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Design of a Novel Microstrip Ultra-Wideband Power Divider for WLAN and Sub-6 GHz 5G Applications

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Abstract: In this work, a novel power divider/combiner based on microstrip technology is investigated and designed for ultra-wideband wireless applications. The design process adopted for this power divider consists of modifying the planar transformers of the conventional power divider using the open artificial transmission technique. The power divider was designed on the basis of the theoretical equations of the open stub technique. It is simulated and optimized using the ADS and CST Microwave Studio solvers. As the simulation results, over the operating band, a bandwidth of 3000 MHz between 1 GHz and 4 GHz was achieved, along the entire band. This gave a maximum return loss of -28 dB at the center frequency and an insertion loss of about 3.5 dB, while maximum isolation of -38 dB was obtained across the output terminals. On the other hand, a prototype of the proposed power divider, fabricated on an FR4 substrate using microstrip technology, gave results confirming those of the simulation. In addition, the final structure considerably reduced the overall dimensions to 75% less than the traditional power divider. Therefore, the proposed power divider could be a suitable solution for wireless applications including 5G, WiMAX, WIFI, and Bluetooth.

Keywords: Open stub resonators, Mobile communication, Microwave power divider, Microstrip technology, Sub-6 GHz 5G.

1. Introduction

Recent on-demand applications requiring more sophisticated circuits and sub-systems mean that miniature RF components are attracting more attention than ever in commercial mobile and wireless systems, particularly those that have been dedicated to fifth-generation 5G. The power divider is one such microwave passive circuit that plays a vital role in various microwave systems, including 5G phased array systems, and its role becomes more critical when it is miniature in size. [1-4]. It is used to divide or combine power in radio frequency communication devices such as base stations to divide a signal between sector antennas, amplifier chains, frequency multipliers, mixers, phase shifters as well as modulators.

The power divider is designed to divide or combine power to meet the design requirements of new transceiver technologies [5-9]. The Wilkinson power splitter/combiner splits the power of the received signal from the input port P1 into two identical parts at its output ports P2 and P3 using quarter-wave transformers and a 100Ω resistor for isolation or combines the power received by both ports P2 and P3 to produce the summed power in port P1.

Fig. 1 depicts the layout of the typical Wilkinson power divider, which consists of two quarter wavelength transmission lines with characteristic impedances of ($Z_c=\sqrt{2}.Z_0$) and a separating resistance ($R=2.Z_0$) connecting the output terminals. This resistor's function is to absorb energy in the case of an output mismatch. Although the Wilkinson power

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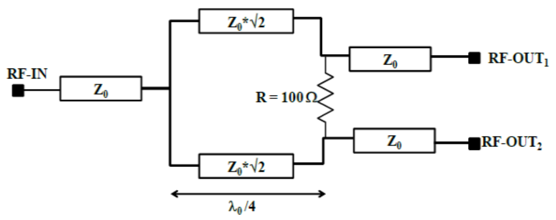

Figure. 1 The electrical diagram of a conventional Wilkinson power divider circuit

is working as a power combiner, this resistor likewise provides isolation for the two output terminals. Two identical quarter-wavelength sections in the fundamental design of a Wilkinson power divider provide excellent matching at all terminals, a similar power ratio, as well as excellent isolation throughout its output terminals. The conventional power divider has a narrow bandwidth and occupies large dimensions, which limits its application and flexibility in microwave circuits due to the requirement for wide bandwidth and miniature size in some mobile and wireless communication systems such as DCS, UMTS, Wifi, and 5G Applications.

Indeed, several efforts have been made to reduce the physical dimensions of the power divider, but with poor results, especially for implementation in WLAN and 5G devices [10-14]. Further strategies have been also adopted in more new studies to minimize the overall length of the Wilkinson power divider/combiner. For example, in [15], the researchers used three-dimensional approaches or 3D techniques that are widely used to design antennas for easy integration and high performance in mobile communications. However, this technique complicates the design of RF active and passive circuits in terms of fabrication and integration into RF systems. In [16-19], these researchers used planar transformers or artificial transmission lines (ATLs) as a design technique. These approaches have been widely used in RF circuit design and achieve good bandwidth performance. In contrast, they require several sections of a planar transmission line, increasing the size of the structure. In [20], the planar transmission line technique loaded with lumped element (capacitor) is proposed to design a reduced power divider. However, the use of the lumped elements is not recommended for microwave frequencies because their behavior changes with frequency. In [21-22], these two investigations used the stepped impedance technique to either modify quarter-wave transformers or load stepped impedances along open stubs. These techniques are effective to design power dividers having reduced size. But, the disadvantage of these techniques is the use of multiple sections of stepped impedances and open stubs in the same structure, complicating theoretical design and simulation optimization. In [23-26], the researchers designed a reconfigurable power divider using varactor diodes. This technique is more appropriate for choosing the frequency of the operating band. Its weakness is the external power supply required to activate the varactor diodes, which increases the size of the structure.

