

ORIGINAL RESEARCH

Design of super wide band 3-way power divider/combiner

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Abstract

A 1:3-way power divider/combiner has been proposed for much improved bandwidth and isolation between output ports. The matching network for the super wide bandwidth frequency range is designed using a combination of the Klopfenstein taper and the triangular taper. The proposed design yields bandwidth from 1.5 to 20 GHz (18.5 GHz) for return loss better than 15 dB and isolation better than 20 dB. The insertion loss for the entire frequency band is 0.8 dB which is only 0.34 dB for the ultra-wide bandwidth (3.1–10.6 GHz). The maximum phase imbalance of 3.32° and amplitude imbalance of 0.199 dB between all the output ports have been achieved over the entire bandwidth. The simulated results have been validated experimentally.

KEYWORDS

impedance matching, power combiners, power dividers, ultra wideband technology

1 | INTRODUCTION

The power divider and the power combiner are the key passive components in wireless systems. These microwave devices are used in the upcoming 5G technology and help in providing better connectivity. Thus, the research on this useful device is going to increase their bandwidth, reduce the Insertion loss (IL) and improve the return loss (RL) at various ports with improved isolation between output ports. There is emphasis to make power dividers and combiners compact.

A T-shaped power divider and resistive type power divider are not suitable because of the isolation problem at the output ports. The Wilkinson type power divider is the most popular device since it eliminates the limitation of isolation, making the power divider a power combiner as well. In the original form, the working bandwidth of this device is limited to just about 20% [1]. Many modifications have been done on the Wilkinson power divider to increase the bandwidth and to reduce the IL. One method to increase the bandwidth is to replace the single quarter wave transformer by multiple quarter wave transformers. Another method to increase the bandwidth is to use the tapered lines for obtaining ultra-wide bandwidth of the power divider. Using multiple quarter wave transformers, the dual-band 2-way power divider/combiner was designed, which had limited bandwidth at two frequencies [2, 3]. Another broadband power

divider/combiner operating between 0.3 and 2.8 GHz was designed having poor isolation of only 10 dB [4]. The power divider/combiner designed by Chiang and B-K. Chung provided an improved RL and isolation of 15 dB over a frequency range of 2–10.2 GHz [5]. Another design employed a non-uniform transmission line that operated in the frequency range of 3.1–10.6 GHz with a limited isolation of 10 dB [6]. An ultra-wide band power divider was designed having an operating frequency range of 3.1–10.6 GHz [7, 8]. To make the power divider/combiner compact, the quarter wave transformer was realised using lumped elements. Though the reduction in the size was achieved, it had a narrow band response [9]. The concept of coupled lines was employed to design a power divider with improved isolation between output ports upto 20 dB for a narrow bandwidth [10]. Harmonic suppression technology was utilised in the design of the power divider to obtain a wide bandwidth, although the suppression of the harmonics was only between 1.74 and 3.71 GHz [11]. A matching network using a Klopfenstein taper in a power divider yielded bandwidth limited to 1–7 GHz [12], and in refs. [13, 14], the RL was only better than 10 dB. An ultra-wide band power divider was proposed using a stub for matching and a single resistor for isolation. Because of only a single resistor, isolation was compromised [15]. Another stub-matched 2-way power divider with compact dimensions was presented; however, the IL for this divider was poor [16].

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The Wilkinson power divider with a multi-section quarter-wave matching was reported for a broader bandwidth but with increased size of the device [17, 18]. A parallel strip line-based modified power divider was reported, which yielded the operational bandwidth of only about 6 GHz [19]. Further, an ultra-broadband 2-way power divider with a super-compact circuit size was presented utilising silicon-based integrated passive device technology. However, the IL of the device was higher [20]. With quarter-wave matching, an unequal 2-way Wilkinson power divider was presented with poor RL of less than 10 dB [21].

