Received: 19 November 2021 | Revised: 14 June 2022 | Accepted: 4 September 2022
DOI: 10.1002/mmce.23415

ORIGINAL ARTICLE

INTERNATIONAL JOURNAL OF RF AND MICROWAVE COMPUTER-AIDED ENGINEERING WILEY

Design of a compact multifunctional power divider loaded with short-ended stub

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Funding information
UTeM Zamalah Scheme; Universiti Teknikal Malaysia Melaka

Abstract
The article presents a compact multifunctional power divider loaded with short-ended stub for RF front end system at 2.5 GHz application. The proposed structure consists of PIN diodes and short-ended stub at the output transmission line. Wilkinson power divider and SPDT switch at 2.5 GHz can be achieved by changing the bias voltage of the integrated PIN diodes. As the proposed design transitions from a power divider to an SPDT switch, a short stub is introduced at the output ports to prevent mismatches from occurring. The proposed SPDT switch design has been mathematically analyzed and presented in detail. Two frequency component functions are combined in a small package with three RF connectors. This proposed design is constructed and characterized for experimental-demonstration purposes. The method proposed in this article is simpler compared to the previous work and easy to fabricate. This technique will reduce the overall size and manufacturing cost. It also can be applied to design the multifunctional power divider at any desired specifications and operating frequencies that compatible with RF/microwave applications, such as smart antennas and phase-array antennas.

KEYWORDS
multifunctional, PIN diode, short-ended stub, SPDT switch, Wilkinson power divider

1 | INTRODUCTION

Current and future communication systems necessitate reconfigurable structures and extended features, which are taken into account in the development of microwave devices such as: filters,[1] antennas,[2] and amplifiers.[3] This holds true for power dividers as well, as reconfigurable power dividers for 5G Cellular networks have recently been proposed.[4–8]

Reconfigurability refers to the ability to adjust or control a power divider's features dynamically while still maintaining acceptable overall performance. Power divider with adjustable power division ratio,[4,9–12] center frequency,[13–19] and transmission mode or function selectivity[20–22] are the key features targeted by reconfigurable power dividers. PIN diodes[9,19] and varactors[4,10–18] are commonly used to achieve reconfigurability.

One type of reconfigurable power divider that has recently gained popularity is switchable power dividers, in which the structure of the power divider can be adjusted to achieve different functionality. Examples of power dividers are discussed in the following paragraphs.

By using the substrate integrated waveguide (SIW) technology, a SPDT switch power divider was constructed in Reference[20]. The circuit, on the other hand, was hard to fabricate and the return loss was not ideal for SPDT switch. Meanwhile, in Reference[21], a reconfigurable power divider by using the CMOS technology is proposed. It can be reconfigured as an equal power dividing mode or a SPDT switch mode. However, the measurement results were not ideal for

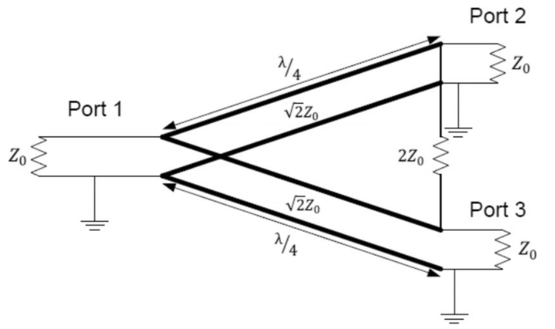

FIGURE 1 Equivalent Wilkinson power divider transmission line circuit

return loss and insertion loss for both modes. Besides, a reconfigurable power divider with four operating modes is proposed in Reference[22]. Switched central-loaded parallel coupled-line (SCLPCL) structure is utilized in the proposed design to achieve different operating modes. However, it can be seen that the proposed design is complex and during in-phase power divider mode, the isolation between the output ports is not ideal.

A compact multifunctional power divider operating at 2.5 GHz is demonstrated in this article. It integrates a conventional Wilkinson power divider with a SPDT switch function by using short stubs and PIN diodes. As a result, a single compact component is created that performs two crucial system functions: power division and signal switching. The system design is simplified, space is conserved, and customized design or fabrication capabilities are demonstrated by incorporating these two functions into a single unit. This design is suitable for applications such as the global positioning system (GPS) and any other application that requires user-controlled signal routing and power division between antennas and receivers. For system flexibility, it includes both a DC-pass RF path and a DC-blocked RF signal path.

