

## Miniaturization of Broadband Wilkinson Power Dividers

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### ABSTRACT

This paper proposed three modified Wilkinson power dividers in order to achieve a size reduction and a wide bandwidth. The first structure presented the power divider using compact folded step impedance transmission lines rather than the uniform microstrip line design for operating center frequency of 3 GHz. The second structure showed the power divider with delta-stub for 2.4 GHz. Finally, the third modified structure introduced the two-section Wilkinson power divider using series-delta stub for center frequency of 2.4 GHz as well. The study managed to get an overall dimension of 15 mm × 9.5 mm for the first proposed design achieving a reduction of 75.6 % and fractional bandwidth of 133 %. For the second proposed structure, the size was 15 mm × 15 mm with a reduction of 56 % and fractional bandwidth of 56 %. While the third design size was 17 mm × 15 mm with a reduction of 63.6 % and the structure achieved a broadband bandwidth with fractional bandwidth of 220 %. The proposed power dividers used RT/duroid 5880 substrate with a thickness of 0.38 mm. Simulation and measurement results indicated that the modified power dividers showed equal power division, good phase balance, high isolation between output ports, and good return loss better than -12 dB covering the operating frequency range.

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## 1. INTRODUCTION

In recent years, encountered problems in fields of spectrum management and radio system engineering are mainly overcome via the use of the wideband technology [1]. For instance, in many microwave circuits, such as mixers, reflectometers, and modulators, power dividers are utilized. The most common power divider is the Wilkinson [2]. Its function is to divide the power in microwave systems because it has high isolation between two output ports, low transmission loss, and a simple fabrication process. It is basically used with quarter-wave transmission lines in order to enable the process of matching the split ports to the common port. However, it has a large size as a result of using quarter-wave transmission lines, especially at lower frequencies and a narrow bandwidth [3].

The design of multi-section was firstly proposed in 1968 [4]. This design significantly enhanced the bandwidth and achieved high isolation. The conventional two-sectioned Wilkinson power dividers with narrowband and broadband were introduced in [5]-[6]. According to [5], single-section and multi-section Wilkinson power dividers were designed for the purpose of operating in regions narrowband (11.5-12.5GHz) and broadband (6-18 GHz), respectively. As suggested by [7], a wideband divider for single operating frequency can be designed using coupled lines without the use of isolation resistors.

Several designs have been introduced to increase the power divider bandwidth such as the step impedance matching network [8], the multilayer PCB technology [9], open or short-ended stubs [10],

cascading [11], port extension [12], and additional isolation network [13]. These designs have the capability to efficiently enhance the input/output return-loss or the isolation bandwidth. However, all the aforementioned studies have a common drawback in which they all cannot satisfy all the requirements simultaneously in a circuit design [14]. The other disadvantages of these techniques are that they increase both the size and insertion loss of the circuit and require more resistors for output ports' isolation. Therefore, it is very important to reduce the quarter-wavelength line sections size in order to obtain compacted passive components. A number of studies have attempted to improve the conventional Wilkinson power dividers [15]-[16]. Tang and Chen [16] also tried to reduce the size of the conventional power divider by folding SITL method. In addition, Sedighy et al. [17] suggested that modifying the Wilkinson power divider can result in a fractional bandwidth of 100 % with -10 dB isolation or a fractional bandwidth of 40 % with -20 dB isolation enhancing the power splitting performance. On the contrary, their structures are very complex and this increases the circuit fabrication complexity.

Delta stub was proposed for the first time by Coimbra [18] while Nadera *at el* [19] were the pioneers to design the series-delta stub and implement it in the single-section Wilkinson power divider to shift the high operating frequency to low frequency while maintaining short branch lines.

In this paper, three Wilkinson power dividers were modified to minimize the size and achieve a high bandwidth range. The proposed folded microstrip line structure is capable of reducing the size of the power divider circuit. The impedance ratio of SITLs is taken into account as the total electrical length of the lines for every wavelength  $\theta_1$  and  $\theta_2$  in order to enhance the size reduction to the optimum. The delta-stub technique is used in each branch line of the power divider circuit to obtain shorter branch lines. Therefore, when adjusting the angle of the delta-stub, the bandwidth is widened. The series-delta stub is implemented in the two-section Wilkinson power divider and folding the microstrip line to achieve more size reduction and broadband bandwidth. In this study, a modified Wilkinson power dividers at centre frequency 3 GHz and 2.4 GHz was fabricated using the RT/Duroid 5880 substrate ( $\epsilon_r = 2.2$ ,  $\tan \delta = 0.001$ , thickness,  $h = 0.38$  mm).