All these reported works are on a 2-way power divider/combiner. Not many optimised designs have been reported on the 3-way power divider/combiner with the improved bandwidth. A multi-layered 3-way power divider was presented utilising the concept electromagnetic coupling. However, this design yielded isolation between output ports less than 15 dB [22]. An unequal 3-way power divider/combiner using the taper line for impedance matching has been reported for the frequency range of 2–12 GHz with RL of only 10 dB and poor isolation was presented [23]. Another 3-way unequal power divider was designed based on the multiple quarter wave transformers, but it only worked in a narrow band at two frequencies [24]. An equal 3-way power divider using the SSPP transmission line was reported for the frequency band of 2–11.8 GHz with poor RL and isolation. [25]. Similarly, various 3-way power dividers/combiners were designed employing different transmission line sections, such as a uniform transmission line [26, 27], 2-stage quarter wave transformers [28, 29] and exponential $\lambda/4$ tapered transmission line transformers [30]. One more 3-way power divider was designed for a frequency band of 1–6.3 GHz, but RL and isolation are just 10 dB [31]. In addition to it, the working frequency of a 3–10-GHz 3-way power divider was designed with good isolation but poor RL [32]. The maximum bandwidth upto 50% was obtained for some of these power dividers/combiners with poor RL, isolation and IL. When the performances of these devices were improved, their bandwidth decreased. The waveguide-based power divider was designed using a tapered rectangular waveguide to work in the frequency range from 12.9 to 14.4 GHz with very high IL of 5.19 dB [33]. A compact planar 3-way power divider was reported. However, its overall performance was compromised [34]. A compact planar 3-way power divider was reported. However, its overall performance was compromised [35]. Another configuration of a 3-way power divider was presented using metamaterial with limited bandwidth [36]. A defected ground structure was employed to design a 3-way power divider, which resulted in higher IL [37]. A parallel-coupled microstrip line-based 3-way power divider with ultra-wide band performance had been reported, which yielded relatively poor impedance matching with RL of only 13 dB and lower isolation [38].

There are some of the reported designs of the power divider/combiner, where the tapered line matching networks have been used. But, none of them have yielded improved performance over the super ultra-wide bandwidth. In the proposed 3-way power divider/combiner, for the first time, the combination of the Klopfenstein taper and triangular taper with 10 isolation

resistors has been used to achieve much improved overall performance. The Klopfenstein taper is divided into 5 sections, and each section of the taper is now designed as a triangular tapered line. This novel configuration has yielded a super wide bandwidth with lower RL, minimal IL, high isolation and much improved amplitude and phase balance simultaneously throughout the super wide bandwidth. Bandwidth achieved is 18.5 GHz with RL better than 15 dB and isolation between the output ports is better than 20 dB. The IL is 0.34 dB in the conventional ultra-wide band frequency range of 3.1–10.6 GHz, which is only 0.8 dB in the entire frequency range of 1.5–20.5 GHz with extremely low amplitude and phase imbalances between three output ports. This type of superlative overall response for the 3-way power divider/combiner is achieved for the first time. This device is designed for the microwave distribution network including 5G applications.

2 | DESIGN OF POWER DIVIDER/COMBINER

In a 1:3-way power divider/combiner, the 50- Ω impedance of three output ports has to be transformed to the value of 150- Ω impedance so that the three together will result in 50- Ω impedance at the input port. Isolation resistances between three output ports ensure their isolation so that a power divider also acts properly as a power combiner.

2.1 | Design of matching network

A power divider/combiner with the multi-section tapered line matching network yields an ultra-wide bandwidth. In the present work, a new type of matching network is designed using the combination of the Klopfenstein taper and the triangular taper. In the Klopfenstein taper, one can choose the maximum allowable reflection coefficient. This is considered as superior among all the tapered lines because better matching is achieved with the optimum length. As suggested in ref. [39], the Klopfenstein tapered line has varying characteristic impedance along with its length as given in

$$\ln Z(z) = \frac{1}{2} \ln Z_0 Z_L + \frac{\Gamma_0}{\cosh A} A^2 \phi\left(\frac{2z}{L-1}, A\right) \quad (1)$$

for $0 \leq z \leq L$

The function $\phi\left(\frac{2z}{L-1}, A\right)$ is defined as Bessel function $\phi(z, A)$

$$\phi(z, A) = -\phi(-z, A) = \int_0^z \frac{I_1(A\sqrt{1-y^2})}{A\sqrt{1-y^2}} dy; \text{ for } |z| \leq 1$$

I_x is the modified Bessel function. This function takes the following special values.