In order to meet requirements for miniature size and high bandwidth, this study proposes a new design for a power divider/combiner based on the open-circuit planar transmission lines technique called open-stubs. The circuit has been developed and optimized using the ADS simulator. The various stages of this investigation are organized as follows:

The second section is dedicated to studying the proposed transformer based on shunt-open stubs. The third section is devoted to the design and discussion of the simulation results of the proposed Wilkinson divider/combiner. In the fourth section, the divider is prototyped and the results are measured. Finally, we conclude our study with an outlook for future work.

2. Study of the proposed shunt-open stubs-based transformer

The approach adopted in this study to design the new divider/combiner architecture is based on conventional power dividers by modeling the planar quarter-wave transmission lines loaded through open stubs. For the typical transformer which is illustrated in Fig. 2 with its equivalent electrical model is modeled using the *ABCD* chain matrix by Eq. (1).

$$M_{\frac{\lambda_g}{4}} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 0 & JZ0 \\ JY0 & 0 \end{bmatrix} \tag{1}$$

The electrical model parameters (L and C) have been estimated from the characteristic impedance *Z0* and the electrical length θ as described in Eqs. (2) and (3):

$$L = {Z_0}/{\omega} \tag{2}$$

$$C = {1}/{(\omega . Z_0)} \tag{3}$$

For artificial wiring consisting of a shunt with an open stub in the center (T-model), as shown in Fig. 3 with its equivalent electrical model. Its model is characterized by its own matrix *ABCD* which is composed of the characteristic impedances (*Za* and *Zb*) and the electrical lengths (θa and θb) as described by Eqs. (4), (5) and (6) [27].

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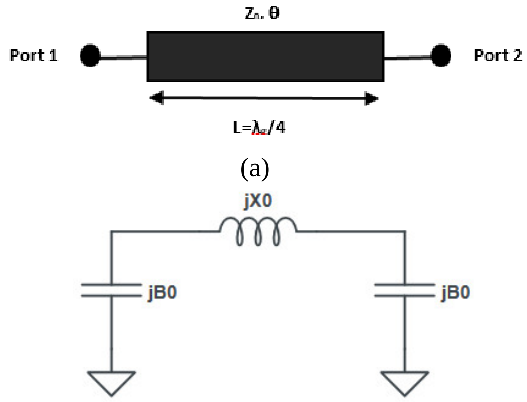
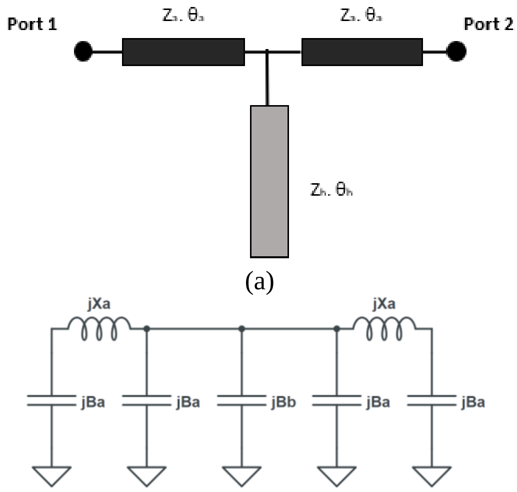


(a)

(b)

Figure. 2 Configurations: (a) the standard transformer and (b) the equivalent electrical model



(a)

(b)

Figure. 3 Configurations: (a) the shunt-stub-based transmission line and (b) the equivalent electrical model

$$M_T = M_a . M_b . M_a \tag{4}$$

Where:

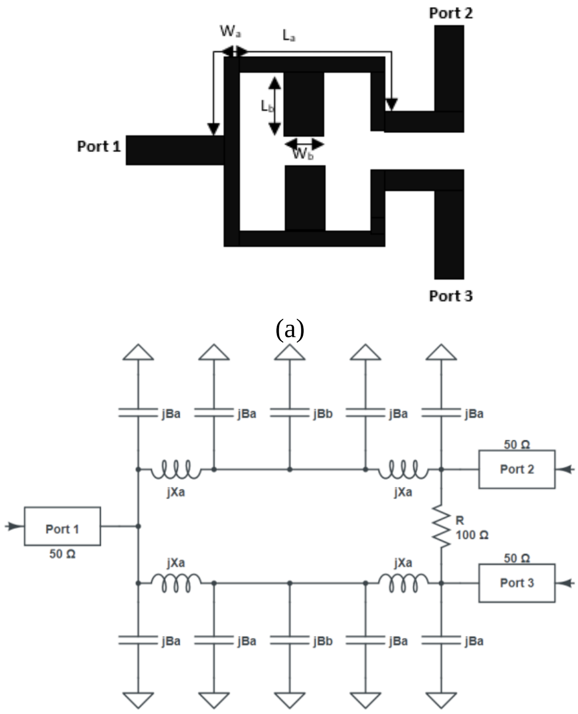
$$Ma = \begin{bmatrix} \cos\theta\, a & jZa \sin\theta\, a \\ jYa \sin\theta\, a & \cos\theta\, a \end{bmatrix} \tag{5}$$

$$Mb = \begin{bmatrix} 1 & 0 \\ jYb \tan\theta\, b & 1 \end{bmatrix} \tag{6}$$

As a result, the design equations for the miniaturized microstrip power divider of the reduced quarter-wavelength transformer can be expressed as depicted in Eqs. (7) and (8):

$$Z_a = \frac{Z_0}{tan(\theta_a)} \tag{7}$$

$$Y_b\, tan(\,\theta_b) = \frac{2}{Z_a\, tan(2\theta_a)} \tag{8}$$



(a)

(b)

Figure. 4 The configurations: (a) the proposed power divider and (b) the equivalent electrical model

Table 1. The optimized values of the developed power divider

Length (mm)	**Width (mm)**
L_a=12.2	W_a=0.6
L_b=3.6	W_b=2.2

In the case where the adopted model has an electrical length θ less than that of a quarter-wave transformer, the parameters of the equivalent electrical model are determined by Eqs. (9), (10), and 11:

$$L_a = \frac{Z_a \sin(\theta_a)}{\omega} \tag{9}$$

$$C_a = \frac{1-cos(\theta_a)}{Z_a\omega\, sin(\theta_a)} \tag{10}$$

$$C_b = \frac{Y_b\, tan(\theta_b)}{\omega} \tag{11}$$

All the design parameters can be calculated from the equations given in the analysis before. All these parameters are listed in Table 1. From the electrical length values, it is clear that the total electrical length is only 56.82°, instead of 90° in a conventional Wilkinson power divider. The layout and its equivalent electrical model of the proposed power divider based on shunt open stubs artificial line is illustrated in Fig.4.

In order to verify our method, the electrical model

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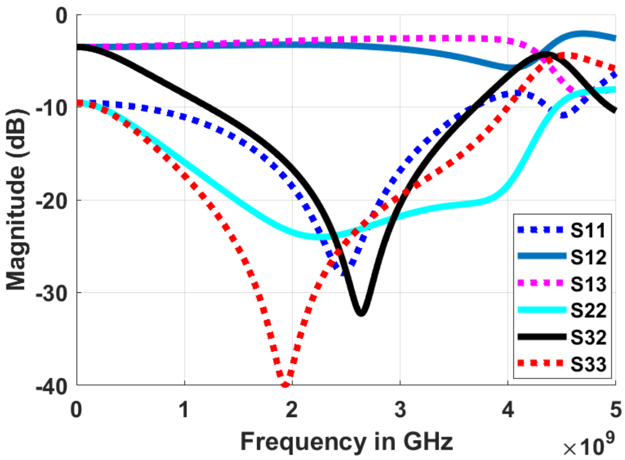

Figure. 5 Simulated S-parameters of the electrical model of the proposed power divider/combiner

