Design of Reconfigurable Power Dividers with Wide Tuning Ranges

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ABSTRACT

This paper presents and investigates a novel two-way power divider design with controllable operating frequenciesby adding a pair of capacitorsin parallel with the transmission lines in a Wilkinson power divider. This methodcan either providea tunable bandwidth by introducing an extra in-band reflection zero, or provide areconfigurable single operating frequency. Two circuits arefabricated to validate the method. For thebandwidth tunable power divider, the added zero- reflection frequency is sensitive to the capacitors so that the bandwidth can be tuned by altering the capacitance of the capacitors. Measured results indicate that the device has a 15-dB fractional bandwidthvarying from 0 to 93%.For thecenter frequency tunable power divider, the single operating frequency also has high sensitivity to the capacitance. The measured tunable center frequency range is$\boldsymbol{f_{Max}}$:$\boldsymbol{f_{Min}}$=4.67:1.

I. INTRODUCTION

Power dividers are essential components for many microwave applications in communication systems, such as antenna arrays and power amplifiers. The features of power dividers in terms of bandwidth, circuit size, insertion loss and isolation will significantly influence the overall performance of the communication system. A Wilkinson-type power divider [1] is one of the most widely used dividers due to its simple structure and low insertion loss.Base on the Wilkinson-type power divider, many wideband, multi-band or frequency tunable power dividers have been designed. Nowadays, frequency-tunable devices are attracting more and more attention because that a single device can be operated over diverse operating frequency bands [2][3][4].However, many designs suffer from complexity of circuits, big size or very limited tuning bandwidth.

This paper introduces a simple and effective method for reconfigurable power divider designs. By applying capacitors in parallel with the main transmission lines, either the bandwidth or the center frequency can be tuned. The detailed design method is presented and explained in this paper, to developa bandwidth tunable power divider and a center frequency tunable power divider.

II. DESIGN OF THE NOVEL POWER DIVIDER

A. Bandwidth Tunable Power Divider

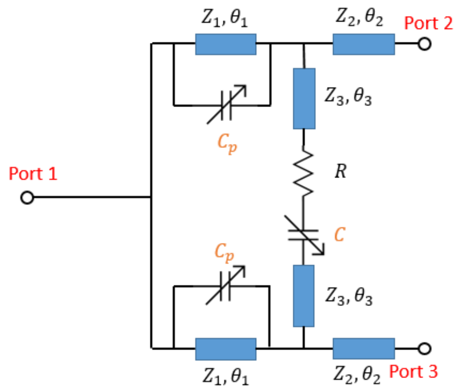


Fig.1

Fig. 1. The proposed bandwidth tunable power divider is designed by adding a pair of capacitors C_P to a Trantanella-type two-way power divider.

Fig. 1shows the structure of the proposed bandwidth tunable power divider.A pair of capacitorsare placed in parallel with the main transmission lines of the Trantanella-type divider[5]. By adding the two capacitors, an additional zero-reflection frequency point can be achieved as defined in our previous work [6]. The characteristic impedances ofthe transmission lines arenormalized to port impedance 50 Ω and the frequency is normalized to the original center frequency $f_o = 1$ GHz. $\overline{C_P}$denotes the normalized capacitance.θ_1, θ_2, and θ_3 represent electrical lengths of the transmission lines at 1 GHz $\overline{Z_1}, \overline{Z_2},and\overline{Z_3}$ are the normalized characteristic impedance of the transmission lines. To simplify the design calculation, let $\overline{Z_1} = \overline{Z_2} = \overline{Z_3} = \sqrt{2}$.Based on the perfect impedance matching condition, the relationship between zero-reflection frequency $\overline{f_z}$ and the capacitance $\overline{C_P}$ can be obtained by:

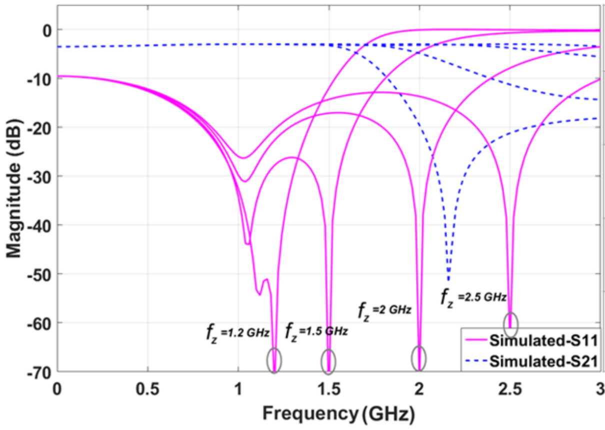
$$2\pi\overline{f_z}\cdot\overline{C_P}=\frac{\tan(\theta_3\overline{f_z})(\tan(\theta_1\overline{f_z})\tan(\theta_2\overline{f_z})+1)}{\sqrt{2}(\tan(\theta_1\overline{f_z})\tan(\theta_3\overline{f_z})+\dfrac{2}{\cos(\theta_1\overline{f_z})}-2)} \quad (1)$$

At the same time, the relationship between θ_i (i=1,2,3)and $\overline{f_z}$ can be expressed as:

$$\frac{\dfrac{\tan(\theta_3\overline{f_z})\tan(\theta_1\overline{f_z})+1}{\tan(\theta_2\overline{f_z})}-2\tan(\theta_3\overline{f_z})-\tan(\theta_1\overline{f_z})}{\dfrac{\tan(\theta_1\overline{f_z})}{\tan(\theta_2\overline{f_z})}-2\tan(\theta_3\overline{f_z})\tan(\theta_1\overline{f_z})+4-\dfrac{4}{\cos(\theta_1\overline{f_z})}}=\frac{\tan(\theta_2\overline{f_z})\tan(\theta_1\overline{f_z})+1}{\dfrac{\dfrac{2}{\cos(\theta_1\overline{f_z})}-2}{\tan(\theta_3\overline{f_z})}+\tan(\theta_1\overline{f_z})} \quad (2)$$

Good physical isolation between two output ports can be realized by connecting a pair of short-length-transmission lines Z_3between the front transmission lines and the isolation circuit consisting of a capacitor C and a resistor R. The good physical isolation not only separates the upper and lower output ports, but also suppresses the undesired coupling between them. The design of the isolation circuit is explained further in Section C.

To simplify the design, the following restrictive conditions are assumed.For Trantanella dividers, there is usually the condition of $\theta_2=90°-\theta_1$.For practical applications, the electrical length of the additional transmission lines θ_3 could be any value but is usually chosen between0° to 15°referringto[7]. In this paper, θ_3 is chosen as7°.For any chosen zero-reflection frequencyf_z($1<\overline{f_z}<3$),θ_1 can be obtained from (2), given that $\theta_2=\pi/2-\theta_1$ and θ_3 is a fixed value. Now capacitance C_p can be calculated by using (1).



f_0 (GHz)	C_p (pF)	θ_1 (degree)
1.2	1.08	34.2
1.5	0.52	45
2	0.16	56.8
2.5	0.015	62.1

Fig. 2. The tendency of additional zero-reflection frequency changing with different $C_P$and θ_1.

Fig. 2 shows the variation tendency of the additional zero-reflection frequency with different $C_P$and θ_1. The original center frequency is assumed to be 1 GHz. By adding the additional capacitors C_P, f_z is varied from 1.2 GHz to 2.5 GHz while the reflection coefficient at the original center frequency is no longer zero (-∞ in dB), but the value is still very low (< -20 dB).The minimum of the return loss $S_{11}$is changed slightly from the original center frequency, but still very close to 1 GHz ($1<\overline{f}$<1.12).It can be observed from Fig. 2, the difference between f_0 and f_z can extend the return loss bandwidth significantly. It can be seen that the higher f_z is, the worse the in-band return loss is. The proposed wideband power divider can achieve optimized bandwidth by properly choosing the design parameters. It has been demonstrated in the previous work [6] that the 15-dB fractional bandwidth can be tuned from 0% to 93%. .