- $\phi(0, A) = 0$
- $\phi(z, 0) = \frac{z}{2}$
- $\phi(1, A) = \frac{\cosh A - 1}{A^2}$

If a function does not take special values, it should be calculated numerically. The total internal reflection of the Klopfenstein taper is given in

$$\Gamma(\theta) = \Gamma_0 e^{-i\beta L} \frac{\cos \sqrt{(\beta L)^2 - A^2}}{\cosh A} \text{ for } \beta L > A \quad (2)$$

If the $\beta L < A$, then $\cos \sqrt{(\beta L)^2 - A^2}$ becomes $\cosh \sqrt{(\beta L)^2 - A^2}$ and the reflection coefficient at the zero frequency with the load impedance of Z_L and input impedance of Z_I will be Γ_0

$$\Gamma_0 = \frac{Z_L - Z_I}{Z_L + Z_I} \approx \frac{1}{2} \ln \left(\frac{Z_L}{Z_I} \right) \quad (3)$$

When $\beta L \geq A$, then it is considered as a passband where the maximum ripple in the passband is given in the Equation (4). By obtaining the maximum ripple, the deciding factor (A) can be obtained by Equation (5)

$$\Gamma_m = \frac{\Gamma_0}{\cosh A} \quad (4)$$

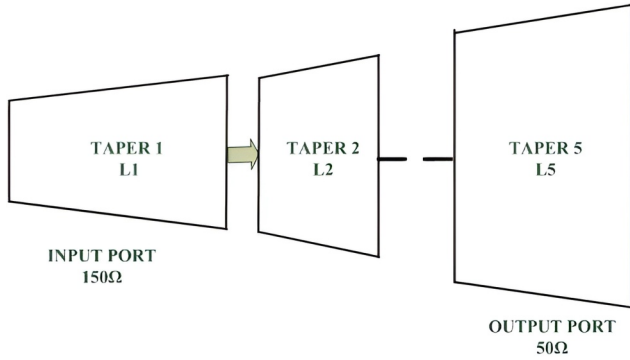


FIGURE 1 Design of the taper section.

$$A = \cosh^{-1} \frac{\Gamma_0}{\Gamma_m} \quad (5)$$

If $\beta L \geq A$ then Γ_0 oscillates between $\pm \Gamma_m$. While designing the Klopfenstein taper, this condition should be satisfied. Here A is a deciding factor for the length of the tapered line. A in turn depends on the maximum allowable reflection (Γ_m), the reflection coefficient at zero frequency (Γ_0) and lower cutoff frequency (f). The length of the tapered line is calculated using

$$L \geq \frac{A}{\beta} \quad (6)$$

The length of the Klopfenstein taper should be greater than the ratio of phase constant (β) and the deciding factor (A). After designing the Klopfenstein taper for the present case, it is divided into 5 parts. These small parts are designed as the triangular taper lines for better matching. With respect to ref. [40], the reflection coefficient of the triangular taper is given as Equation (7).

$$\Gamma_\theta = \frac{1}{2} e^{-i\beta L} \ln \left(\frac{Z_L}{Z_0} \right) \left(\frac{\sin \left(\frac{\beta L}{2} \right)}{\frac{\beta L}{2}} \right)^2 \quad (7)$$

$$\Gamma_\theta \propto \left(\frac{\sin \left(\frac{\beta L}{2} \right)}{\frac{\beta L}{2}} \right)^2$$

When $\beta L = 2\pi$ then there will be less reflection loss. So $\beta L \geq 2\pi$ is chosen. Now, each segment is designed by following the above condition for less reflection loss. The length of each triangular tapered line is optimised using the simulator CST Microwave studio. Figure 1 shows the design of the matching network between the input and output port by using a combination of the Klopfenstein taper and the triangular taper.