## 2. DESIGN PROCEDURES

### 2.1. Wilkinson Power Divider with Stepped Impedance Transmission Lines (SITLS)

In this section, the uniform branch line of the conventional power divider was modified with non-uniform SITLs to get physical length reduction [20]. The stepped-impedance-stub lines design equations provide two degrees of freedom for the determination of the circuit dimensions. These degrees of freedom are used to reduce the circuit size. The SITL possesses two different characteristic impedance lines and they are symmetrical. A stepped-impedance transmission line consisting of a low impedance line section and two identical high impedance line sections is depicted in Figure 1.

The low impedance line section is in the middle with characteristic  $\theta_1$  and the two identical high impedance line sections with characteristic impedance  $Z_2$  and electrical length  $\theta_2$  are on both sides. In this work, the total area size of SITL is reduced by 75.5 % compared to the conventional design.  $K$  is the impedance ratio of the SITL; it is defined as  $K = Z_2/Z_1 \gg 1$ .  $K$  is desired to be very high; however, this requires that  $Z_2$  should be very high as well resulting in a very narrow width. In addition, if  $Z_1$  is extremely low, this will result in a very wide line. Due to this, it will be difficult to fabricate. Thus, the desired total electrical length of the structure is  $\theta_t = \theta_1 + \theta_2$  and the  $\theta_t$  should be less than  $74^\circ$  at center frequency of 3 GHz. Selecting a very high impedance ratio,  $K$  is necessary to achieve compactness in the lines length; however, the limitations for achieving very high impedance lines  $W/h \ll 1$  and very low impedance lines  $W/h \gg 1$  should be taken into account. Furthermore, high impedance ratio,  $K$  leads to high discontinuity effects. The values of SITL at center frequency of 3 GHz have been calculated using equations in [21]. They are tabulated in Table 1.

Table 1. Design parameter values for Figure 1(b)

Parameters	Values	Parameters	Values
$K$	1.25	$L_3$	1.0 mm
$Z_1$	102 $\Omega$	$L_4$	6.0 mm
$Z_2$	81 $\Omega$	$L_5$	0.2 mm
$\theta_1$	42°	$L_6$	0.5 mm
$\theta_2$	19°	$W_1$	0.3 mm
$L_1, L_2$	1.5 mm	$W_2$	0.5 mm