B. Center Frequency Tunable Power Divider

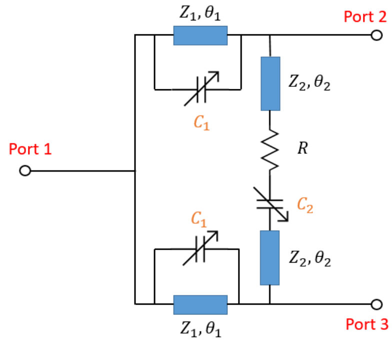


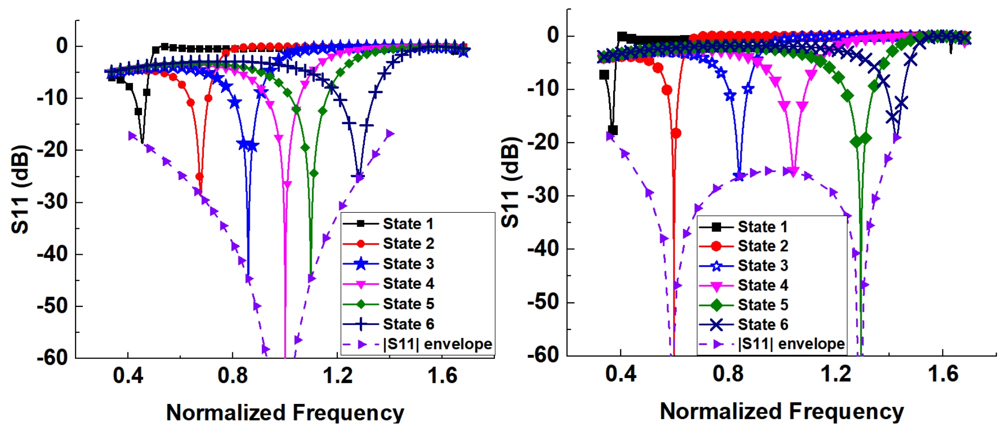
Fig.3. The proposed center frequency tunable divider.

Fig.3presents anovel center frequency tunable divider. As Fig.3illustrates, a pair of varactors are added in parallel with the main transmission lines of the Horst-type power divider[8]to realize tunability.C_1represents the capacitance of the added varactor diodes on the front transmission lines while$C_2$is the capacitance of the varactor diode on the isolation circuit which connected in series with the resistor.Let θ_1 andθ_2 be independent variables, θ_1 can be assigned to determine the operational frequency while θ_2 should be chosen from small valuessuch as $0^\circ \leq \theta_2 \leq 20^\circ$ to simplify the layout for practical applications. Moreover, it is necessary to bend the front transmission lines for placing the varactors in parallel with them to achieve a compact size. Hence, Z_1 should not be too large and the length should not be too short. It means that the ratio of length and the width of the front transmission lines should be large. The main difference of this design from the one shown in Fig. 1 is that the pair of transmission lines Z_2 in Fig. 1 are no longer used. As a result, the power divider will have a tunable center frequency, rather than a tunable bandwidth. To determine the zero-reflection frequencyf_z, the relationship between the front and short-length transmission linesshould satisfy:

$$\overline{Z_1} = \frac{\left(2\overline{P}+\sqrt{8P^2+2}\right)\sin(\theta_1\overline{f_Z})}{\left(\cos(\theta_1\overline{f_Z})+1\right)\cdot\left(2\overline{P}^2+1\right)} \quad (3)$$

$$\overline{P} = \frac{\tan(\theta_1\overline{f_Z})}{\overline{Z_2}} \quad (4)$$

If (3) and (4) are satisfied, the input port will be well matched at the target frequencyf_z.When the capacitance decreases, the center frequency will move to a higher frequency. The reflection minimum varies by following a certain trail which is called envelope curve of the S_{11} minima. The envelope can be changed by altering the impedance of the front transmission lines. Fig. 4(a) shows that the envelope curve just has one minimum with Z_1 equal to Z_{match}. It means that when C_P is changing, only one reflection zero will be generated. If Z_1 decreases slightly (Z_1=α·Z_{match}, α< 1), as shown in Fig. 4(b) there will be two reflection zero frequencies generated. The relationships amongZ_1, Z_2 and reflection zero frequencies can be summarized as shown in Fig. 5. When Z_2 is chosen, the difference between the two reflection zero frequencies in the envelope curve is enlarged if Z_1 decreases. The difference between the two reflection minima of the envelope curve determines the center frequency tuning range. By properly choosing design parameters, the center frequency tuning range can be greatly broadened. Then, the corresponding capacitance of the varactor diodes can be calculated accordingly. Fig.6depicts an example of the required capacitance C_1 and C_2 for a wide frequency tuning band.



(a)(b)

Fig. 4. Theoritical S_{11} envelope curves for different impedance of front transmission lines (a) Z_1=Zmatch, (b) Z_1=α·Zmatch.