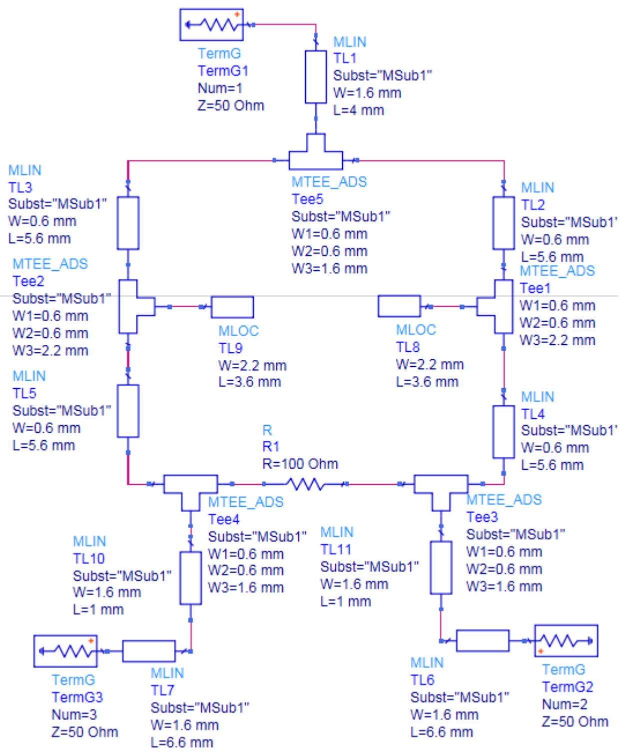

Figure. 6 The 2D schematic of the proposed power divider

using lumped elements was simulated under ADS and the results obtained are depicted in Fig. 5. As can be seen, the results obtained in terms of isolation, transmission, and impedance matching at the three ports show that the splitter/combiner meets the requirements.

3. Design and simulation results

The proposed power divider configuration was developed using a planar structure based on microstrip technology on an Epoxy-FR4 substrate with a dielectric height of 1.58mm and an electrical dielectric constant of 4.4 and is intended to operate

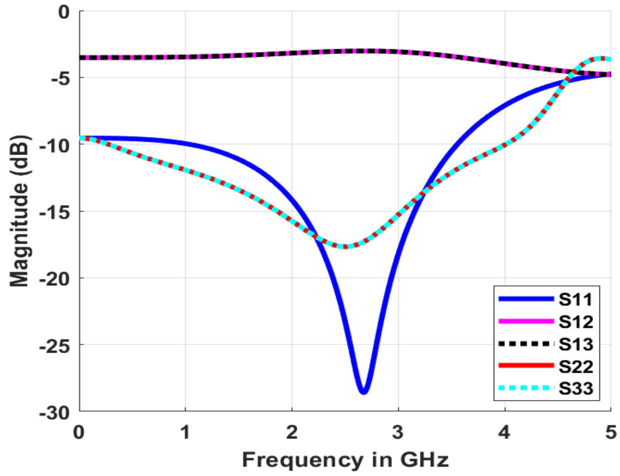

Figure. 7 The computed S-parameters

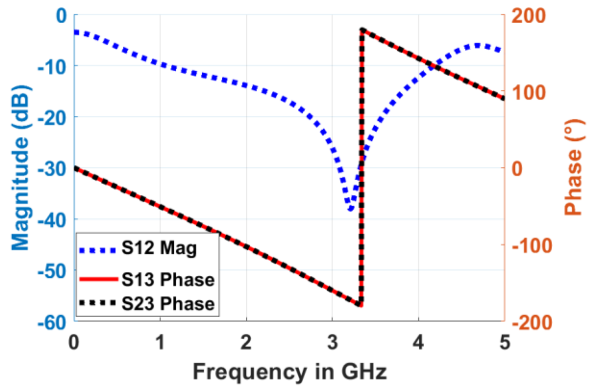

Figure. 8 Isolation and phase difference between the output terminals

over a wide frequency spectrum ranging from 1GHz to 4GHz, with a midfrequency of 2.45GHz dedicated for WLAN and Sub-6 GHz 5G applications. Fig. 6 depicts the 2D structure developed through the ADS schematic approach.

