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A NOVEL DUAL-BAND MULTI-WAY POWER DIVIDER USING COUPLED LINES

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Abstract—In this paper, coupled lines are used in the design of a dual band planar multi-way Bagley polygon power divider to reduce the size is proposed. For the input port matching and transmission characters are affected by the even mode impedance only, analysis of the multi-way Bagley polygon power divider and equivalent circuit based on coupled lines, closed form design equations are presented with even mode impedance, and odd mode impedance is obtained arbitrarily. To validate the design procedure, two dual band three-way Bagley polygon power dividers are designed, simulated, and fabricated using coupled lines with areas of $3.17\,\mathrm{cm}^2$ and $2.53\,\mathrm{cm}^2$, and the corresponding conventional divider with areas of $17.86\,\mathrm{cm}^2$ and $11.74\,\mathrm{cm}^2$, respectively. When coupled lines are used, the layout is more compact with a reduction in size of more than nearly 80% compared to the conventional design.

1. INTRODUCTION

Power divider is a well-known three-port device, and very important for microwave and millimeter wave system, which can be widely used in balanced power amplifier, radar system and phase shifter etc. As well known, the original Wilkinson power divider developed by Wilkinson [1] consists of two quarter-wavelength lines and operates in a single band. Many efforts have been made to enhance its performance, such as ultra-wideband or broadband Wilkinson power divider and Gysel power divider [2–7], dual-band and optional isolation power dividers using parallel strip line and open stubs [8, 9], compact coupled-line and stepped-impedance transmission lines dual-band Wilkinson

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power dividers [10–13], and dual-band unequal Wilkinson power divider using asymmetric coupled-line [14], in [15], seven ports power divider with various power division ratios was presented. More than that, one of the power dividers, which has been a new area of research, is the Bagley polygon power divider (BPD) [16–25]. Compared to other power dividers, BPD does not use lumped elements, such as resistors, and can be easily extended to any number of output ports. In [16], reduced size 3-way and 5-way BPDs, using open stubs, were presented. In [17], an optimum design of a modified 3-way Bagley rectangular power divider was presented. In [18, 19], a general design of compact multi-way dividers (with odd number of output ports) based on BPDs was introduced. In [20], a compact dual-frequency 3-way BPD using composite right/left handed (CRLH) transmission lines was implemented. Recently, based on the generalized 3-way BPD, pass band filter section was presented in [21]. In [22], a loop-type compact multi-way power divider of dual-band, wide-band or easy fabrication is presented. Moreover, compact non-uniform transmission line 3-way and 5-way BPDs with harmonics suppression were proposed in [23]. Three different topologies of dual-frequency modified 3-way BPDs are designed and analyzed in [24]. A general design of an equal-split N-way power divider with an even number of output ports is proposed in [25].

In this paper, coupled lines are used in the design of dual band multi-way BPD to reduce the size. It is found that the input port matching and transmission parameters are affected by the even mode impedance only in [26]. The BPDs mainly focus on input port matching and output port transmitted power only. Once even mode impedance is fixed, the odd mode impedance is obtained arbitrarily. A smaller odd mode impedance results in a smaller spacing between the coupled lines, and thus it miniaturizes the layout of the BPDs.

2. STRUCTURE AND THEORETICAL

Based on the conventional BPD, compact modified BPD was proposed in [18]. To reduce the size of multi-way BPD, coupled lines are designed to replace the conventional microstrip line. The $2n + 1$-way BPD is illustrated in Fig. 1(a). Here, Z_{m1e}, Z_{m2e}, $Z_{1e} \ldots Z_{ne}$ represent the even characteristic impedances of coupled lines; Z_{m1o}, Z_{m2o}, $Z_{1o} \ldots Z_{no}$ represent the odd characteristic impedances of coupled lines; θ_{m1}, θ_{m2}, $\theta_1 \ldots \theta_n$ represent the electric lengths of coupled lines respectively. Noting that this multi-way BPD is symmetric around its center line, an equivalent circuit (looking from Port 1 to the right or left side) can be drawn as shown in Fig. 1(b). The characteristic impedance