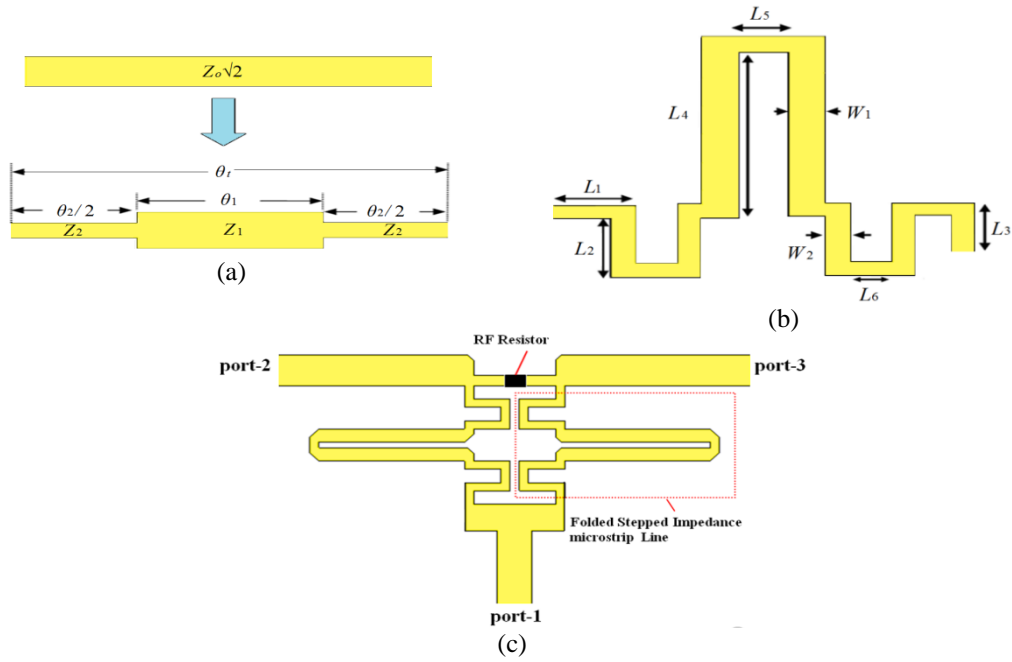


Figure 1. (a) Replacing the uniform transmission line with non-uniform SITLs transmission line (b) Dimensions diagram of folded step impedance transmission lines (SITL) (c) Power divider design layout

## 2.2. Wilkinson Power Divider with Delta-Stub

The second modified Wilkinson power divider is shown in Figure 2(c) consisting of folded microstrip transmission line and delta-stub [20]. Delta-stub is modified based on single delta open stub [22], [23]. By considering the single delta-stub shown in Figure 2(a), it can be divided into  $n$  discrete segments of microstrip transmission line of length  $\delta$ . The length  $\delta$  should obey the condition  $\delta \ll \lambda_g$ , where  $\lambda_g$  is the electrical wavelength. The narrow width segment of the stub which has higher characteristic impedance is merged with the microstrip transmission line of the power divider while the wide last segment of the stub with low impedance plays a role as open ended discontinuity. The analytical design procedures of delta-stub are demonstrated by the transmission line widths and  $W_n$  of the segment is calculated using (1):

$$W_{n\delta} = (2n\delta) \times \tan(\theta/2) \quad \text{where } n=0,1,\dots,N \tag{1}$$

where subscript  $n$  is the number of the segments and  $\theta$  is the vertex angle of the delta-stub. It is worth to mention that  $\theta = 26^\circ$  was chosen in order to get the desired center frequency of 2.4 GHz. The input impedance,  $Z_{in(n)}$  of each  $n$ -segment is obtained by (2) with the exception of the final section ( $Z_{in(N)}$ ), since it has the open-ended discontinuity. When  $W_n/h > 1$ , the input impedance,  $Z_{in(n)}$  of each  $n$ -segment is calculated:

$$Z_{in(n+1)} = Z_{in(n)} \frac{Z_{o(n)} + jZ_{in(n)} \tan(\beta\delta)}{Z_{in(n)} + jZ_{o(n)} \tan(\beta\delta)} \tag{2}$$

where the characteristic impedance,  $Z_{o(n)}$  of each  $n$ -segment is expressed as:

$$Z_{o(n)} = \frac{120\pi}{\sqrt{\epsilon_e \left\{ (W_{n\delta}/h) + 1.393 + 0.667 \ln \left[ (W_{n\delta}/h) + 1.444 \right] \right\}}} \tag{3}$$

The effective dielectric constant,  $\epsilon_e$  in (3) is given as:

$$\epsilon_e = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \frac{1}{\sqrt{1 + 12h/W_{n\delta}}} \tag{4}$$

The input impedance of the delta-stub can be found from the computation of the input impedance of each cascaded transmission line with incremental distance  $\delta$ . According to equations (1) to (3),  $n$  was chosen to be 42 to enable calculating the impedance of the delta-stub,  $Z_{in}(1) = 57.94 \Omega$  and  $Z_{in}(N) = 83 \Omega$ . The electrical parameters for the delta-stub were computed as  $W_g = 0.5 \text{ mm}$ ,  $L = 1.88 \text{ mm}$ ,  $r = 1.14 \text{ mm}$ ,  $\theta = 26^\circ$ ,  $W = 0.95 \text{ mm}$ , and  $\delta = 0.048 \text{ mm}$ . By adding delta-stub in each branch, the conventional quarter-wave line  $\theta_i$  will be reduced by 80 % at the same center frequency of 2.4 GHz. The values of transmission line dimensions using RT/duroid 5880 substrate with  $h = 0.38 \text{ mm}$  at 2.4 GHz in Figure 2(b) are  $L_1 = 3 \text{ mm}$ ,  $L_2 = 6.2 \text{ mm}$ ,  $L_3 = 2 \text{ mm}$ ,  $W_1 = 0.66 \text{ mm}$ , and  $W_2 = 0.42 \text{ mm}$ .