Fig. 7 depicts the simulation results for the power split configuration in terms of impedance matching at the three terminals and the power transmission across the input terminal P1 and the two output terminals P2 and P3. The input terminal, as shown in the figure, has very good matching over a wide band from 1GHz to 4GHz, with a return loss of less than -10dB over the entire operating band and about -28dB at the center frequency, while the two output terminals have a match of about -17dB at the center frequency and less than -10dB over the band up to 4GHz. The design also ensures a -3dB difference over the entire operating spectrum up to 4GHz, ensuring strong transmission between the input and output terminals.

Other critical variables for the power divider to work properly include phase shift, which must be zero, and isolation, which must be less than -10dB to ensure that no power passes across the two output terminals. Fig. 8 illustrates these two values, showing

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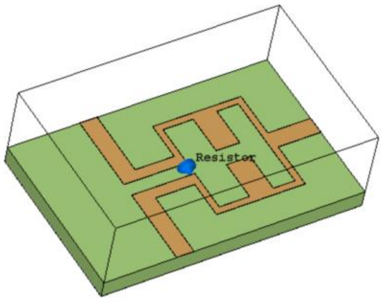
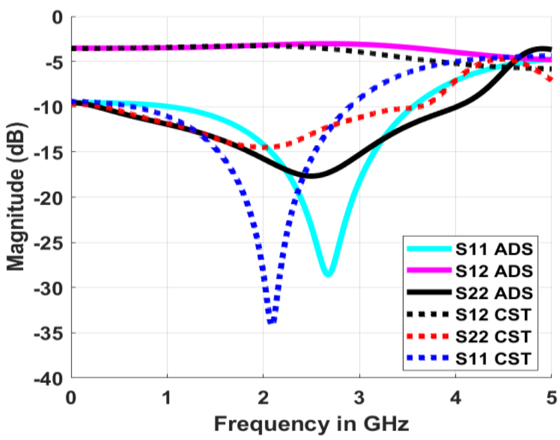
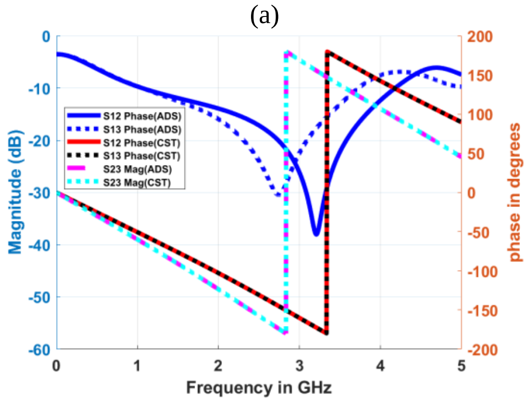


Figure. 9 The 3D layout of the developed power divider/combiner



(a)



(b)

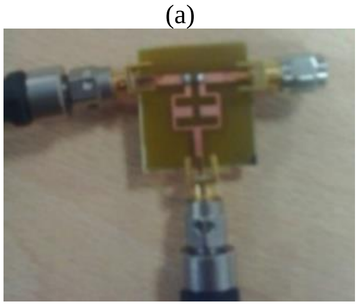
Figure. 10 The computed using ADS and CST: (a) S-parameters and (b) Phase difference between S21 and S31

that the 100Ω resistor produces zero phase shift and adequate isolation between the output terminals.

To ensure the accuracy of the design, the results obtained by ADS were verified using the CST Microwave Studio electromagnetic simulator before prototyping the proposed structure. Fig. 9 shows the 3D structure using CST.

The proposed layout of the structure is a fairly simple one, with a complete ground plan. It has the advantage of being fabricated on a single layer of the reported substrate. The architecture has a 75% reduction in the area with less than conventional structures. The simulation results from both simulators are shown in Figs. 10(a) and 10(b).

(a)



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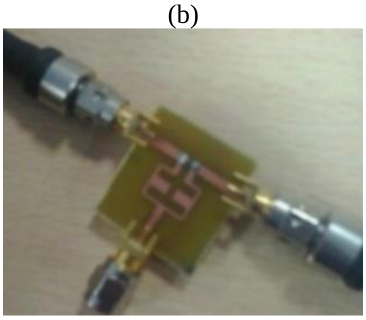

(c)

Figure. 11 Prototype of the proposed power divider under test: (a) input return loss, (b) insertion loss, and (c) isolation ratio

The simulated results demonstrate that any signal entering operating frequencies 1.8GHz, 2.45GHz, or 3.5GHz of the WLAN and sub-6GHz 5G applications at the input port splits into two in-phase signals on port P2 and port P3. In addition, the structure does not have any losses, all ports are significantly matched, and 3dB coupling factor for any output signal of operating frequencies. We can conclude that the results obtained by ADS were confirmed by the comparative results obtained by the CST software.

