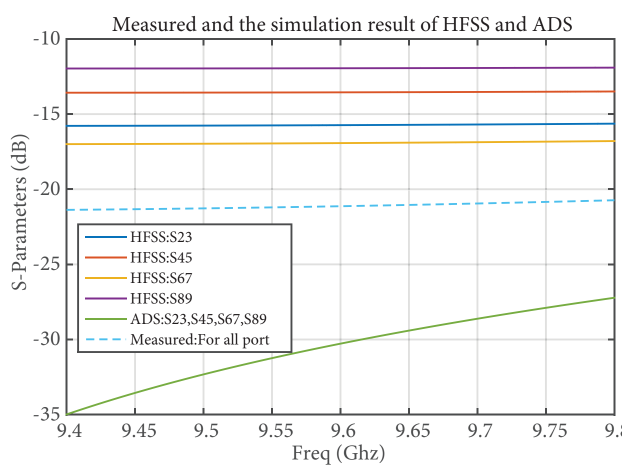

Figure 17. Isolation results.

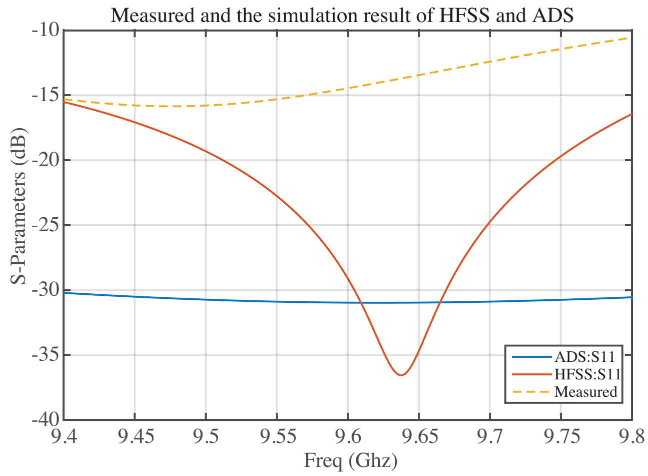

Figure 18. Isolation results.

Simulation results are shown in Table 1 and Table 2. As can be seen in Table 1, the moment solving method in ADS 2019 is less accurate compared to the finite element method in ANSYS HFSS 17.

Table 1. Simulation results for return loss and insertion loss.

Power splitter	S11	S12	S13	S14	S15	S16	S17	S18	S19
Eight-way (ADS)	-30 dB	-9.03 dB	-9.03 dB	-9.03 dB	-9.03 dB	-9.03 dB	-9.03 dB	-9.03 dB	-9.03 dB
Eight-way (HFSS)	-34 dB	-9.3 dB	-9.2 dB	-9.2 dB	-9.3 dB	-9.2 dB	-9.2 dB	-9.2 dB	-9.3 dB
Fabrication	-13 dB	-10.6 dB	-10.6 dB	-10.6 dB	-10.6 dB	-10.6 dB	-10.6 dB	-10.6 dB	-10.6 dB

Table 2. Simulation results for isolation.

Power splitter	S23	S45	S67	S89
Eight-way (ADS)	-29.4 dB	-29.4 dB	-29.4 dB	-29.4 dB
Eight-way (HFSS)	-15.7 dB	-13.5 dB	-16 dB	-11.9 dB
Fabrication	-21.4 dB	-21.4 dB	-21.4 dB	-21.4 dB

3. Conclusion

In this paper, the design procedure for an eight-port equal power splitter based on a two-way Wilkinson power splitter is described. The center frequency is set to 9.65 GHz, and an epoxy laminate FR4 substrate is chosen for the design. The necessary element for the two-way divider is designed and simulated in ADS 2019, and the final eight-port splitter is simulated in ANSYS HFSS 2017. As can be seen in simulation results, the eight-port power splitter operates well at 9.65 GHz center frequency.

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