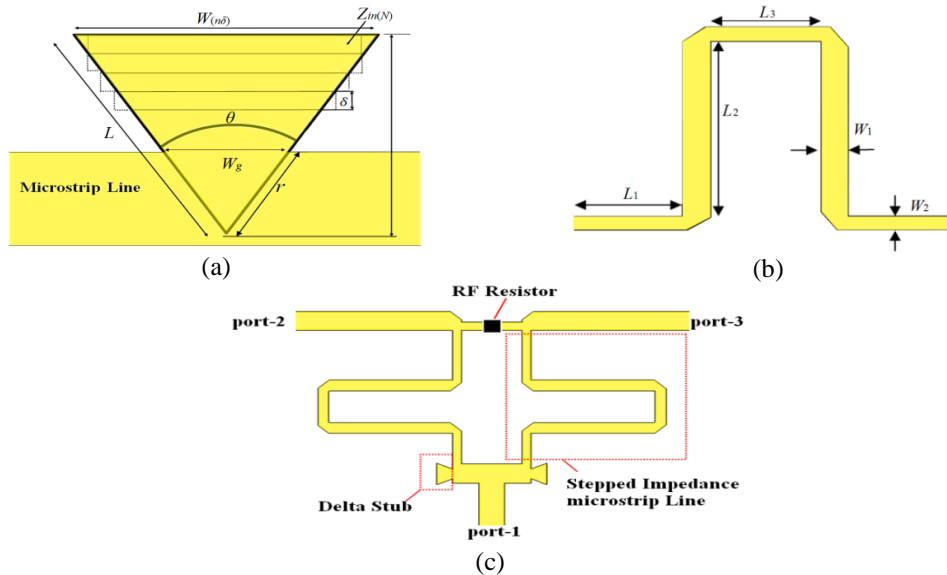


Figure 2. (a) Geometry of the delta-stub, (b) dimensions diagram of transmission lines, (c) proposed design layout

**2.3. Two Section of Wilkinson Power Divider with Sires-daimnond stub**

The third modified Wilkinson power divider circuit is shown in Figure 3(a). In order to achieve a broadband bandwidth two sections of WPD attached with three series delta-stub on ache branch. The three series delta-stub is modified based on a single delta open stub shown in Figure 2(a). Implementing the serie delta-stub help to shift the high frequency to low frequency while maintaining the shorter branch lines. The analytical design procedures in [19] used to design the three series-delta stub.

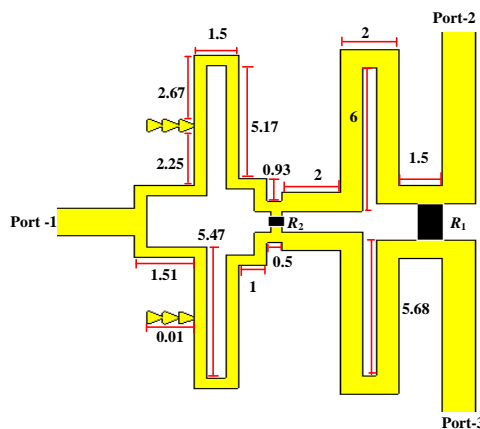


Figure 3. The layout circuit of two-section wilknon power divider with sires-delta stub, (the dimensions in mm unit)

The  $Z_1$  and  $Z_2$  value are stepped impedance transformer sections matching  $Z_0$  at output to  $2Z_0$  at the input over the band of  $f_2/f_1$ . The impedances  $Z_1$  and  $Z_2$  are calculated using Binomial transformer technique [24] and the following equation are used to calculate the resistors  $R_1$  and  $R_2$  values:

$$R_1 = \frac{2Z_1Z_0}{[(Z_1 + Z_2)(Z_1 - Z_2\psi)]^{1/2}} \tag{5}$$

$$R_2 = \frac{2R_1(Z_1 + Z_2)}{[R_1(Z_1 + Z_2) - 2Z_1]} 2Z_0 \tag{6}$$

where

$$\psi = \pi/2 \left[ 1 - 1/\sqrt{2} \left( (f_2 - f_1)/(f_2 + f_1) \right) \right], \quad f_1 = 1 \text{ GHz and } f_2 = 6.4 \text{ GHz}$$

The characteristic impedances and dimensions of the two-section WPD are listed in Table 2.

