

A Novel Multi-Way Power Divider Design with Enhanced Spurious Suppression

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Abstract — In this article, a multi-way Bagley Polygon power divider using a novel technique for enhanced harmonic suppression is presented. In this technique, a T-shaped transmission line with open stub is designed to replace each quarter-wavelength transmission line of the conventional Bagley Polygon power divider. The proposed power divider characterizes arbitrary multi-harmonic suppression in theory, and not only exempt from backside etching or lumped reactive components, but also offering a high level of attenuation over a wide stop band bandwidth. The closed form design equations of the proposed Bagley Polygon power divider have been obtained by rigorous derivation. For verification, a 5-way Bagley Polygon power divider is fabricated and measured. The bandwidth for the suppression of the single third harmonic above 20 dB approximates 37% and enhanced the second-, third-, and fourth-harmonic above 30 dB over 3 GHz at operation frequency of 1.0 GHz.

Index Terms — Bagley Polygon power divider, enhanced spurious suppression, multi-way, T-shaped transmission line.

I. INTRODUCTION

Power dividers are very important for microwave and millimeter-wave systems [1-4], which can be widely used in balanced power amplifier, radar system, feeding networks for antenna arrays, measurement systems, mixers and phase shifters, etc. Bagley Polygon Power Divider (BPPD), using no-lumped elements, such as resistors, can be easily extended to any number of output ports in recent researches [5-7]. In [5], a

general design of compact multi-way power divider similar to BPPD with simple design theory was introduced. In [6], a compact dual-frequency 3-way BPPD using Composite Right/Left Handed (CRLH) transmission lines with shunt connections of open and short stubs for comparison was implemented. A novel design method for a compact BPPD with dual transmission lines is proposed in [7]. Moreover, a loop-type compact 5-way BPPD for dual-band, wide-band operation and easy fabrication was presented in [8]. The main drawback of the conventional BPPD is the presence of spurious response due to the adoption of quarter-wavelength transmission lines as conventional Wilkinson Power Divider (WPD).

Many efforts have been made to overcome spurious response, such as studies on Electromagnetic Band Gap (EBG) cells [9], Defected Ground Structure (DGS) [10], extended line [11], coupled line with DGS and capacitor [12], stubs with inductor [13], and series inductors [14]. However, all of the above-mentioned approaches usually require either backside etching or suppress only single harmonic frequency. Furthermore, other techniques have been used for enhanced harmonic suppression, such as applying anti-coupled line [15], embedded resonators [16], artificial transmission lines and short-circuited LC tank [17], non-uniform transmission transformers [18], and stubs with extended line [19-22]. Recently, a new circuit topology [23] was proposed with harmonic suppression from the 2nd to the 6th by using band-stop filter and extended line. Another design approach is given in [24], capable of harmonic suppression from the 2nd to the 12th harmonic by using low-pass filter and

open stubs. Unfortunately, except for [18], most of these methods were used to suppress harmonic of equal/unequal WPDs, 3-way modified WPD and dual-band WPD.

In this article, a novel circuit topology for enhanced harmonic rejection to the multi-way BPPD is introduced. T-shaped transmission lines are designed to achieve harmonic suppression. For demonstration, the simulated and measured performance of an experimental BPPD operating at a center frequency of 1.0 GHz is shown.

II. STRUCTURES AND THEORY

A. Conventional multi-way BPPD

Conventional multi-way BPPD is illustrated in Fig. 1 (a) [5]. Signals fed on port 1 are equally divided into $2n+1$ part, and the lengths of $\theta_1, \theta_2 \dots \theta_n$ are chosen arbitrarily, which control the phase difference of output ports, here, $n=1, 2, \dots$. Decomposing the symmetry structure, the equivalent circuit can be obtained as depicted in Fig. 1 (b).