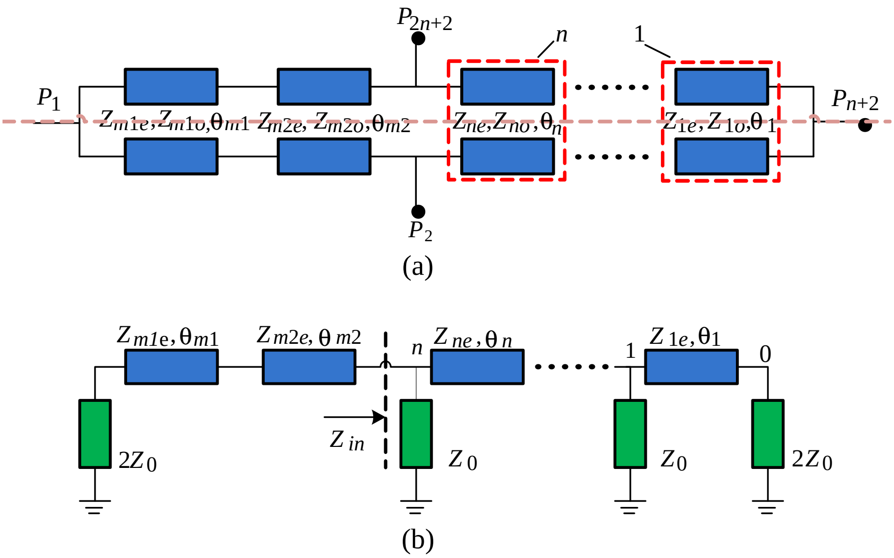

Figure 1. Schematic diagram of the proposed compact multi-way BPD using (a) coupled lines, and (b) its equivalent circuit.

Z_0 of the lines connected to the all ports is usually considered as $50\,\Omega$. 0 corresponds to the opposite output port of the input port, and r ($r = 1, 2 \ldots n$) corresponds to the two symmetric ports numbering from the nearest port of the opposite port to the nearest port of input port. From the equivalent circuit shown in Fig. 1(b), one may easily understand that if we make the value of Z_{1e} to be $2Z_0$, we can obtain the best match at the final point 0, independent on the line length θ_1. Subsequently, if we want to get match at the next point which denoted by n, we may make the value of Z_{ne} to be (1), to get the best mach also independent on the line length θ_n.

$$Z_{ne} = \frac{2Z_0}{2n-1} \tag{1}$$

The input impedance at the right side of the Z_{m2e} is then

$$Z_{in} = \frac{2Z_0}{2n+1} \tag{2}$$

To achieve a dual band operation, the conventional quarter-wave section is replaced by two coupled-line sections, and the characteristic impedances (Z_{m1e}, Z_{m2e}) and the line lengths (θ_{m1}, θ_{m2}) for the two sections can be evaluated using the following Equations (2)–(6) [27], where, p can be arbitrary integers but should be chosen carefully to make it easy to fabricate in engineering (usually $p = 1$). The relationship between the first frequency f_1 and the second frequency f_2 is defined as $f_2 = qf_1$, where,q is the frequency ratio and $q \geq 1$.

$$\theta_{m1} = \frac{p \cdot \pi}{q+1} \quad (3)$$

$$\theta = \theta_{m1} = \theta_{m2} \quad (4)$$

$$\alpha = \tan^2(\theta) \quad (5)$$

$$Z_{m1e} = \sqrt{\frac{2Z_0}{2\alpha}(Z_{in} - 2Z_0) + \sqrt{\left(\frac{2Z_0}{2\alpha}(Z_{in} - 2Z_0)\right)^2 + (2Z_0)^3 \cdot Z_{in}}} \quad (6)$$

$$Z_{m2e} = \frac{2Z_0 \cdot Z_{in}}{Z_{m1e}} \quad (7)$$

From the analysis above, (1)–(7) can be used to obtain the even mode impedances of multi-way BPD. The BPD mainly focuses on input port matching and output port transmitted power. Once even mode impedance is fixed, the odd mode impedance is obtained arbitrarily. Because a smaller odd mode impedance results in a smaller spacing between the coupled lines, we choose the spacing so as to make it easy to fabricate.