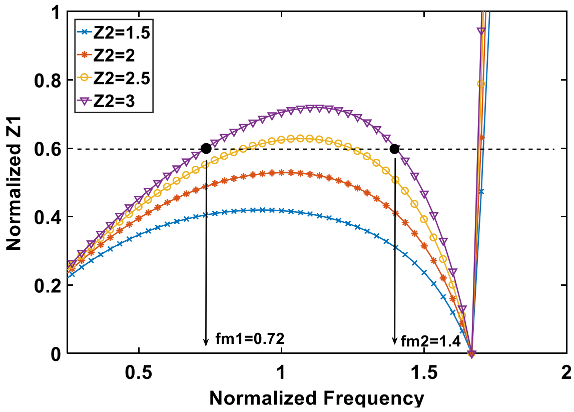


Fig. 5. Theoretical reflection zero frequency curve with changing Z_1 and Z_2

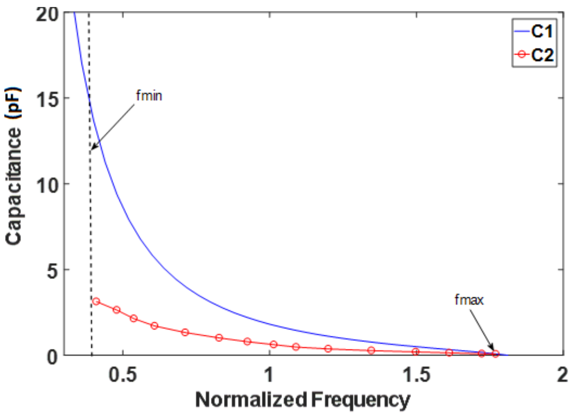


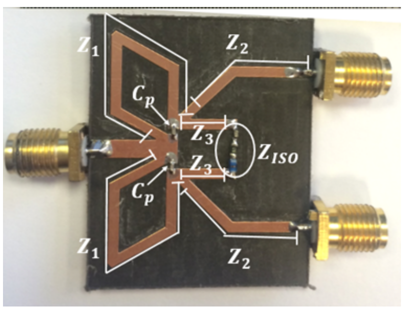
Fig.6. Required capacitance C_1 and C_2 versus normalized frequencies in the tuning band with $\overline{Z_2}$ =2 when $\overline{Z_1}$=0.4, $\theta_1 = 30°$ and$\theta_2 = 18°$.

C. Design of the Isolation Networks

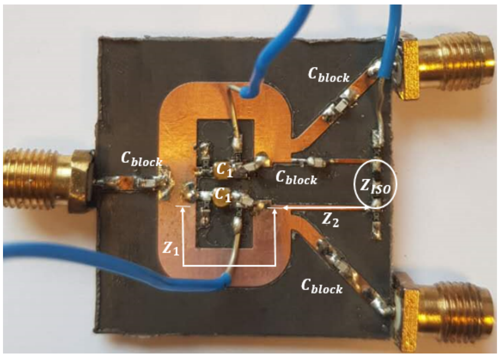
The design parameters on the isolation circuit can be calculated under the condition of impedance matching for output ports. The output impedance should be equal to the port impedance at the center frequencyf_0. The total impedance of the isolation network Z_{ISO}can be determined by substituting the design parameters of the transmission lines that have been described in the previous section. The relationship between R, C and other parameters in terms of perfect isolation between output ports 2 and 3 can be found through analysing the isolation using the method that was presented in [9]. The total admittance between both ends of the isolation circuit is zero when the circuit is perfectly isolated.

III. FABRICATION AND MEASUREMENTS RESULTS

The proposed two power dividers are designed and fabricated on a Rogers RT/5880 substrate with ε_r=2.2 as shown in Fig. 7(a) and(b), respectively.The thickness of the substrate is 0.79 mm and the conductor cladding is 35 μm thick.The circuit is measured by a vector network analyser Agilent FieldFox N9917A.



(a)



(b)

Fig. 7. Photograph of proposed (a) wideband power divider, (b) center frequency tunable power divider.