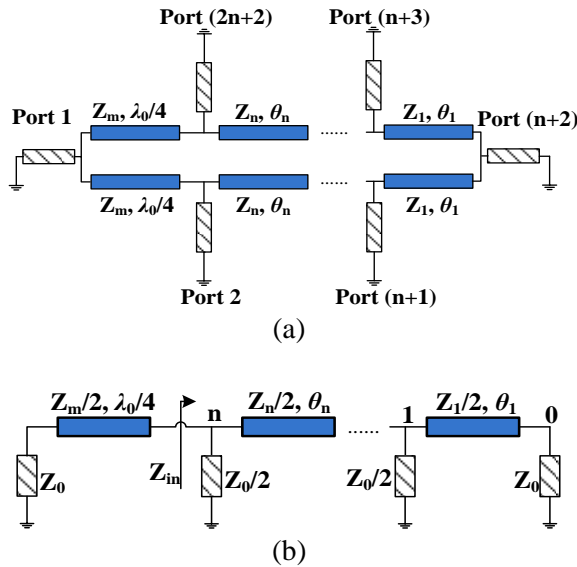


Fig. 1. (a) Conventional $2n+1$ -way BPPD, and (b) equivalent circuit.

To reach the matching goal at the input port, there should be an impedance matching network between Z_n and Z_0 , and $\lambda/4$ transformers are used in the multi-way BPPD. The impedance of ports, Z_0 is usually considered as 50Ω . Obviously, the following relations (1a)-(1c) are obtained from Fig. 1 (b):

$$Z_n = \frac{2Z_0}{2n-1}, \quad (1a)$$

$$Z_{in} = \frac{Z_0}{2n+1}, \quad (1b)$$

$$Z_m = \frac{2Z_0}{\sqrt{2n+1}}. \quad (1c)$$

B. T-shaped transmission line

Figure 2 shows the configuration of the T-shaped transmission line, which consists of two series transmission lines with characteristic impedance of Z_{T1} and one shunt open stub located in the center of the two series transmission lines with characteristic impedance of Z_{T2} ; these three lines have two electrical lengths of θ_1 and θ_2 [25].

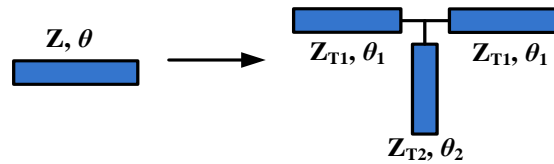


Fig. 2. Configuration of the T-shaped transmission line.

In order to study the T-shaped transmission line model which is equivalent to the conventional transmission line, the $ABCD$ matrix is utilized. The $ABCD$ matrix of the transmission line model is:

$$M = \begin{bmatrix} \cos \theta & jZ \sin \theta \\ j \frac{\sin \theta}{Z} & \cos \theta \end{bmatrix}. \quad (2)$$

The $ABCD$ matrix of the T-shaped transmission line model is

$$M_T = M_{T1} \cdot M_{T2} \cdot M_{T1}, \quad (3)$$

where

$$M_{T1} = \begin{bmatrix} \cos \theta_1 & jZ_{T1} \sin \theta_1 \\ j \frac{\sin \theta_1}{Z_{T1}} & \cos \theta_1 \end{bmatrix}, \quad (4)$$

and

$$M_{T2} = \begin{bmatrix} 1 & 0 \\ j \frac{\tan \theta_2}{Z_{T2}} & 1 \end{bmatrix}. \quad (5)$$

Since the T-shaped transmission line is used to replace the quarter-wavelength connecting line, θ

is assigned to be 90° . Therefore, the **ABCD** matrix of the transmission line becomes (6) and has the following relation (7):

$$M = \begin{bmatrix} 0 & jZ \\ j\frac{1}{Z} & 0 \end{bmatrix}, \quad (6)$$

$$M = M_T. \quad (7)$$

To further simplify the equations (3)-(7), we can easily find the relations as below:

$$Z_{T1} = Z \tan \theta_1, \quad (8)$$

$$Z_{T2} = Z \frac{\cos^2 \theta_1 \cdot \tan \theta_2}{1 - 2 \sin^2 \theta_1}. \quad (9)$$

C. Multi-way enhanced harmonic suppressed BPPD

To suppress the harmonics, the T-shaped transmission line is used to match between Z_0 and Z_{in} , and impedances Z_i ($i=1,2,3\dots n$) can be achieved by the cascade of T-shaped transmission lines. Accordingly, the geometry of the proposed $2n+1$ -way BPPD is drawn in Fig. 3, in which the characteristic impedances and electrical lengths are also defined; the following relationships (10) of the parameters are obtained based on (1a)-(1c), (8) and (9). We need to indicate that once the θ_{Tp} is obtained, the Z_{Tp} will be determined like as (10), here, $p=1,2,3\dots$:

$$Z_{Tm1} = \frac{2Z_0}{\sqrt{2n+1}} \cot \theta_{m1}, \quad (10a)$$

$$Z_{Tm2} = \frac{2Z_0}{\sqrt{2n+1}} \cdot \frac{\cos^2 \theta_{m1} \cdot \tan \theta_{m2}}{1 - 2 \sin^2 \theta_{m1}}, \quad (10b)$$

$$Z_{T3} = \frac{2Z_0}{2n-1} \cot \theta_{T3}, \quad (10c)$$

$$Z_{T4} = \frac{2Z_0}{2n-1} \cdot \frac{\cos^2 \theta_{T3} \cdot \tan \theta_{T4}}{1 - 2 \sin^2 \theta_{T3}}, \quad (10d)$$

$$Z_{T1} = \frac{2Z_0}{2n-1} \cot \theta_{T1}, \quad (10e)$$

$$Z_{T2} = \frac{2Z_0}{2n-1} \cdot \frac{\cos^2 \theta_{T1} \cdot \tan \theta_{T2}}{1 - 2 \sin^2 \theta_{T1}}. \quad (10f)$$

Therefore, the procedure to design the multi-way enhanced harmonic suppression BPPD is briefly summarized as follows:

- (1) According to the practical requirements, the n and p are determined, due to the arbitrary electrical lengths of Z_i , the arbitrary enhanced

- harmonic suppression can be achieved by multiple different T-shaped transmission lines;
- (2) Determine requisite characteristic impedances from (1a)-(1c) and (10a)-(10f);
- (3) According to suppression of the harmonic frequencies, chose θ_{m1} , θ_{m2} , θ_1 , θ_{T1} , $\theta_{T2}\dots$ carefully to make engineering tradeoff between easy fabrication and compact circuit.

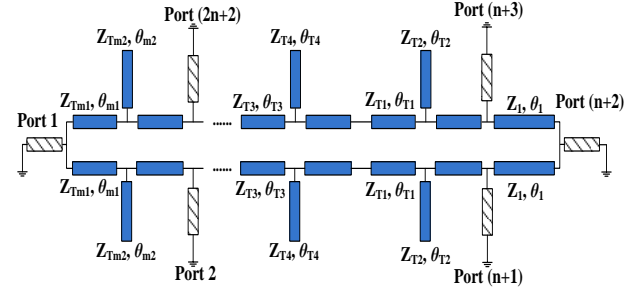


Fig. 3. Configurations of the proposed harmonic suppressed BPPD.

III. SIMULATION AND EXPERIMENT

To certify this proposed structure, we take the 5-way BPPD as an example ($n=2$). In order to achieve a compact T-shaped transmission line in Fig. 2, θ_1 should be less than 45° , the electrical length of the stub segment can be fixed to $\theta_2 = \pi/(2q)$ by the desired q th harmonic suppression ($q=1,2\dots$). For example, an electrical length θ_2 of 45° , 30° or 22.5° correspond to the second-, third-, or fourth-harmonic suppression, respectively. Assuming $Z_0=50 \Omega$, Fig. 4 (a) plots the values of Z_{Tm1} , Z_{Tm2} versus θ_{m1} ($5^\circ \leq \theta_{m1} < 45^\circ$) with θ_{m2} of 45° , 30° or 22.5° , and Fig. 4 (b) plots the values of Z_{T1} , Z_{T2} versus θ_{T1} ($5^\circ \leq \theta_{T1} < 45^\circ$) with θ_{T2} of 45° , 30° or 22.5° , respectively.

The design for the T-shaped transmission line with open stub is essential for a compact BPPD with desired harmonic suppression. For appropriate characteristic impedances and easy fabrication in engineering, we choose $\theta_{m1}=\theta_{T1}=\theta_{T3}=30^\circ$, the impedances Z_{Tm1} , Z_{Tm2} , Z_{T1} , Z_{T2} , Z_{T3} , Z_{T4} and Z_1 between 20Ω and 100Ω can be easily determined according to the Fig. 4 or analytical design equations (1a)-(1c) and (10a)-(10f). Since θ_i can freely control the phase difference from output ports, θ_1 is chosen as 30° manually, the detailed design parameters are listed in Table 1 based on third-harmonic suppression as an example.