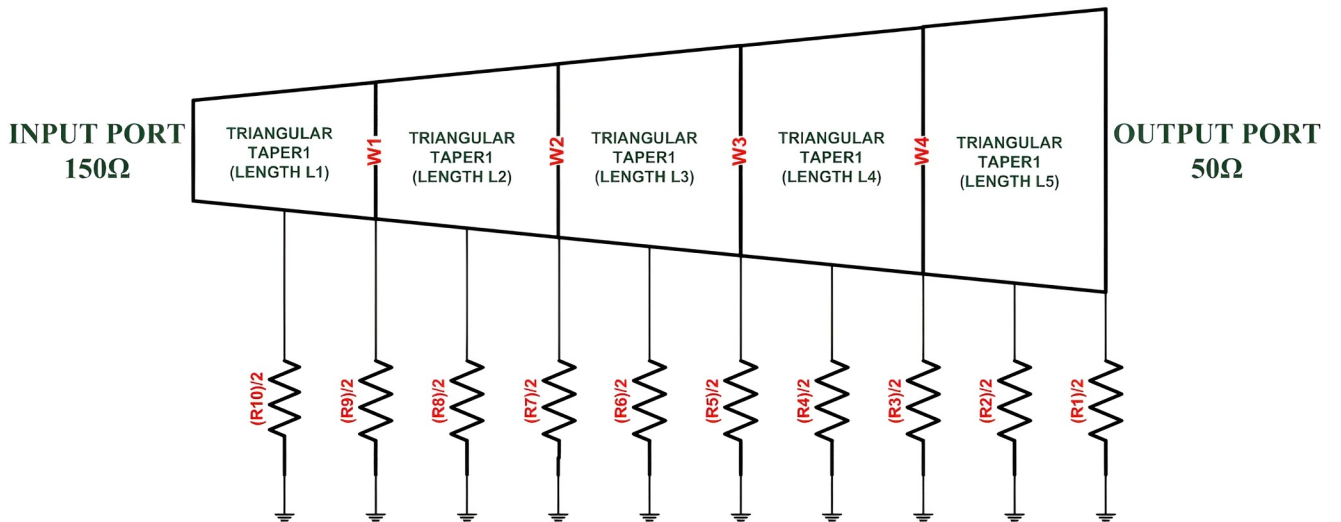


FIGURE 2 Design of the taper section with resistors placement.

2.2 | Isolation between the output ports

In a single-stage Wilkinson power divider/combiner, the calculation of the isolation resistor is straight forward. But, when it comes to a multi-stage transformer, the calculation of isolation resistor values in this design is very involved. So, the values of the isolation resistors are found by the optimisation method using the CST design studio for the desired isolation of 20 dB. In ref. [5], values of resistors were arrived at through optimisation. Initial values of isolation resistors are determined by using odd mode analysis in ref. [41]. To get the realisable values of these isolation resistors for fabrication, further optimisation has been carried out using the CST studio.

TABLE 1 Values of 10 isolation resistors in ohms (Ω) between 2 ports.

R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
600	600	600	500	500	500	400	400	400	200

TABLE 2 Calculation of each section of the tapered line.

Characteristic impedance(Ω)	Width of the line (mm)	Effective Dielectric (ϵ_e)	Wavelength (mm)
150	0.1803	1.70	230.01
102.68	0.603 (W1)	1.75	226.78
92.97	0.765 (W2)	1.76	226.13
74.69	1.208 (W3)	1.80	223.61
61.63	1.705 (W4)	1.83	221.77
50	2.321	1.87	219.38