The proposed multifunctional power divider is first presented in the next section followed by the mathematical analysis of the multifunctional power divider as a SPDT switch. Lastly, the performance of the proposed multifunctional power divider loaded with short-ended stub is analyzed and the overall performance of the proposed design is concluded.

2 | DESIGN OF MULTIFUNCTIONAL POWER DIVIDER LOADED WITH SHORT-ENDED STUB

The Wilkinson power divider is introduced by Ernest Wilkinson in 1960. It provides isolation between the output

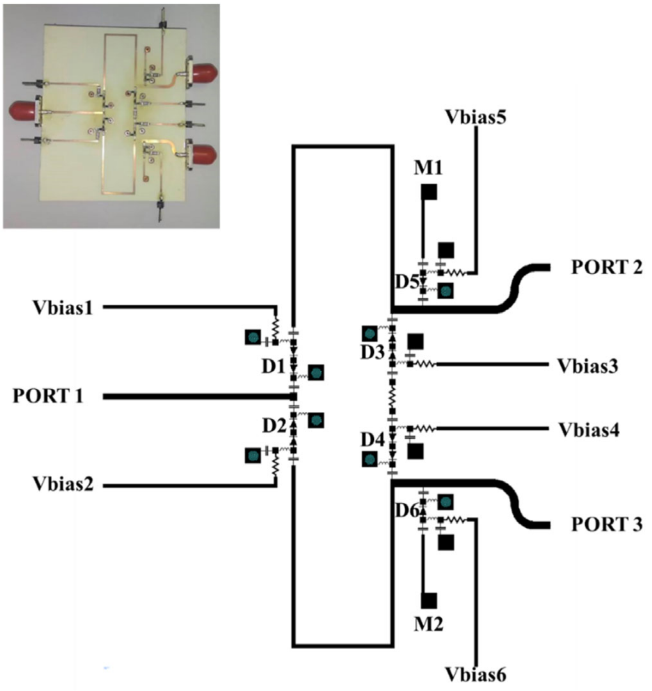

FIGURE 2 The circuit configuration of the compact multifunctional power divider and circuit prototype

ports. Besides, it is also able to match in all ports and can be lossless as long as the output ports are matched.[23] The equivalent Wilkinson power divider transmission line circuit with equal force supplied to both output ports is depicted is Figure 1.[24]

Every quarter-wave transmission line is the same to the characteristic impedance transmission line at the input which is multiplied with variables of $\sqrt{2}$. as appears in Figure 1. In addition, the internal resistor linking the two ports at the output is same to the characteristic impedance at the input of the line transmission by multiplied it with variables of 2. This impedance let power divider Wilkinson's output become matched and isolated, while allow the input flow to the power divider to make it matched.[23] The Wilkinson power divider's perfect scattering matrix is as follows:

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

From Equation (1), the scattering matrix indicates that the signal entering ports two and three will be identical with each other. S11, S22, and S33 are equal to zero as the ports are matched. When the signal enters port one, the power divider will be lossless.[24]

Figure 2 depicts the circuit configuration of the compact multifunctional power divider and circuit prototype.