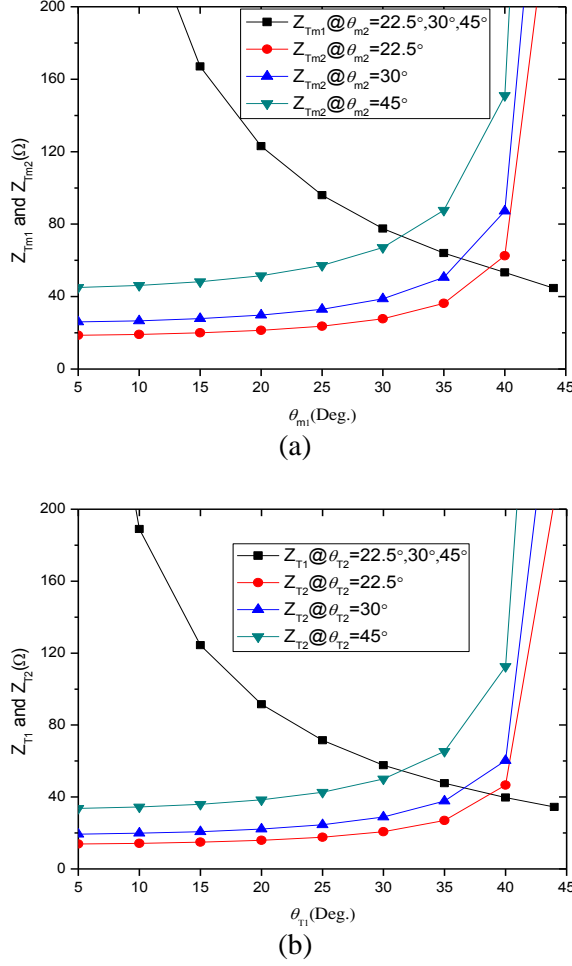


Fig. 4. Design curves for: (a) Z_{Tm1} , Z_{Tm2} versus θ_{m1} , and (b) Z_{T1} , Z_{T2} versus θ_{T1} .

Table 1: Design parameters of the 5-way third harmonic suppression BPPD

$f_0=1.0$ GHz, $Z_0=50$ Ω , $\theta_{m1}=\theta_{T1}=\theta_{T3}=\theta_1=30^\circ$			
Case 1	$\theta_{T2}=\theta_{T4}=\theta_{m2}$	$Z_{Tm1}(\Omega)$	$Z_{Tm2}(\Omega)$
	30°	77.5	38.8
	$Z_{T1}=Z_{T3}(\Omega)$	$Z_{T2}=Z_{T4}(\Omega)$	$Z_1(\Omega)$
	57.7	29	100

According to these design parameters, the 5-way BPPD third-harmonic suppression is designed and simulated (Case 1), the amplitude responses of S -parameters are shown in Fig. 5. Obviously, ideal return loss of input port and insertion loss are attained, and the BPPD suppression of the third harmonic frequency with a minimum attenuation of 40 dB with S_{21} and S_{61} . The minimum attenuation over 50 dB with 1 GHz bandwidth of

S_{31} , S_{41} and S_{51} . Note that ideal lossless transmission lines are used in simulation.

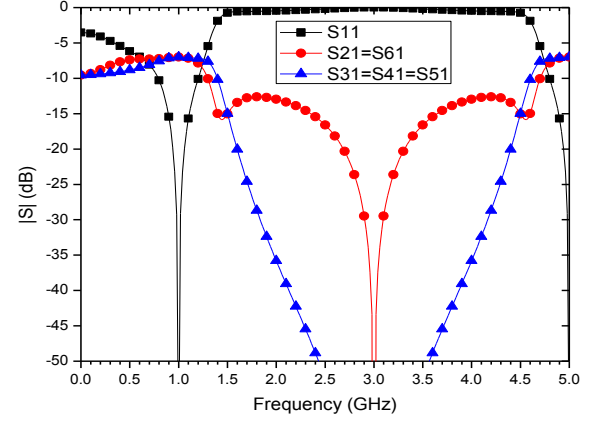


Fig. 5. The amplitude responses S -parameters of 5-way third harmonic suppression BPPD.