Therefore, the procedure to design the compact multi-way BPD is briefly summarized as follows:

1) According to the practical requirements, determine the n, p, q and $\theta_1 \ldots \theta_n$;
2) Determine θ_{m1} and θ_{m2}, from (3)–(4);
3) Determine characteristic impedances Z_{m1e}, Z_{m2e}, $Z_{1e} \ldots Z_{ne}$ from (1)–(7);
4) Chosen Z_{m1o}, Z_{m2o}, $Z_{1o} \ldots Z_{no}$ carefully to make easy fabricate and compact in engineering tradeoff.

3. SIMULATION AND EXPERIMENT

In this section, a 3-way coupled lines BPD will be presented to achieve size reduction as an example of the proposed multi-way BPD, and illustrated in Fig. 2. Thanks to the analysis above, the following relations are obtained:

$$Z_{in} = \frac{2Z_0}{3} \quad (8)$$

$$Z_{1e} = 2Z_0 \quad (9)$$

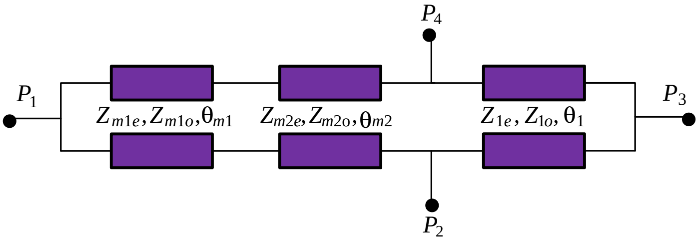

Figure 2. Schematic diagram of the proposed compact 3-way BPD.

Table 1. Design parameters of the proposed 3-way coupled lines BPDs.

$f_1 = 1.0$ GHz, $Z_0 = 50\,\Omega$, $p = 1$										
	q	θ (deg.)	θ_1 (deg.)	Z_{m1e} (Ω)	Z_{m1o} (Ω)	Z_{m2e} (Ω)	Z_{m2o} (Ω)	Z_{1e} (Ω)	Z_{1o} (Ω)
Case 1	2.4	52.94	30	64.6	49	51.57	40.4	100	71.2
Case 2	3.5	40	30	52.3	40.8	63.8	48.45	100	71.2

Table 2. Physical definition of the proposed 3-way coupled lines BPDs.

	q	w_1 (mil)	l_1 (mil)	w_2 (mil)	l_2 (mil)	w_3 (mil)	l_3 (mil)	$s_1 = s_2 = s_3$ (mil)
Case 1	2.4	52.3	1070	74.4	1053.8	22.4	624.5	30
Case 2	3.5	73	797	53.4	807	22.4	624.5	30

To certify this structure and design parameters, two typical 3-way coupled lines BPDs are designed, fabricated, and measured. The Rogers R04350B substrate with a relative dielectric constant of 3.48 and a thickness of 30 mil is used in these two examples. The first 3-way coupled lines BPD (Case 1) operating frequency is $f_1 = 1.0$ GHz and $f_2 = 2.4$ GHz; the second 3-way coupled lines BPD (Case 2) operating frequency is $f_1 = 1.0$ GHz and $f_2 = 3.5$ GHz, and the calculated electrical parameters of them are illustrated in Table 1. In addition, the accurate physical dimension values of the typical 3-way coupled lines BPDs are shown in Table 2. It should be emphasized that choosing a different value for θ_1 will not affect the matching at the input port and the equal split property of this 3-way coupled lines BPDs, Moreover, the BPD area will be increased with the increasing of θ_1. In order to design and fabricate easily, tradeoff choose the spacing between the coupled lines. The final photograph of the fabricated 3-way coupled lines BPDs are shown in Fig. 3, which occupy areas of only $0.45 \times 6.98\,\text{mm}^2$ (Case 1) and $0.447 \times 5.66\,\text{mm}^2$ (Case 2), respectively.