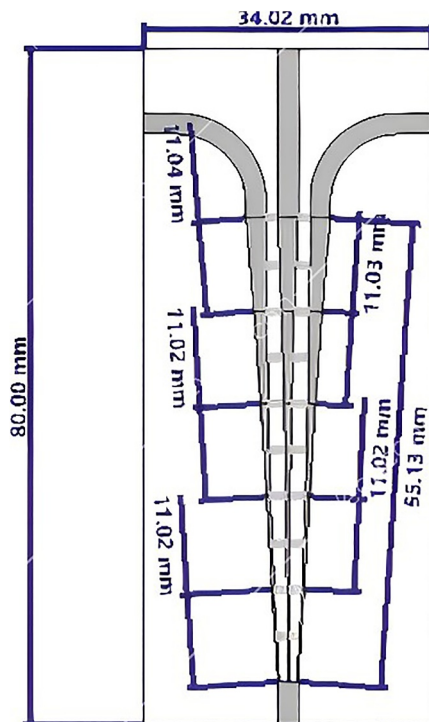


FIGURE 3 Simulated design layout in CST.

The same technique has been employed for the realisation of values of the resistors, starting with a higher value from the output side to the lower value towards the input side. These resistors and their placements are shown in Figure 2. Proper isolation between three output ports is ensured so that the proposed power divider also works as a power combiner over the super ultra-wide bandwidth. In the proposed design, for a super wide band response, 10 isolation resistors have been used. The number of resistors depends on the number of sections of the tapered lines and their length. As the number of resistors in between the output ports increases, the isolation bandwidth also

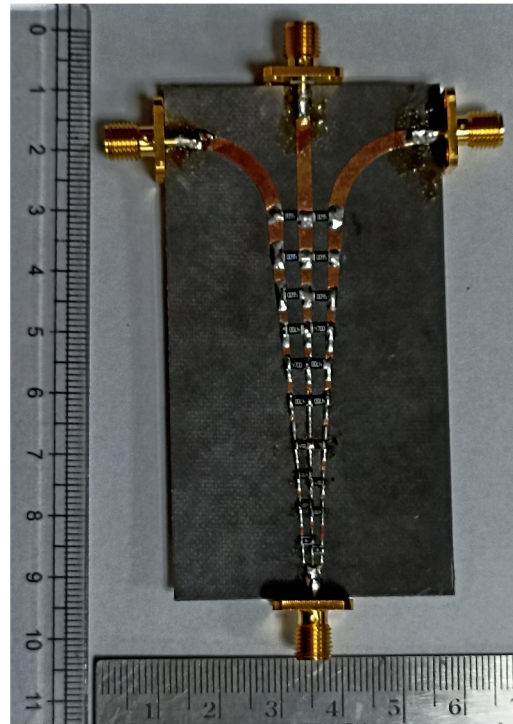


FIGURE 4 Photograph of the fabricated 3-way power divider/combiner.

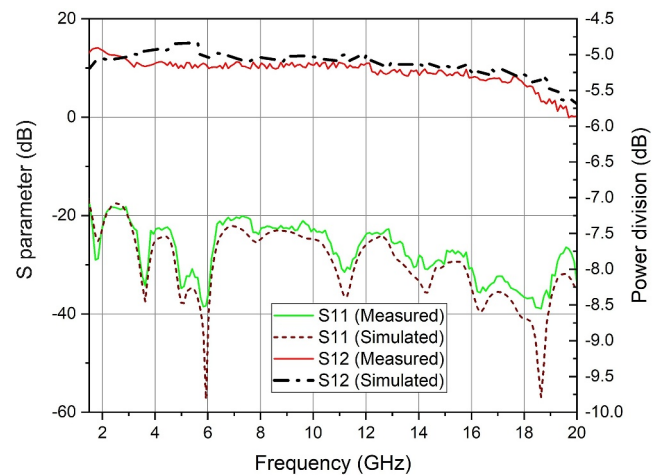


FIGURE 5 Simulated and measured results of reflection coefficient of port 1 and power division of 3-way power divider/combiner.

increases. In the proposed design, resistors are placed at the end of every triangular tapered section and also at the middle of the triangular taper line using 10 resistors. Placements and values of each of the isolation resistors are optimised through simulations, which are listed in Table 1. In total, 20 resistors are required to isolate all the three output ports.