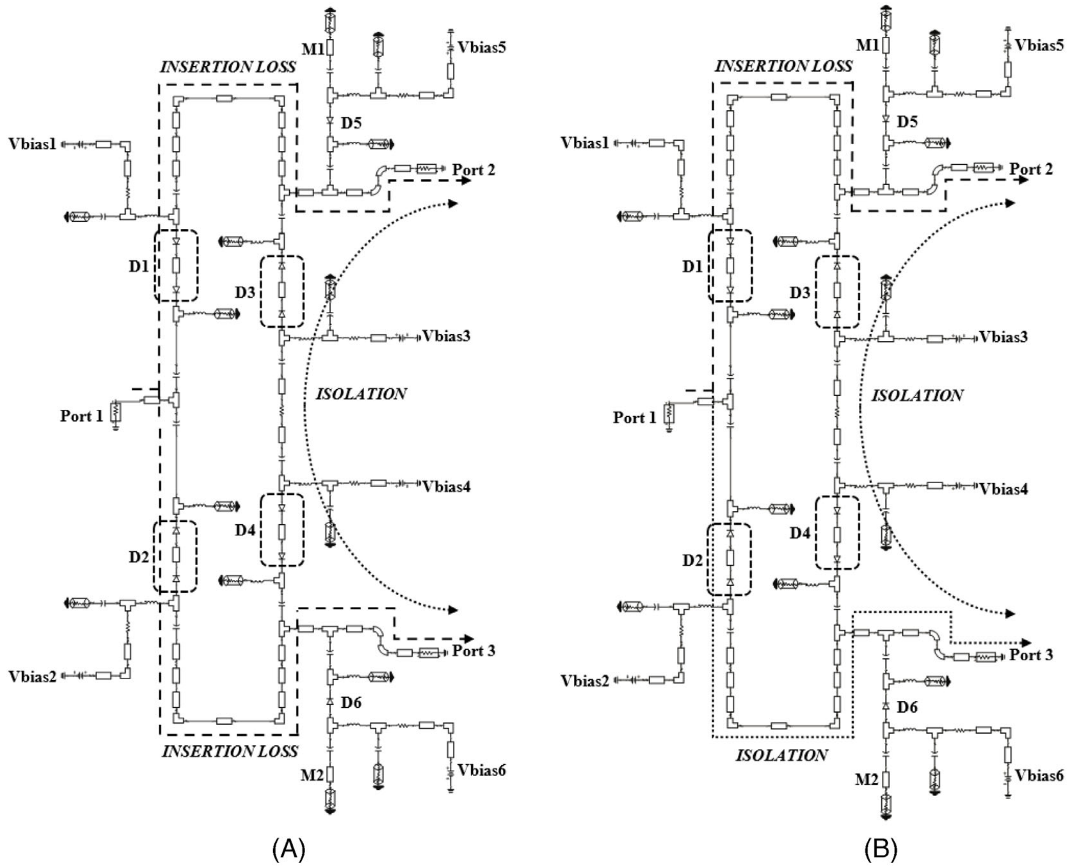

FIGURE 3 The circuit operation of the proposed design as (A) a power divider and (B) a SPDT switch

TABLE 1 Summary of circuit operation for the proposed design

	Power divider (dB)			SPDT switch (PORT 2 is in "ON" state) (dB)		
Technology	Voltage bias	PIN diode	ON/OFF state	Voltage bias	PIN diode	ON/OFF state
Vbias1	+5 Volt	D1	ON state	+5 Volt	D1	ON state
Vbias2	+5 Volt	D2	ON state	−5 Volt	D2	OFF state
Vbias3	+5 Volt	D3	ON state	−5 Volt	D3	OFF state
Vbias4	+5 Volt	D4	ON state	−5 Volt	D4	OFF state
Vbias5	−5 Volt	D5	OFF state	+5 Volt	D5	ON state
Vbias6	−5 Volt	D6	OFF state	−5 Volt	D6	OFF state

Based on Figure 2, the PIN diodes, D1, D2, D3, and D4, were switched on with +5 V voltage control to achieve a power divider function. Simultaneously, the D5 and D6 PIN diodes have been turned off with voltage control of -5 V or 0 V. Meanwhile, the PIN diodes, D1 and D5, were switched on with +5 V voltage control to achieve SPDT switch function. The PIN diodes, D5 and D6, control the short-ended stubs (M1 and M2), which are used to compensate for mismatch. Without turning on the PIN diode D5, the operating frequency shifted since half of the circuit is turned off. Figure 3A and 3B show the circuit operation of the proposed design as a power divider and a SPDT switch respectively. The summary of the circuit operation of the proposed design is shown in Table 1.