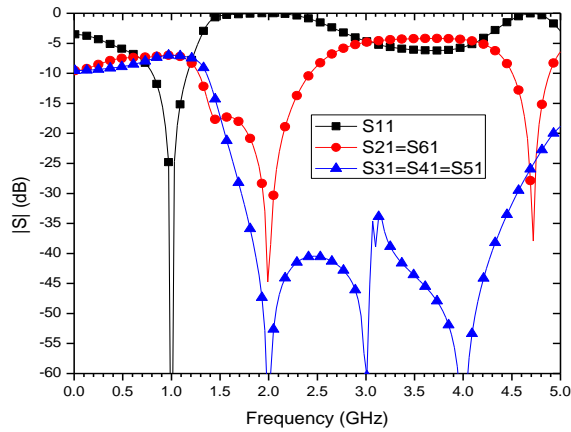
To achieve enhanced spurious suppression, we can take the $\theta_g=\pi/(2r)$ as different values ($g=m2$ and $T2, T4\dots$; $r=2,3,4\dots$). Here, θ_1 is chosen as 30° manually, θ_{m2} , θ_{T2} and θ_{T4} is chosen as 45° , 22.5° and 30° , and suppression of the second-, fourth-, and third-harmonic frequency, respectively (Case 2). In order to further validate the proposed BPPD, we utilize three T-shaped transmission lines between the port 2 (6) and port 3 (5), impedances and electrical lengths are named as Z_{T5} , Z_{T6} , θ_{T5} and θ_{T6} , respectively, and suppression of the second-, third-, fourth-, and fifth-harmonic (Case 3). The $Z_{T1}=Z_{T3}=Z_{T5}=57.7$ Ω , and the Z_{Tm1} , Z_{Tm2} , Z_{T2} , Z_{T4} , Z_{T6} and Z_1 can be easily determined according to the analytical above design equations, and the detailed design parameters are listed in Table 2.

According to these design parameters, the 5-way BPPDs (Case 2 and Case 3) with enhanced harmonic suppression are designed and simulated, the amplitude responses of S -parameters are shown in Fig. 6. Obviously, ideal return loss of input port and insertion loss are attained. Figure 6 (a) shows the power divider suppression of the second-harmonic frequency with S_{21} and S_{61} , and suppression of the second-, third- and fourth-harmonic frequencies with S_{31} , S_{41} and S_{51} , simultaneously. Figure 6 (b) shows the power divider suppression of the third harmonic frequency with S_{21} and S_{61} , and suppression of the second-, third-, fourth- and fifth-harmonic

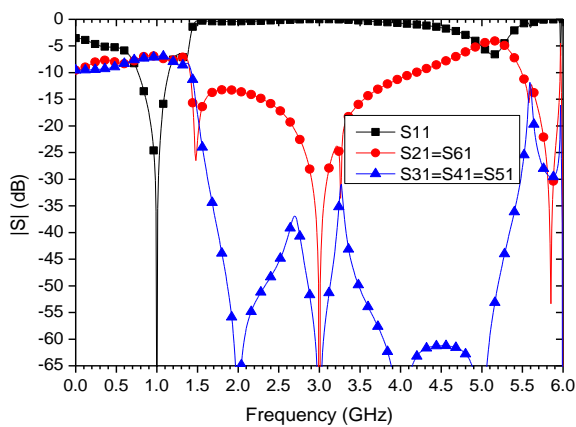
frequencies with S_{31} , S_{41} and S_{51} , simultaneously. So, increase the number of T-shaped transmission lines, the multi-harmonic suppression will be easy to get.

Table 2: Design parameters of the 5-way enhanced harmonic suppression BPPDs.

$f_0=1$ GHz, $Z_0=50$ Ω , $\theta_{m1}=\theta_{T1}=\theta_{T3}=\theta_{T5}=\theta_1=30^\circ$					
Case 2	θ_{T2}	θ_{T4}	θ_{T6}	θ_{m2}	$Z_{Tm1}(\Omega)$
	22.5°	30°	\	45°	77.5
	$Z_{Tm2}(\Omega)$	$Z_1(\Omega)$	$Z_{T2}(\Omega)$	$Z_{T4}(\Omega)$	$Z_{T6}(\Omega)$
	67	100	20.7	29	\
Case 3	θ_{T2}	θ_{T4}	θ_{T6}	θ_{m2}	$Z_{Tm1}(\Omega)$
	22.5°	45°	18°	30°	77.5
	$Z_{Tm2}(\Omega)$	$Z_1(\Omega)$	$Z_{T2}(\Omega)$	$Z_{T4}(\Omega)$	$Z_{T6}(\Omega)$
	38.8	100	20.7	50	18.7



(a)



(b)

Fig. 6. The amplitude responses S -parameters of 5-way enhanced harmonic suppression BPPDs: (a) Case 2, and (b) Case 3.