Table 2. The characteristics impedance of two section WPD

Specification	1 <sup>st</sup> section	2 <sup>nd</sup> section
Impedance ( $Z_2$ & $Z_1$ ) ( $\Omega$ )	81.99	60.98
Resistance ( $R_2$ & $R_1$ ) ( $\Omega$ )	100	200
Width ( $w$ ) mm	0.404	0.766

### 3. RESULTS AND ANALYSIS

The first proposed Wilkinson power divider results using compact folded step impedance transmission lines (FSITL) design for operating center frequency of 3 GHz are shown in Figure 3. Figure 3(a) shows the simulation results, while Figure 3(b) shows the measurement results. From Figure 3(b), it can be noted that  $S_{11}$  slightly shifted to 2.8 GHz. The return losses,  $S_{11}$  and isolation,  $S_{23}$  for both simulation and measurement were less than -13 dB and -10, respectively in the frequency interval of 1.5 GHz to 4.8 GHz. The insertion loss,  $S_{21}$ ,  $S_{13}$  were -3.4 dB indicating that the proposed power divider can split an incoming signal into two parts successfully and the fractional bandwidth was 133 %. Figure 4 proposed the results of the second modified power divider at center frequency 2.4 GHz. The return losses,  $S_{11}$  of both simulation and measurement were less than -12 dB across the frequency interval 1.5 GHz to over 3 GHz, which is equivalent to 70 % fractional bandwidth, and the isolation,  $S_{23}$  was -10 dB in the frequency interval 1.5 GHz to 3 GHz. The insertion loss,  $S_{21}$ ,  $S_{13}$  were -3.2 dB indicating that the proposed power divider can split an incoming signal into two parts successfully. Figure 5 showed the results of the broadband two section Wilkinson power divider using series delta-stub with folded transmission lines design for operating center frequency of 2.4 GHz. The return losses,  $S_{11}$  was less than -10 dB from 1.1 GHz to 6.4 GHz, which is equivalent to 220 % of the fractional bandwidth. The isolation,  $S_{23}$  was less than -10 dB from 1.1 GHz to 5.8 GHz and the insertion loss,  $S_{21}$ ,  $S_{13}$  were -3.4 dB over the same band.

Figure 6 depicts the circuit Photograph of the proposed power dividers. Figure 6(a) shows the first circuit. Herein, this divider has a circuit size of 15 mm × 9.5 mm and Figure 6(b) shows the second circuit with total size of 15 mm × 15 mm. Both circuits have achieved a reduction of 75.6 % and 56 %, respectively compared with conventional wilknsn power divider. Finally, Figure 6(c) show the third circuit design with total size of 17 mm × 15 mm which achieved a reduction of 63.6 % compared with conventinal two section power divider.