4. Fabrication and measurement results

The prototype of the proposed power divider is shown in Fig. 11. It was printed on an FR4 substrate with a dielectric thickness of 1.58mm. A network analyzer (HP8719ES) was used to measure the various parameters of the proposed prototype. These measurements for WLAN and 5GHz sub-6GHz operating frequencies are presented and compared.

Fig. 12 depicts the measurement results. As can be noticed, the S11 splitter's input return loss is less than -10dB in the operational band. Return loss measurements at S22 and S33 outputs are likewise

Table 2. Performance summary of the proposed power divider and related works

Ref.	F-Band-width (GHz)	PDR	RL (dB)	IS (dB)	Relative size	Methods	Prototyping Complexity
[28]	[1.2,3.3]	2:1 equal split	>-35	>-25	34.5%	EBG Cells	Complex and costly
[29]	[1,3.2]	2:1 equal split	>-16	>-30	44%	Resonator Cells	Complex and costly
[30]	[1,3.1]	2:1 equal split	>-26	>-21	36.5%	Open Stubs	Simple and low cost
[31]	[1.5,2.6]	2:1 equal split	>-37	>-38	55%	Resonator Cells	Complex and costly
[32]	[2.1,3.7]	2:1 unequal split	>-15	>-25	31 %	Short and open stubs	average
[33]	[2.4,2.6]	2:1 equal split	>-16	>-15	70%	Lumped Elements & Resonator Cells	Complex and costly
[34]	[1.5-3.2]	2:1 equal split	>-25	>-30	53%	Transformers Lines	Simple and low cost
This Work	[1.2,3.7]	2:1 equal split	>-28	>-38	75%	Open stubs	Simple and low cost

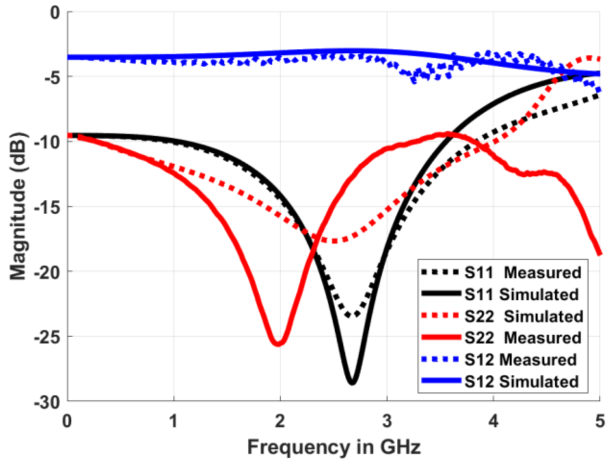

Figure. 12 Measured results of output ports isolation. Measured results of the phase difference

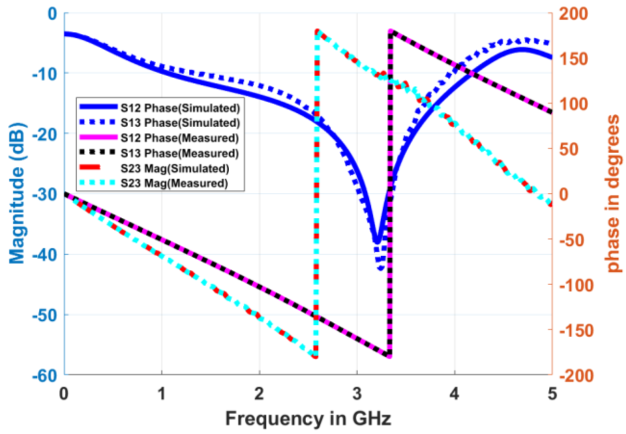

Figure. 13 Measured results of output ports isolation. Measured results of the phase difference

less than -10dB. Similarly, S12 and S13 transmission coefficient measurements are in the -3dB range over the full working spectrum. The isolation between the two output terminals is also greater than -10dB in the 1GHz to 4GHz band.