For experimental verification, a BPPD designed to operate at 1.0 GHz was prototyped and characterized. This circuit was fabricated on Rogers substrate with a dielectric constant of 3.48 and thickness of 20 mil. Figure 7 shows the top view of the physical layout and the physical dimensions of the circuit whose circuit parameters are obtained from Table 3. All the measured results are shown in Fig. 8, collected from the Agilent N5230C network analyzer over the frequency range from 10 MHz to 5.0 GHz.

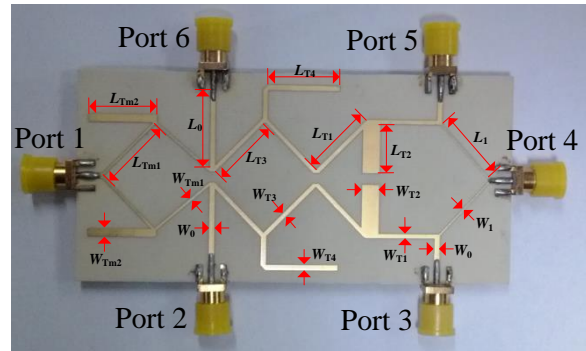


Fig. 7. Photograph of the fabricated proposed BPPD.

Table 3: Physical dimensions of the proposed 5-way BPPD (unit: mil)

W_{Tm1}	L_{Tm1}	W_{Tm2}	L_{Tm2}
19	620	65	590
W_{T4}	L_{T4}	W_{T3}	L_{T3}
44	900	35	605
W_{T2}	L_{T2}	W_{T1}	L_{T1}
150	425	35	605
W_1	L_1	W_0	L_0
10	633	44	850

The measured S -parameters of the 5-way BPPD show an excellent performance with the return loss of input port, insertion loss, and the suppression of the third harmonic frequency by $S_{21}=S_{61}$, and suppression of the second-, third- and fourth-harmonic frequencies by S_{31} , S_{51} and S_{41} , simultaneously. In particular, Fig. 8 (a) indicates that an octave stop-band bandwidth over 37% (2.62-3.36 GHz) is achieved with a minimum attenuation of 20 dB. The suppression levels, evaluated at the third harmonic frequency (3 GHz), are better than 35 dB. Figure 8 (b) indicates that an octave stop-band bandwidth over 3 GHz

(1.7-4.7 GHz) is achieved with a minimum attenuation of 30 dB. The suppression levels, evaluated at the second-, third-, and fourth-harmonic frequencies (2, 3, and 4 GHz), are better than 50 dB. It is believed that the small

discrepancies between the simulated and measured results were mainly caused by the fabrication tolerances. For comparative purposes, Table 4 gives a brief summary of some previously reported divider topologies.