2.1 | Mathematical analysis of compact multifunctional power divider loaded with short-ended stub as a SPDT switch

In this section, mathematical analysis is focused on a multifunctional power divider as a SPDT switch as shown in Figure 3B. Due to the fact that this proposed design

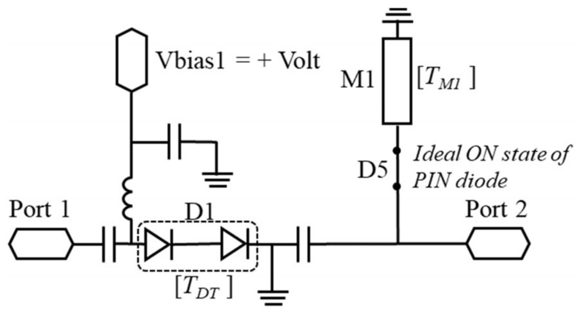

FIGURE 4 Two port network of series connected PIN diode (ON state) with short-ended stub

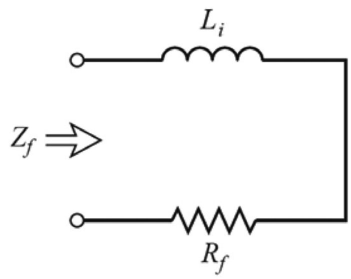

FIGURE 5 Equivalent circuit of PIN diode during "ON" state

makes use of a conventional Wilkinson power divider for which the design equations are established by David Pozar,[24] a simple mathematical analysis of the multifunctional power divider working as an SPDT switch is performed.

2.1.1 | The insertion loss

The multifunctional power divider's insertion loss as a SPDT switch is mathematically analyzed and discussed in this section. An ABCD matrix of the two-port network was evaluated based on Figure 3B in the multifunctional power divider as a SPDT switch operating at 2.5 GHz by considering the ON state PIN diodes of Port 2 (D1 and D5) as shown in Figure 4. Figure 5 shows the equivalent circuit of PIN diode during "ON" state.

Additionally, the series PIN diode (D5) was turned on, which controls the short-ended stub, M1. Therefore, the following is the ABCD matrix of this state of design:

$$[T] = [T_{DT}][T_{MI}] = \begin{bmatrix} A & B \\ C & D \end{bmatrix}, \tag{2}$$

where

$$[T_{DT}] = \begin{bmatrix} 1 & 2R_f + 2jwL_i \\ 0 & 1 \end{bmatrix}, \tag{3}$$

$$[T_{MI}] = \begin{bmatrix} 1 & 0 \\ \dfrac{1}{jZ_s\,tan\,(x)} & 1 \end{bmatrix}. \tag{4}$$

By substituting Equations (3) and (4) into Equation (2),

$$[T] = \begin{bmatrix} 1 & 2R_f + 2jwL_i \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \dfrac{1}{jZ_s\,tan\,(x)} & 1 \end{bmatrix}, \tag{5}$$

$$[T] = \begin{bmatrix} 1 + \dfrac{cos\,(x)\left(2R_f + 2jwL_i\right)}{jZ_s\,sin\,(x)} & 2R_f + 2jwL_i \\ \dfrac{cos\,(x)}{jZ_s\,sin\,(x)} & 1 \end{bmatrix}, \tag{6}$$

where T_{DT} is the transfer function ABCD matrix of total series PIN diodes in ON state (D1), R_f is the resistance of the PIN diode during forward bias, L_i is the inductance of PIN diode, T_{MI} is the transfer function ABCD matrix of the short-ended stub.[24] The ABCD matrix (2) is then converted to S-parameter, S_{21}, which expressed as follows:

$$S_{21} = \frac{2}{\left(A + \frac{B}{Z_0} + CZ_0 + D\right)}. \tag{7}$$

Substituting the result of Equation (6) into Equation (7) gives,

$$S_{21} = \frac{2}{\left(\left(1 + \frac{cos\,(x)\left(2R_f + 2jwL_i\right)}{jZ_s\,sin\,(x)}\right) + \frac{\left(2R_f + 2jwL_i\right)}{Z_0} + \left(\frac{cos\,(x)}{jZ_s\,sin\,(x)}\right)Z_0 + 1\right)}. \tag{8}$$

Consider $x = \frac{\pi}{2}$ (a quarter wavelength), $Z_S = 1$, $R_f + jwL_i \approx 0$, and a normalized characteristic of impedance, $Z_0 = 1$. Hence, the S_{21} of became

$$S_{21} \approx 1,$$

or in decibel

$$|S_{21}|^2 dB = 20\,log\,(1) = 0dB. \tag{9}$$

It is proved that 0 dB insertion loss, S_{21}, can be obtained theoretically. An ideal insertion loss was obtained from Equation (8). To produce low insertion loss, this insertion loss characteristic was applied in the multifunctional power divider as a SPDT switch.