Fig. 13 depicts the measured phase difference, which shows that there is a little offset between the measurement and the simulation, although the phase difference is always the same for the outputs, confirming the accuracy of the simulation.

To complete this analysis, we can state that, this divider has a single input terminal and two output terminals which can be perfectly matched to the operating frequency if the impedances of the transmission lines making up the divider are correctly selected. The power supplied to P1 is sent to the two output terminals and divided equally into two power signals, P2 and P3. The two output terminals are completely separated from each other, partly by a 100Ω resistor known as the isolation resistor, which ensures that the output signals have zero phase shift. To have a power of 3dB at the output, the line sections must be quarter-wave and have a characteristic impedance of 35.36Ω (because the characteristic impedances of the access ports are 50Ω). Simulation and measured results for the *Sij* magnitude parameters of this splitter show the same magnitude between the two output paths in the [1GHz - 4GHz] band. Outside this band, there is a degradation in the operation of the splitter. These results also show that we have excellent matching for all ports and very good isolation between the output ports. In terms of phase, the output signals on ports P2 and P3 are in phase. The simulated and measured results are in good agreement for the same operating frequencies and there is a shift for other frequencies due to manufacturing, welding of surface resistance, and ports.

The proposed power divider parameters are compared to related works in terms of bandwidth, power output ratio (PDR), matching (RL), isolation (IS), size miniaturization, and the complexity of the method employed in manufacturing. The comparison results are listed in Table 2.

Compared to the conventional structure, the proposed power divider provides excellent isolation across the output terminals and has a high miniaturization rate of around 75%. These results are better than previous techniques used in published work, which achieved maximum miniaturization of around 70%. In terms of bandwidth, the new design offers a wide bandwidth of around 3000 MHz from 1 GHz to 4 GHz. These achievements open up the possibility of using the proposed divider for a wide range of applications since the design is simple to manufacture and inexpensive.

5. Conclusion

In this research, a new design of microwave power divider is conceived and realized based on the open stub transmission line. This microwave power divider has brought excellent characteristics in both electrical and physical parameters, as well as low-cost fabrication. Measurement results revealed an impedance bandwidth of 3000MHz [1GHz-4GHz] offering excellent matching (-28dB) and isolation (-38dB) across the output terminals, covering a wide range of wireless applications. The miniaturization rate is around 75% compared to the traditional structure. These excellent features ensure the suitability of the new power divider for integration into new wireless system technologies for WLAN and 5G applications. As a perspective, our future work will focus on miniature, high-performance multiple-output power dividers and combiners for millimeter-wave bands intended for 6th generation applications.

Conflicts of interest

The authors declare no conflict of interest.

Author contributions

The first and second authors were equally involved in the conceptualization, methodology, formal analysis, writing, and preparation of the original version. The third and fourth authors participated in conceptualization, fabrication, validation, and measurement. All authors participated in writing, revising, and editing the final version.

Notation list

Parameters	Notations
$\boldsymbol{M}_{\frac{\lambda_g}{4}}$	Quarter wavelength transformer chain matrix
A, B, C, D	Chain matrix parameters
Z0 and *Y0*	Characteristic Impedance of the quarter wavelength transformer and its admittance
L and *C*	Inductance and Capacitance of the electrical model of the transmission line
$\boldsymbol{\omega}$	Pulsation of the radio frequency signal
M_T	Chain matrix of T-Model method
M_a	Chain matrix of the principal transmission line of the T-Model method
M_b	Chain matrix of the open-stub
$\boldsymbol{Za}$ and $\boldsymbol{Ya}$	Characteristic Impedance of the principal transmission line of the T-Model and its admittance
$\boldsymbol{Zb}$ and $\boldsymbol{Yb}$	Characteristic Impedance of the open-stub and its admittance
$\boldsymbol{\theta_a}$	Electrical length of the principal transmission line of the T-Model
$\boldsymbol{\theta_b}$	Electrical length of the open-stub
$\boldsymbol{L_a}$ and $\boldsymbol{C_a}$	Inductance and Capacitance of the electrical equivalent circuit of the T-Model principal transmission line
$\boldsymbol{C_a}$	Capacitance of the electrical equivalent circuit of the open-stub

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