The optimisation process has been carried out with the target of isolation between output ports of 20 dB or better than 20 dB throughout the entire band of frequency of 1.5–20 GHz, keeping RL of 20 dB and IL as low as possible.

3 | RESULTS AND DISCUSSIONS

The design of the 3-way power divider/combiner has been simulated by using the CST microwave studio. A 4.8 dB 3-way power divider is designed on the RT Duriod 5880 substrate with a thickness of 0.787 mm $\epsilon_r = 2.2$ and $\tan\delta = 0.001$. The 50 Ω output ports with respective widths of 2.321 mm are transformed to 150 Ω having a width of 0.1803 mm with a tapered section whose width is constantly changed throughout the length. The total length of the tapered line has been calculated from Table 2, which shows the widths of each section. After the calculation is done, it is carefully optimised to achieve a super ultra-wide bandwidth. The maximum allowable reflection (Γ_m) is 0.01, which means 99% power is transferred and only 1% is reflected. The lower working frequency is 1 GHz. In accordance with the conditions, the determining factor (A) is calculated as 4.699 using Equation (5). From Equation (6), the length of Klopfenstein taper (L) is calculated as 172.01 mm. This Klopfenstein taper is divided into 5 equal sections. Each section has a triangular taper design. This combination results in a 55-mm taper line, which has a reduction in length. As the power divider/combiner has been designed in microstrip configuration on the

dielectric substrate with dielectric constant ($\epsilon_r = 2.2$), which reduces the dimension of the device. Additionally, when the single quarter wave Klopfenstein taper is designed, its length is 172.01 mm. This total length is divided into five equal sections of triangular taper. With the placement of resistors and further optimisation, the total length of five sections reduces to 55 mm, making the device compact. The final design layout is shown in Figure 3. The length of each triangle taper is optimised using the CST microwave studio, which are $L_1 = 11$ mm, $L_2 = 11$ mm, $L_3 = 11$ mm, $L_4 = 11$ mm and $L_5 = 11$ mm.

Figure 4 shows the photograph of the fabricated 3-way equal power divider/combiner. Figures 5–7 compare the simulated and measured plots of S-parameters of all the plots of the 3-way power divider/combiner. There is a very good match between simulated and measured results over the entire bandwidth of 1.5–20 GHz. The RL of the input port is better

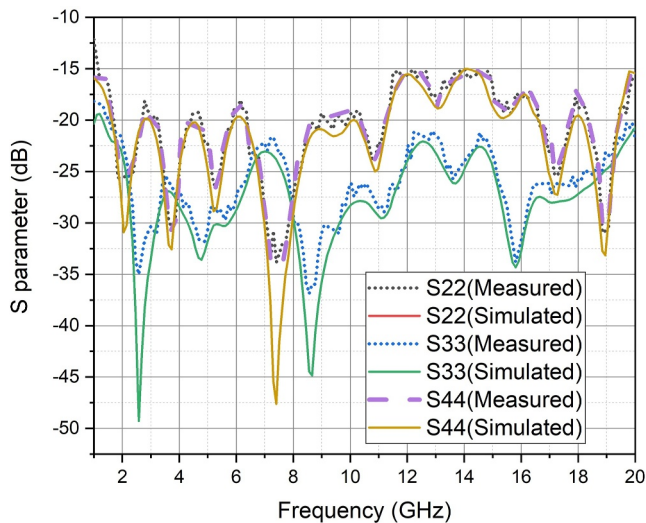


FIGURE 6 Simulated and measured results of the reflection coefficient of port 2, port 3 and port 4 of the 3-way power divider/combiner.