Table 4: Brief summary of reported power divider designs

Ref.	Approach	Suppression	Type of Power Divider
[9]	Electromagnetic Bandgap (EBG)	$3f_0, 5f_0$ only -32.5 dB @ $3.0f_0$ -12 dB @ $5.0f_0$	Wilkinson Power Divider (WPD)
[10]	Defected Ground Structure (DGS)	$2f_0, 3f_0$ only -26 dB @ $2.0f_0$ -25 dB @ $3.0f_0$	WPD
[11]	Extended line	$3f_0$ only -37 dB @ $3f_0$	WPD
[12]	Coupled line+DGS+capacitor	$3f_0$ only -35 dB @ $3.0f_0$	WPD
[13]	Stubs+inductor	$3f_0$ only -44 dB @ $3f_0$	WPD
[14]	Series inductors	$2f_0, 3f_0, 4f_0$ -28 dB @ $2f_0$ -32 dB @ $3f_0$ -20 dB @ $4f_0$	Arbitrary power division WPD
[15]	Anti-coupled line	$2f_0 \rightarrow 3f_0$ -20 dB @ $2.5f_0$	WPD
[16]	Embedded resonators	$3f_0 \rightarrow 5f_0$ -30 dB @ $4f_0$	WPD
[17]	Artificial transmission lines +Short-circuited LC tank	Broadband harmonic suppression	Dual-band WPD
[18]	Non-uniform transmission line transformers	Odd harmonics only	Bagley Polygon Power Divider (BPPD)
[19]	Single stub+extended line	$2f_0 \rightarrow 3f_0$ -30 dB @ $2.5f_0$	WPD
[20]	Stubs+extended line	$2f_0 \rightarrow 4f_0$ -25 dB @ $2.5f_0$ -30 dB @ $3.5f_0$	WPD
[21]	Single stub+extended line	$2f_0, 3f_0$ only -35 dB @ $2.0f_0$ -40 dB @ $3.0f_0$	Unequal WPD
[22]	Stubs+extended line	$2f_0 \rightarrow 4f_0$ -25 dB @ $2.5f_0$ -27 dB @ $3.5f_0$	3-way modified WPD
[23]	Bandstop filter+extended line	Broadband harmonic suppression $2f_0 \rightarrow 6f_0$	WPD
[24]	Low-pass filter+stubs	$2f_0 \rightarrow 12f_0$	WPD
This work	T-shaped transmission line	Arbitrarily enhanced harmonic suppression	Multi-way BPPD

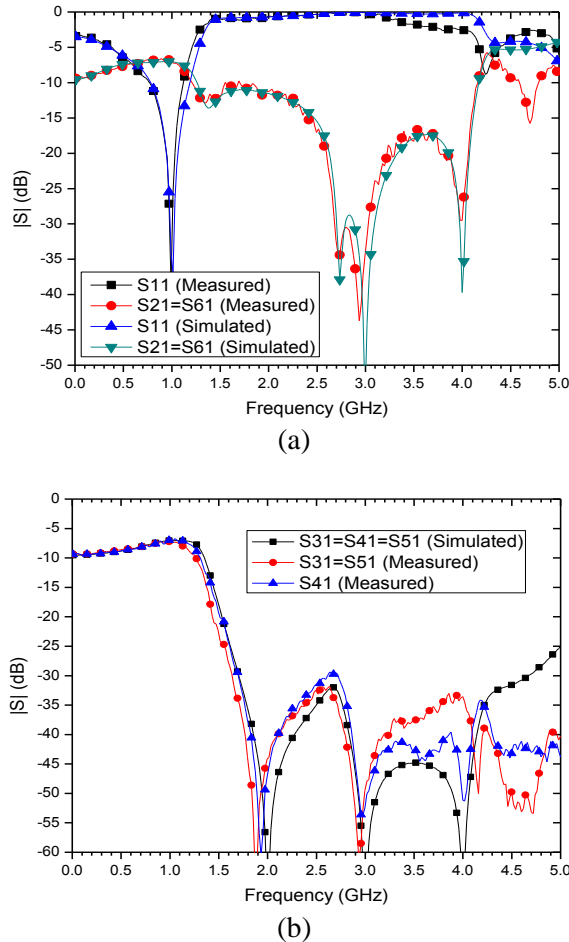


Fig. 8. Measured and simulated: (a) Port 2 and Port 6 have third harmonic suppression, and (b) Port 3, Port 4 and Port 5 have second, third and fourth enhanced harmonic suppression simultaneously.

IV. CONCLUSION

The design and implementation of a novel multi-way BPPD with enhanced harmonic suppression using T-shaped transmission lines has been described. The proposed power divider not only has the advantage of no backside etching or lumped reactive components, but also offers a high level of attenuation over a wide stop band bandwidth. Furthermore, the symmetric output ports with the same phase, by adjusting electrical length between the output ports, can arbitrarily adjust the phase difference asymmetric output ports. Finally, the design concept is validated through simulation and experiment. A fabricated 5-way BPPD shows an excellent performance with the return loss of input port, insertion loss,

and suppression of enhanced the second-, third-, and fourth-harmonic. Actually, this proposed power divider can be easily realized on the planar PCB procedure and MMIC, and very suitable for microstrip circuit implementation in balanced power amplifier, Doherty power amplifier and feeding network for antenna array etc.

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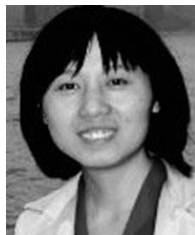


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