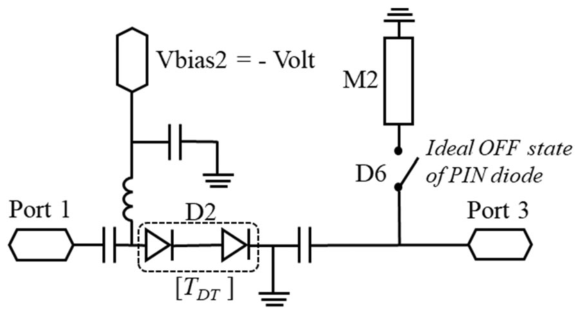

FIGURE 6 Two port network of series connected PIN diode (OFF state) with short-ended stub

2.1.2 | The Isolation

The multifunctional power divider's isolation as a SPDT switch is mathematically analyzed and discussed in this section. The ABCD matrix of the two-port network was observed based on Figure 3B by considering Port 3's OFF state PIN diodes (D2) in multifunctional power divider as a SPDT switch operating at 2.5 GHz as shown in Figure 6. Figure 7 depicts the equivalent circuit of PIN diode during "OFF" state.

Thus, the following is the ABCD matrix of this state of design:

$$[\mathrm{T}] = [T_{DT}] = \begin{bmatrix} A & B \\ C & D \end{bmatrix}, \tag{10}$$

$$[T] = [T_{DT}] = \begin{bmatrix} 1 & 2R_r + 2jwL_i - \frac{2j}{wC_j} \\ 0 & 1 \end{bmatrix}, \tag{11}$$

where T_{DT} is the transfer function ABCD matrix of total series PIN diodes in OFF state (D2), R_r is the resistance of PIN diode during reverse bias, L_i is the inductance of PIN diode and C_j is the junction capacitance. The ABCD matrix of Equation (10) is then converted to S-parameter, S_{31}, which expressed as follows:

$$S_{31} = \frac{2}{\left(\mathrm{A} + \frac{\mathrm{B}}{Z_0} + \mathrm{C}Z_0 + \mathrm{D}\right)}. \tag{12}$$

Substituting the result of Equation (11) into Equation (12) gives,

$$S_{31} = \frac{2}{\left(2 + \frac{\left(2R_r + 2jwL_i - \frac{2j}{wC_j}\right)}{Z_0}\right)}. \tag{13}$$

Consider $C_j \approx 0$. $R_r + jwL_i$ can be ignored since it is usually small relative to the series reactance due to the junction capacitance and a normalized characteristic of impedance, $Z_0 = 1$. Hence, the S_{31} became

$$S_{31} \approx 0,$$

or in decibel

$$|S_{31}|^2 dB = 20\,log\,(0) = \infty dB. \tag{14}$$

It is proved that if $C_j \approx 0$, infinite isolation, S_{31}, could be obtained theoretically. From Equation (13), ideal infinite isolation was produced. In multifunctional power divider as a SPDT switch, high isolation is produced by using this attenuation characteristic.

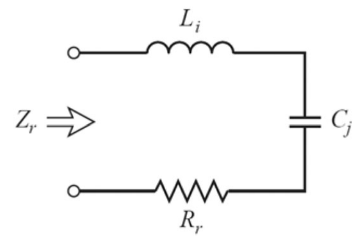

FIGURE 7 Equivalent circuit of PIN diode during "OFF" state

3 | RESULTS AND DISCUSSIONS

Figures 8 and 9 show the comparison between the simulation and measurement results of the proposed design function as a SPDT switch and a power divider operating at 2.5 GHz, respectively. During SPDT switch function, the simulation result S11 showed a return loss of 24.53 dB at 2.5 GHz, an insertion loss of 1.06 dB, an isolation of S23 of 21.84 dB, and a S13 of 20.59 dB at 2.5 GHz. In contrast, during the power divider function, the simulation result of return loss was 36.84 dB, isolation (S23) was 15.08 dB, and insertion loss (S21 and S31) were 3.88 dB.

The proposed design was fabricated to validate the simulation results after designing with ADS software. The S-parameters of the prototype in Figure 2 were analyzed with the aid of a vector network analyzer.