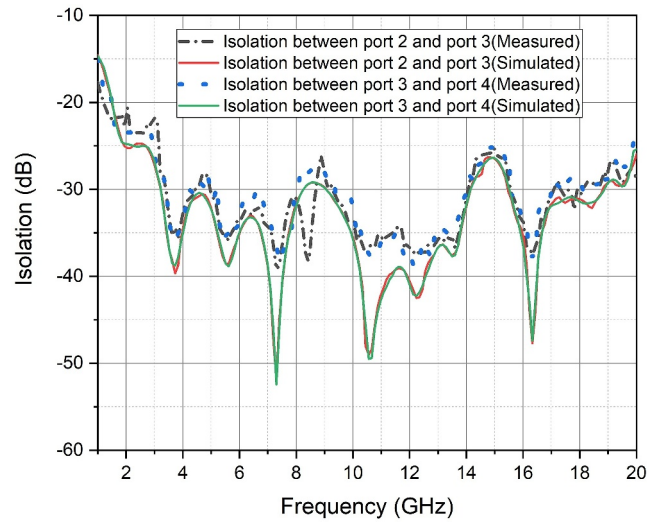


FIGURE 7 Simulated and measured results of isolation between all 3 ports.

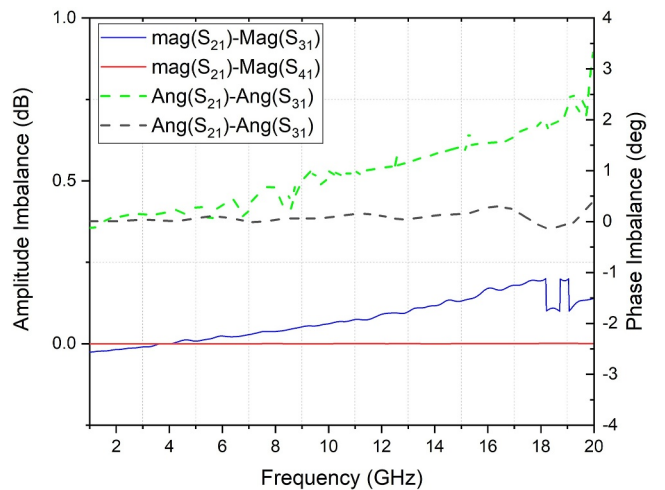


FIGURE 8 Magnitude and phase imbalance at output ports of the 3-way power divider/combiner.

TABLE 3 Performance comparisons of the proposed 3-way power divider/combiner with the previous work.

References	Frequency range for RL $\leq$ 15 dB	Total bandwidth	Bandwidth ratio	Insertion loss	Isolation	Amp imb	Ph imb	Dimensions (mm)
[22]	2.0–12.0 GHz	10.0 GHz	1:6.0	1.0 dB	15 dB	N/A	N/A	$l = 30; w = 20$
[23]	3.0–12.0 GHz	9.0 GHz	1:4.0	N/A	10 dB	N/A	N/A	$l = 59.18; w = 11.81$
[24]	1.0–2.0 GHz	1.0 GHz	1:2.0	N/A	N/A	0.2 dB	0.3°	$l = 81; w = 62$
[25]	3.4–5.5 GHz	2.1 GHz	1:1.6	6.5 dB	9 dB	N/A	9.0°	$l = 345.8; w = 324.4$
[26]	0.7–1.4 GHz	0.7 GHz	1:2.0	N/A	N/A	N/A	N/A	$l = 53.9; w = 47.9$
[27]	3.0–4.0 GHz	1.0 GHz	1:1.3	0.4 dB	20 dB	N/A	N/A	N/A
[28]	16.5–23.8 GHz	7.3 GHz	1:1.4	0.2 dB	11.8 dB	N/A	N/A	N/A
[29]	1.2–1.8 GHz	0.6 GHz	1:1.5	0.4 dB	14.9 dB	N/A	N/A	$l = 60$
[31]	5.5–7.2 GHz	1.7 GHz	1:1.3	0.8 dB	10 dB	N/A	5.0°	$l = 28.83; w = 32$
[32]	3.0–10.0 GHz	7.0 GHz	1:3.3	5.8 dB	25 dB	N/A	N/A	$l = 60; w = 33$
[33]	12.4–15.0 GHz	2.6 GHz	1:1.2	5.2 dB	20 dB	0.4 dB	N/A	N/A
[34]	1.7–3.2 GHz	2.5 GHz	1:1.9	4.8 dB	17.5 dB	N/A	N/A	$l = 43; w = 28$
[35]	2.1–3.1 GHz	1.0 GHz	1:0.68	1.5 dB	10 dB	N/A	N/A	$l = 35; w = 12$
[36]	1.0–2.2 GHz	1.2 GHz	1:2.2	N/A	10 dB	N/A	N/A	N/A
[37]	1.8–2.8 GHz	1.0 GHz	1:1.56	5.2 dB	N/A	N/A	N/A	$l = 26.5; w = 20.8$
[38]	3.0–11.0 GHz	8.0 GHz	1:3.67	N/A	15 dB	1 dB	N/A	$l = 25 \text{ mm}; w = 25$
Proposed work	1.5–20.0 GHz	18.5 GHz	1:13.3	0.8 dB	20 dB	0.2 dB	3.32°	$l = 80; w = 34.02$