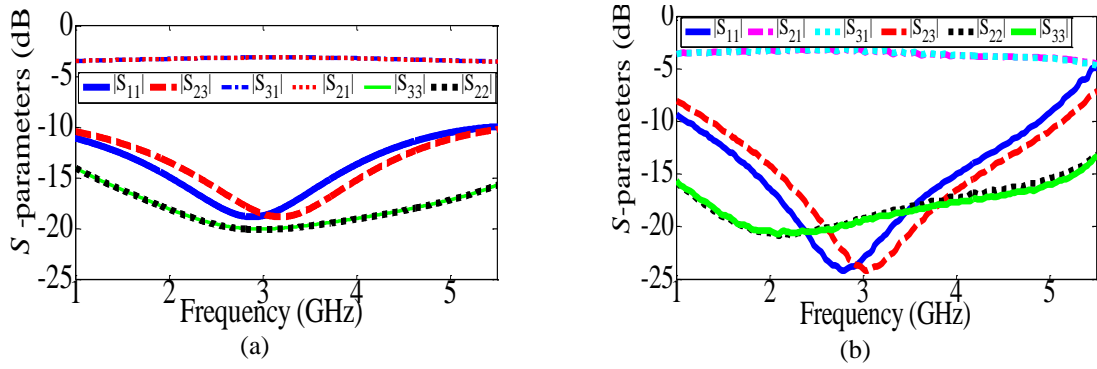


Figure 3. S-parameters for (a) simulation and (b) measurement results

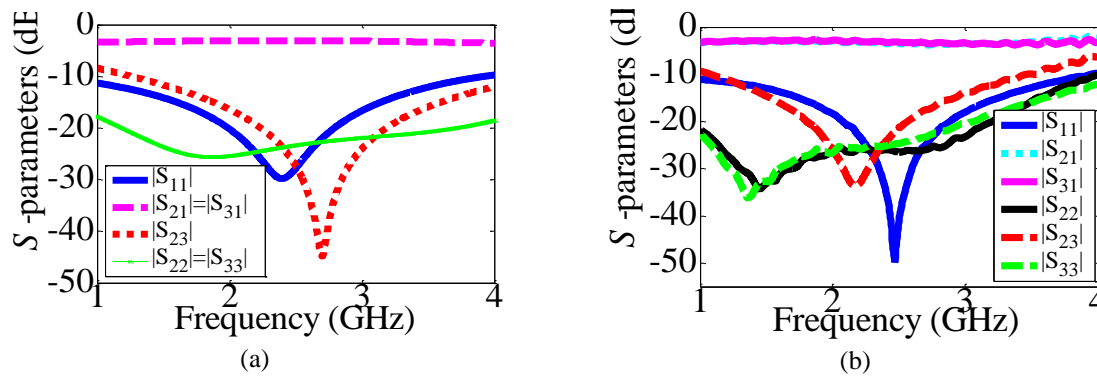


Figure 4. S-parameters for (a) simulation and (b) measurement results. (c) The second proposed power divider circuit photograph compared to conventional Wilkinson power divider

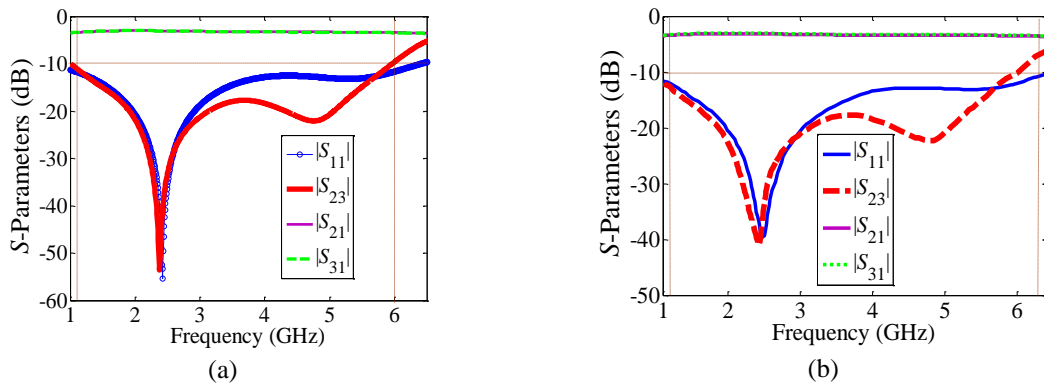


Figure 5. S-parameters for (a) simulation and (b) measurement results

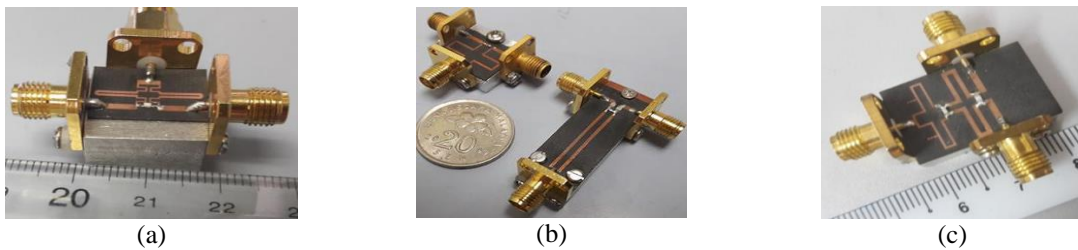


Figure 6. Circuits photograph for (a) first design, (b) second design, and (c) third design

#### 4. CONCLUSION

This study proposes three equal-split dividers. The first design presents the Wilkinson power divider using compact folded step impedance transmission lines (FSITL) for operating center frequency of 3 GHz while the second design presents the FSITL with delta-stub for center frequency of 2.4 GHz and the third design presents the two section Wilkinson power divider with series delta-stub at center frequency of 2.4 GHz. The proposed power dividers design enhanced the size reduction at the aforementioned frequencies. The measurement and simulation results showed good agreement in terms of phase balance, high isolation between output ports, and return loss at the operating frequency range.

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