As shown in Figure 8, during SPDT switch function, there was a frequency shift of approximately 350 MHz. The proposed design's return loss (S11) measured at 2.84 GHz was 31.43 dB, insertion loss (S21) was 1.39 dB, isolation of S23 was 30.71 dB, and S13 was 29.45 dB. Meanwhile, Figure 9 shows that during the power divider function, there was around a 500 MHz frequency shift from the simulation results. At a resonance frequency of 2.02 GHz, the measurement result S11 was 12.80 dB,

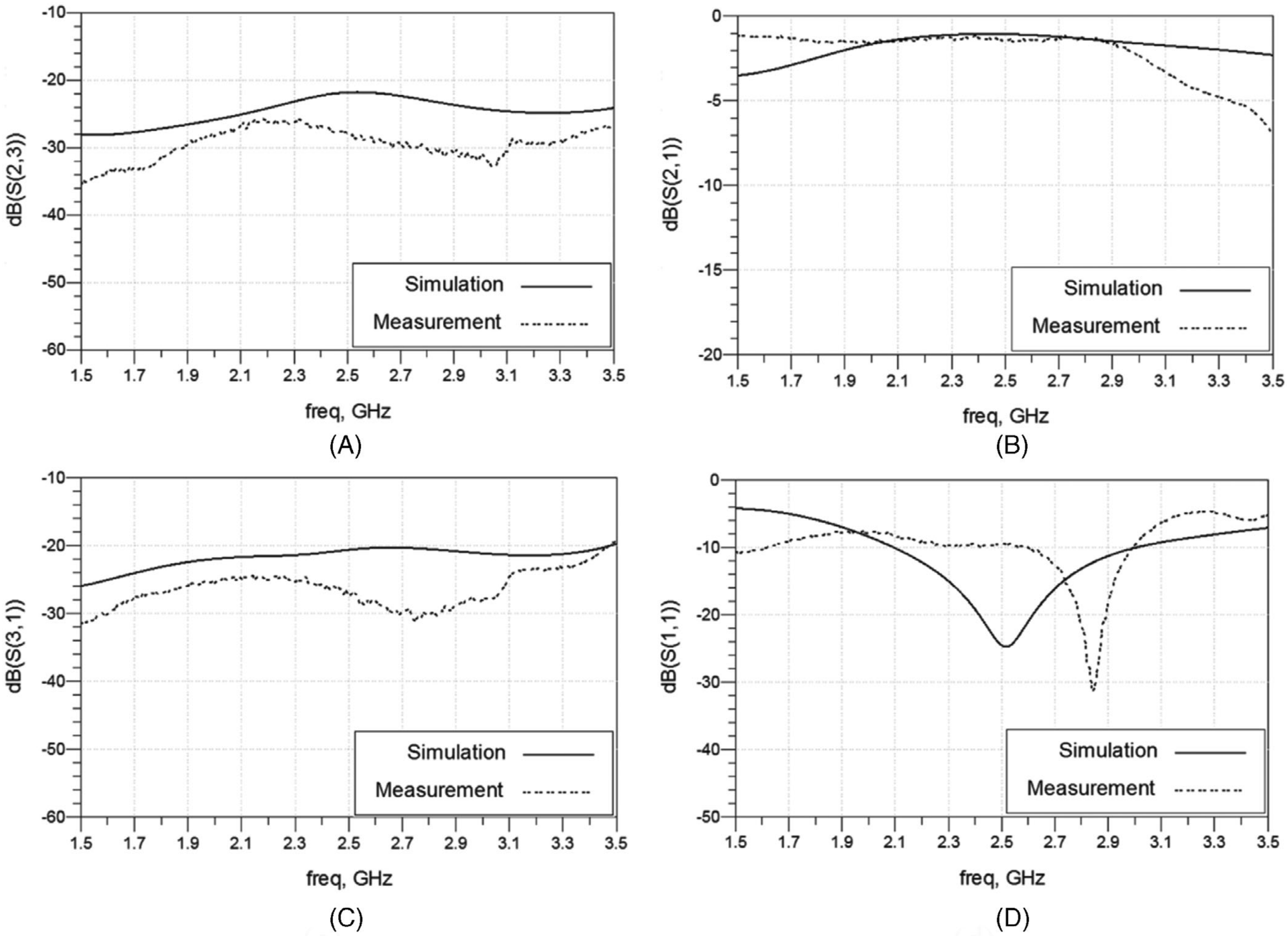

FIGURE 8 The simulated and measured S-parameters, (A) S23, (B) S21, (C) S31, and (c) S11, during SPDT switch function at 2.5 GHz