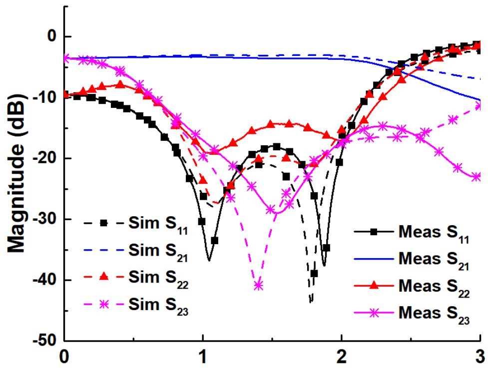
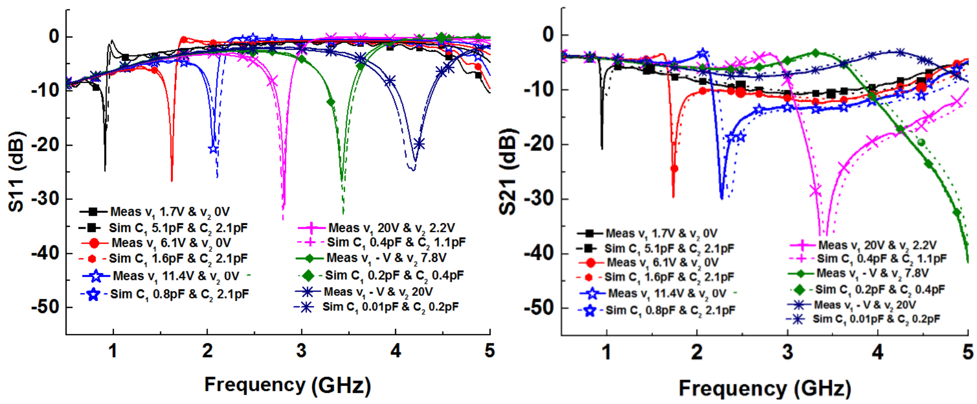


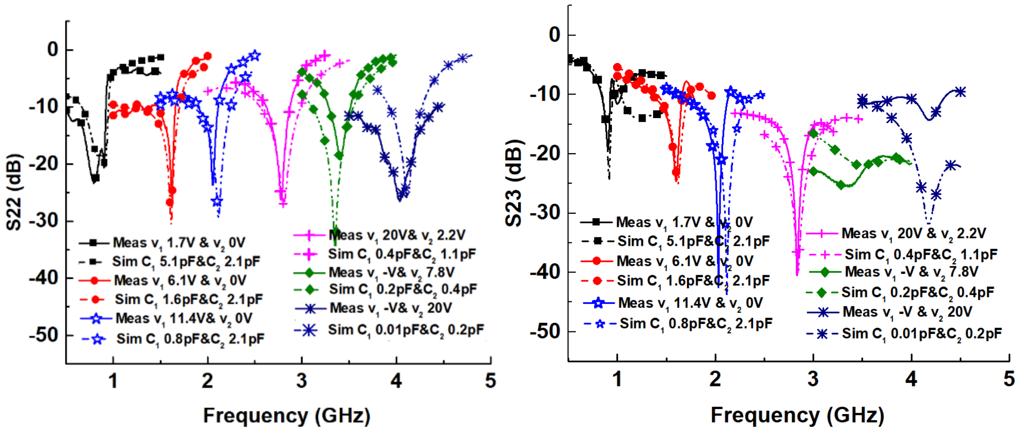
Fig. 8. Measurement and simulation comparison of wideband power divider.

The original center frequency of the bandwidth tunable power divider is designed to bef_0= 1 GHz. Firstly,$\theta_3 = 7°$ and$Z_1 = Z_2 = Z_3 = 70.7\ \Omega$ arechosen.Then, to introduce an additional zero-reflection frequencyf_Z at 1.8 GHz, the electrical length of the transmission lines and the capacitanceC_P are calculated using (1) and (2) as$\theta_1 = 58°$ andC_P= 0.2 pF.The optimized lumped elements used in the isolation circuit are chosen asR=130 Ω, C_s=1.2 pF based on isolation circuit analysis and the EM optimization.The fabricated circuit has a compact size of 29 mm × 32 mm and the two output ports are widely apart.

The measured results of the wideband power divider withC_P=0.2 pF is shown inFig. 8. It can be seen that a reflection zero is generated as expected. In the measurement, the 15-dB-return-loss bandwidth starts from 0.7 GHz to 2.1 GHz. The fractional bandwidth is 100% ($f_{H-15\,dB}/f_{L-15\,dB} = 3:1$), which is much greater than that of a traditional Wilkinson power divider or typical Trantanella ones. In terms of reflection and isolation performance, S_{22} and S_{23} are also very good (<-15 dB) in the desired operational band as Fig. 8shows. The measured insertion loss S_{21} is flat at around -3 dB over the whole operational band. The measurement results are in very good agreement with the simulation ones. The bandwidth can be tuned by changing the capacitance ofC_P as shown in Fig. 1[6].