The simulation is based on lossless coupled-line models, and

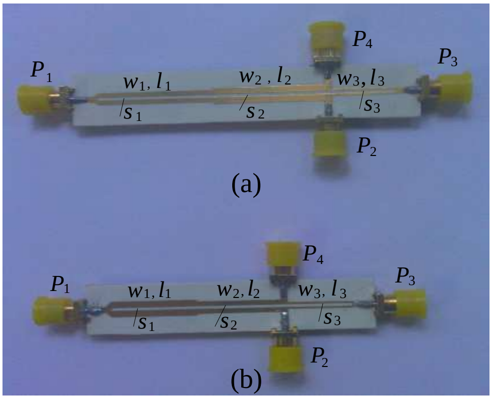

Figure 3. Photographs of the fabricated 3-way coupled lines BPDs, (a) Case 1, and (b) Case 2.

Table 3. Measured results are briefly summarized of the fabricated BPDs.

	Case 1		Case 2	
Operating frequency	f_1=1.0 GHz	f_2 = 2.4 GHz	f_1 = 1.0 GHz	f_2 = 3.5 GHz
$S_{11} < -15$ dB bandwidth /fractional bandwidth	0.75∼1.21 GHz /46%	2.06∼2.52 GHz /19.2%	0.77∼1.15 GHz /38%	3.17∼3.55 GHz /10.9%
S_{21} (−4.9 dB±1 dB) bandwidth /fractional bandwidth	0.65∼1.33 GHz /68%	1.95∼2.57 GHz /25.8%	0.67∼1.22 GHz /55%	3.11∼3.61 GHz /14.3%
S_{31} (−4.9 dB±1 dB) bandwidth /fractional bandwidth	0.65∼1.33 GHz /68%	1.97∼2.56 GHz /24.6%	0.67∼1.22 GHz /55%	3.14∼3.58 GHz /12.6%