isolation (S23) was 13.48 dB, and insertion loss (S12 and S13) were 4.09 ± 0.02 dB. The frequency shift is caused by the PIN diode's parasitic reactance (capacitance or inductance). Diodes can be replaced by Microelectromechanical Systems (MEMS) devices in future work. Furthermore, the measurement results for power divider function between S12 and S13 showed slightly different for its insertion loss, which indicates the prototype was almost symmetrically fabricated and soldered component.

4 | COMPARISON WITH THE PREVIOUS WORK

The comparison between the performance of the proposed multifunctional power divider (PD) and published works is summarized in Table 2.

Compared with the other works, a competitive performance on S-parameters can be obtained in this design. The design's technology used in References 20,25 was the SIW. Despite this, the design was difficult and hard to fabricate. In Reference20, only simulation results were included. Furthermore, the result of output port isolation was excluded. Besides, in Reference21, the proposed design used CMOS technology. Nevertheless, the design is complex and the isolation between the output ports during in phase power divider was not ideal. Meanwhile, in References 27,28, the designs were based on microstrip lines, and they were simple. However, the results for the isolation between the output ports were not included. Moreover, in Reference 28, the result of the return loss for SPDT switch function was not ideal. This work was simpler in design compared to previous works.[20–22,25,26] The proposed design modified the conventional Wilkinson power divider's design integrated with short-ended stubs and PIN diodes[29] in order to accomplish multifunctional properties. In addition, compared to the others, this proposed design gives good performance especially during SPDT switch function.