than 20 dB and the RL of the output ports is better than 15 dB. The isolation between all the three output ports is better than 20 dB including isolation between ports 2 and 4. Insertion loss at all the three output ports is less than 0.8 dB for the whole bandwidth of 18.5 GHz and only 0.34 dB for the ultra-wide band frequency. The device is designed for broadband applications. To minimise the radiation loss in the circuit, at the design stage itself, the thickness of the substrate is chosen as 0.8 mm. The radiation loss has been calculated using ref. [42]. For the maximum width of 2.321 mm, the radiation loss comes out to be 0.00,093 dB at the lower frequency (1.5 GHz), which increases to 0.167 dB for the higher frequency of 20 GHz, because of increased electrical thickness. This also contributed to higher IL of the device at the higher frequency end of the bandwidth. Figure 8 shows the phase and amplitude imbalance between three output ports. It has a very less phase imbalance of 3.32° (maximum) and amplitude imbalance of only 0.199 dB, showing much balanced three ports over the entire bandwidth range of 18.5 GHz. There is a slightly higher phase imbalance due to the increased length at port 2 and port 4 with respect to that of port 3 because of bending in output ports and fabrication inaccuracies. This is much improved performance of the 3-way power divider/combiner reported so far.

Table 3 gives the performance comparison of the proposed 3-way power divider/combiner with earlier reported configurations. As noted from the comparison, the proposed device has a super wide bandwidth with more than 100% increase in bandwidth as compared to any of the reported 3-way power divider/combiner configurations. The proposed novel design

yielded super wide bandwidth with low RL, high isolation of greater than 20 dB, minimal IL of less than 0.8 dB and least amplitude and phase imbalance between output ports concurrently throughout the super wide bandwidth.

4 | CONCLUSION

A microstrip line-based 3-way equal power divider/combiner having the super wide bandwidth is proposed in this paper. The combination of the Klopfenstein taper and the triangular taper is used for matching network. Because of this combination, the optimised length of the tapered line becomes compact. The length of each triangular taper of total five sections, along with values and placement of 10 isolation resistors, are optimised to have perfect impedance matching over the entire super ultra-wide bandwidth. The isolation between all the three output ports is better than 20 dB and RL is better than 15 dB throughout the frequency band with very low IL. This compact device can have many applications in small electronic systems.

AUTHOR CONTRIBUTIONS

Nagarakshith Mungara: Conceptualization; methodology; writing—original draft. **Kamla Prasan Ray:** Supervision; validation; writing—review and editing.

CONFLICT OF INTEREST STATEMENT

None.

DATA AVAILABILITY STATEMENT

Research data are not shared.

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How to cite this article: Mungara, N., Ray, K.P.: Design of super wide band 3-way power divider/combiner. IET Microw. Antennas Propag. 1–8 (2024). <https://doi.org/10.1049/mia2.12504>



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2024-11

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<https://doi.org/10.1049/mia2.12504>

Mungara N, Ray KP. (2024) Design of super wide band 3way power divider/combiner. IET Microwaves, Antennas & Propagation, Volume 18, Issue 11, November 2024, pp. 830-837