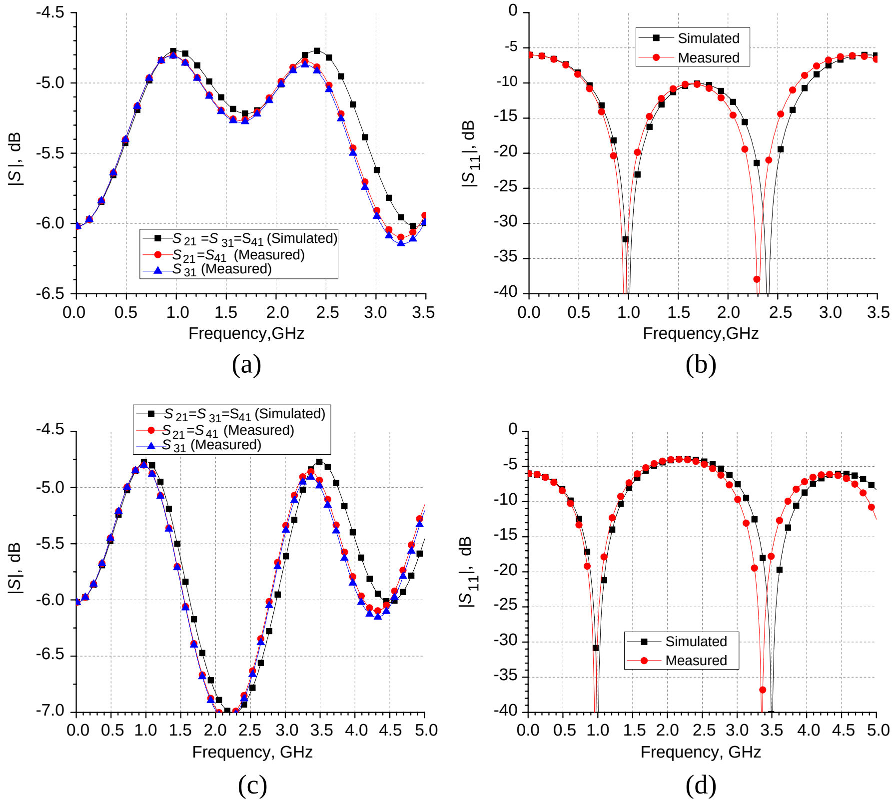

Figure 4. Simulated and measured results of the fabricated BPDs, (a) (b) Case 1, and (c) (d) Case 2.

Table 4. Design parameters and physical definition of the conventional 3-way BPDs.

$f_1 = 1.0\,\text{GHz},\ Z_0 = 50\,\Omega,\ p = 1$										
	q	Z_{m1} (Ω)	Z_{m2} (Ω)	Z_1 (Ω)	W_1 (mil)	L_1 (mil)	W_2 (mil)	L_2 (mil)	W_3 (mil)	L_3 (mil)
Case A	2.4	64.6	51.57	100	42.4	1074	63	1056	15.6	630
Case B	3.5	52.3	63.8	100	61.6	799	43.4	811	15.6	630

the measurement is accomplished by using Agilent N5230A network analyzer. Fig. 4 shows the simulated and measured results of the 3-way coupled lines BPDs Case 1 and Case 2.

Both simulation and measurement results prove the validity of the

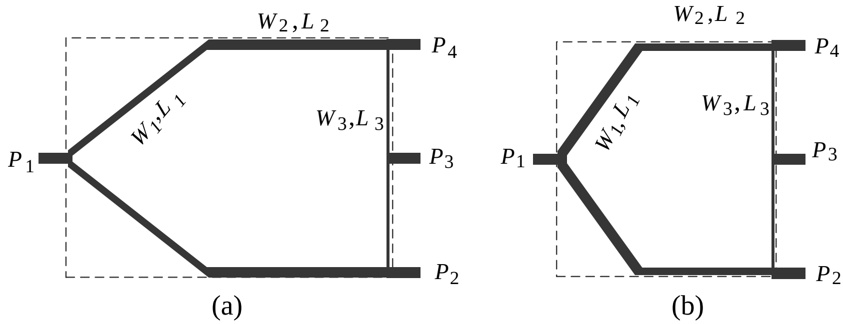

Figure 5. The physical definition of the conventional 3-way BPDs, (a) Case A, and (b) Case B.

design. Very good matching at the input port is achieved, and good transmission parameters are obtained. In details, when the input port matching and transmission parameters are considered, the measured results are illustrated in Table 3.

Finally, to compare the size with conventional 3-way BPD, Fig. 5 shows the physical definition of the conventional 3-way BPDs named Case A and Case B, by using the same substrate and frequency with Case 1 and Case 2, respectively. The detailed physical dimension values are shown in Table 4. Areas of the conventional 3-way BPDs are $3.69 \times 4.84\,\text{cm}^2$ (Case A) and $3.59 \times 3.27\,\text{cm}^2$ (Case B), and the reduction in size of 82.26% and 78.45%, respectively.

4. CONCLUSION

A novel dual band multi-way planar BPD using coupled lines to reduce the size is proposed. All the lines in this structure are coupled lines, which makes the circuit size compact. To validate the design procedure, two dual band 3-way BPDs are designed, simulated, and fabricated. Very good matching at the input port is achieved, and good transmission parameters are obtained. The layout is more compact with a reduction in size of 82.26% and 78.45% compared to the conventional ones respectively. Actually, this proposed compact BPD can be easily realized in the planar PCB procedure or monolithic microwave integrated circuit (MMIC).

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