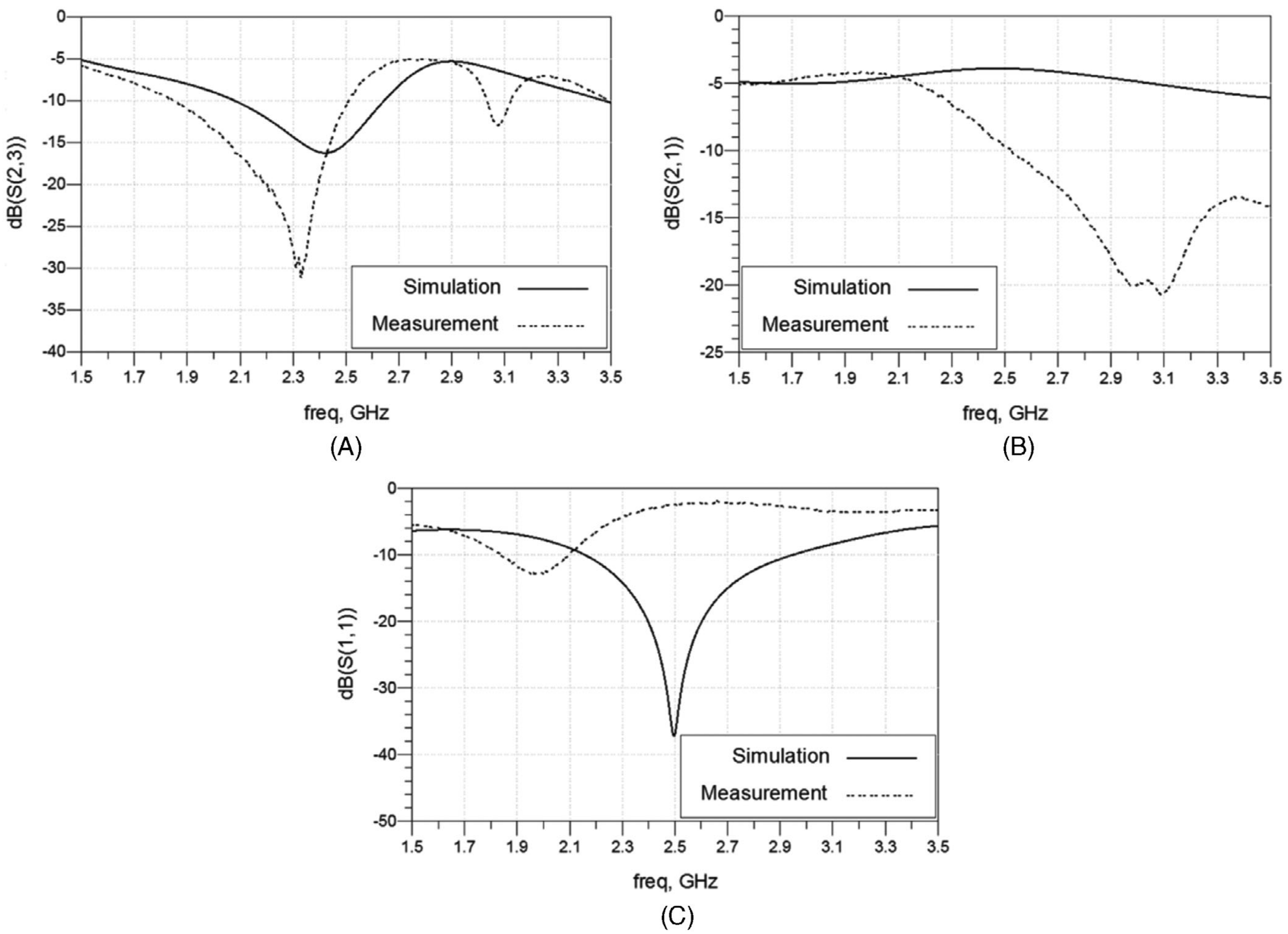

FIGURE 9 The simulated and measured S-parameters, (A) S23, (B) S12, and (C) S11, during power divider function at 2.5 GHz

TABLE 2 Comparison with the earlier studies on the multifunctional power divider

			Power divider (dB)			SPDT switch (PORT 2 is in "ON" state) (dB)			
Ref.	Technology	Operating frequency (GHz), f	S11	S21/ S31	S23	S11	S21	S31	S23
Proposed design	Microstrip	2.5[a]	36.84	3.88	15.08	24.53	1.06	20.59	21.84
		2.02 PD / 2.84 SPDT Switch	12.80	4.09 ± 0.02	13.48	31.43*	1.39	29.45	30.71*
20	SIW	60[a]	23	3.5	NA	11.5	1.4	32	NA
21	CMOS	28	4	9.2/ NA	17.2	7.4	6.4	6	28.4
22	Microstrip	2.4	19.5	4.5/ 4	9.5	8	2.7	28	26
25	SIW	4.95	14.5	7.4	4.35	15	1.35	23	27
26	Microstrip	5	17	≤4.91	≥31.5	14.3	1.7	≥28.8	≥28.3
27	Microstrip	2.12	<34	>3.5	<25	<26	0.5	NA	NA
28	Microstrip	2.14	>20	<4	>20	17	0.8	>20	NA

[a]are simulated values.

5 | CONCLUSION

This article presents a compact multifunctional power divider that combines a Wilkinson power divider and a SPDT switch using short-ended stubs. As a result, a single compact unit has been developed which is capable of performing two crucial system functions: power division and signal switching. The system design is simplified, space is conserved, and customized design or fabrication capabilities are demonstrated by incorporating these two functions into a single unit. Additionally, it includes two conventional component functions that are now impedance matched and performance optimized when working together. The simulation results indicated that both functions performed well, with return loss (S11) more than 20 dB and isolation was less than −10 dB. Furthermore, the insertion loss (S21 and S31) during power divider function was less than −4 dB. Meanwhile, during SPDT switch function, the insertion loss was less than 1.5 dB. Even though the measured resonant frequency had been shifted, the measurement results remained correlated with the simulation results.

ACKNOWLEDGMENT

We are grateful to Universiti Teknikal Malaysia Melaka (UTeM) under Zamalah Scheme for their encouragement and help in supporting financially to complete this research work.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article

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How to cite this article: Edward N, Shairi NA, Zakaria Z. Design of a compact multifunctional power divider loaded with short-ended stub. *Int J RF Microw Comput Aided Eng*. 2022;e23415. doi:10.1002/mmce.23415