(a) (b)



(c) (d)

Fig. 9. Measurement and simulation comparison center frequency tunable power divider (a) S_{11}, (b) S_{21}, (c) S_{22}, (d) S_{23}.

For the center frequency tunable power divider, the electrical lengths are $\theta_1 = 30^\circ$and $\theta_2 = 18^\circ$ at 1 GHzand according to (2) the corresponding characteristic impedances of the circuit are chosen as$Z_1 = 20.3\ \Omega, Z_2 = 120\ \Omega$. Resistor R on the isolation circuit is chosen as 100Ω according to the isolation network analysis. Based on the previously calculated values of C_1 andC_2, surface mount tuning varactors MA46H202 (7-0.5 pF) are chosen forC_1, while C_2 is realized by varactor diode SMV2202 (2.1-0.23 pF). Because the capacitance range of these varactor diodes cannot cover the tuning range of C_1 and C_2, additional capacitors of 0.01 pF and 0.2 pF are used here. Fig. 7(b) shows the fabricated circuit with bias circuits supplying voltages to the diodes. The front transmission lines are bentin order to connect the varactors in parallel with them. There are three DC bias circuits applied to the divider. The 20 pF capacitors and 10 kΩ resistors are used for the DC block and RF block in the bias circuits, respectively. Six sampled operating frequencies are chosen at 0.9 GHz, 1.7 GHz, 2.1 GHz, 2.8 GHz, 3.45 GHz and 4.2 GHz.

Fig. 9(a)-(d) show the comparison of simulated and measured S-parameter responses for the six sampled frequency bands. The measured S_{11} and S_{22} are below -20 dB at each sampled frequency band. The insertion loss varies between -3.2 dB and -4 dB. Fig. 9(a) and (d) plot the S_{22} and S_{23} curves at the interested frequency ranges. The measured isolation $S_{23}$is below -20 dB at most of the frequencies, while the S_{23} equals to -17 dB at 4.2 GHz, that is probably caused by fabrication error and the accuracyofC_2. The measured tunable operating frequency ranges from 0.9 GHz to 4.2 GHz which corresponds to a bandwidth of 4.67:1 as the measured results indicate. Overall, the curves comparison proves that the measured results are in very good agreement with the simulated ones. To show the advances of the proposed power divider, Table I lists the performance comparison between this work and other works in recent years. As the table illustrated, the measured in-band return loss (better than 25 dB) is relatively superior and the frequency tuning range (when S_{11}<-20 dB) for the proposed work is much wider than other relative works. Moreover, the circuit is very compact for such a wide-band response.

TABLE I
THE BIAS VOLTAGE AT DIFFERENT SAMPLED FREQUENCIES

Ref.	Tuning Range (GHz)	Return Loss (dB)	Insertion Loss (dB)
[2]	0.5-1.3 (2.6:1)	≥ 17	4.6-3.5
[3]	0.83-2.4 (2.9:1)	>23	3.5-3.3
[4]	0.85-2.4 (2.82:1)	>20	2.16 -5.6
This work	**0.9-4.2 (4.67:1)**	**≥ 25**	**4-3.2**

IV. CONCLUSION

Compact and reconfigurable power dividers are more and more desirable in modern microwave communication systems. The method by adding capacitors in parallel with the transmission lines of Wilkinson-type power dividers has been investigated in this paper. One wideband power divide is realized and the measured 15-dB-return-loss bandwidth of the two-way divider is 3:1 while the useful bandwidth in terms of other S-parameters is 2.73:1 (or a fractional bandwidth of 93%). The simulated and measured results confirm that this proposed method can provide a broadband and tunable response compared to other works. The other proposed power divider can achieve a very wide center frequency tuning range. A prototype with a frequency tuning range from 0.9 GHz to 4.2 GHz (4.67:1) has been designed and fabricated.The measured and simulated results have good agreement with each other and the frequency tuning range is much wider than others works. It can be seen from the results that this method is very simple and useful for forming a compact reconfigurable power divider.

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