A Miniaturized Balanced-to-Unbalanced In-Phase Filtering Power Divider With Wide Upper Stopband and Wideband Common-Mode Suppression

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ABSTRACT A miniaturized balanced-to-unbalanced in-phase filtering power divider with wide upper stopband and wideband common-mode suppression is proposed. The in-phase feature is realized by the coupled/non-coupled lines. The stub with shunt-capacitor is used to realize the functions of filtering and miniaturization. The closed-form design equations are provided and discussed. To verify the design equations, one prototype with a center frequency of 1.0 GHz is designed and fabricated. The measured differential return loss is greater than 15 dB in the range of 0.82-1.22 GHz (39.2%). The upper stopband rejection is better than 20 dB from 1.41 to 3.57 GHz. Common-mode suppression is greater than 20 dB from 0 to 3.7 GHz. The measured results are in good agreement with electromagnetic simulations.

INDEX TERMS Balanced to unbalanced, filtering power divider, circuit miniaturization, in-phase, wide stopband.

I. INTRODUCTION

Due to the function of splitting an input signal or combining two input signals, power dividers have been widely used in a large variety of microwave systems, such as antenna feeding networks [1] and power amplifiers [2]. With the development of the high-speed communication system, the enhancement of signal stability has drawn more attention. The electromagnetic interference noise similarly plays a very important role on the performance of overall systems. Hence balanced components like balanced power divider [3], balanced coupler [4], [5], and balanced filter [6], [7] with the advantages of good common-mode suppression (CMS) and high immunity to environmental and device electronic noise have been widely studied. Moreover, for the microwave circuits comprising both balanced and unbalanced ports, an additional balun is required, which leads to bulky size and large in-band insertion loss. Therefore, balanced-to-unbalanced (BTU) components are also widely studied to avoid a larger size and realize common-mode rejection in the meantime.

Most of the existing BTU power dividers have the out-of-phase output characteristic [8]. A phase inverter must be used in the in-phase feeding networks of the antenna array and power amplifiers, which also causes large size. Moreover, a conventional BTU power is composed of four quarter-wavelength branch lines and one half-wavelength transmission line [9], thus occupies a considerable area that exceeds practical limitations of modern miniaturization-oriented systems [10], [11].

Multifunctional components which integrate multiple functions into one structure can meet the requirement for the efficiency and compactness of modern miniaturization-oriented systems. The co-design of the BTU power divider and filter is widely used to improve integration. In [12], a BTU filtering power divider is proposed, but the usage of slot line transition structure occupies a large area. Coupled lines are used to realize the filtering function in [13], [14]. However, these designs do not consider the circuit miniaturization.

In this paper, a miniaturized BTU in-phase filtering
power divider (FPD) is proposed. Coupled/non-coupled lines and stubs are used to realize in-phase and filtering functions, respectively. Shunt capacitors are used to minimize the size. Even- and odd-mode analysis is used to derive the closed-form design formulas. One prototype is fabricated and measured. Both the theoretical and experimental results are given and discussed.

II. MINIATURIZED BTU FPD CIRCUIT AND ANALYSIS

As shown in Fig. 1(a), the proposed miniaturized BTU filtering power divider is composed of a pair of short-circuited coupled lines (in Block 1), three branch lines \((Z_{12})\), three shunt stubs \((Z_0)\), six shunt capacitors \((C_1\) and \(C_2)\), and an isolation resistor \(R\). All the transmission-line (TL) sections have the same electrical length \(\theta\). There are four ports in this structure. Ports 1+ and 1− are the differential pairs whereas Ports 2 and 3 are unbalanced ports. The short-circuited coupled lines can be equivalent to a phase inverter cascaded by a \(\pi\)-type network [15], as shown in Fig. 1(b). The relation between the even- and odd- characteristic impedance \(Z_e\) and \(Z_o\) of the short-circuited coupled lines and its equivalent circuit is given as

\[
\begin{align*}
Z_e &= Z_1 \\
\frac{1}{Z_{12}} &= \frac{1}{2} \left( \frac{1}{Z_0} - \frac{1}{Z_e} \right)
\end{align*}
\]

\[(1)\]

The equivalent circuit of the proposed filtering power divider is shown in Fig. 1(c), which is symmetrical along line \(AA'\) except the phase inverter. Therefore, the signals at the lower and upper bisections have the same magnitude.

A. Even-Mode Analysis

The even-mode equivalent circuit of the proposed miniaturized BTU filtering power divider is shown in Fig. 2. A transmission-line section can be decomposed into a \(J\)-inverter \(J_a\) and two shunt stubs \(B_a\) as shown in Fig. 3. The relation between the \(J\)-inverter \(J_a\), shunt stubs \(B_a\), and transmission-line section are given as

\[
\begin{align*}
J_a &= \frac{Y_a}{\sin \theta} \\
B_a &= -Y_a \cot \theta
\end{align*}
\]

\[(2)\]

\[(3)\]

After decomposing the transmission-line sections \((Z_{12})\), the equivalent even-mode circuit can be obtained as Fig. 4(a), which can be further described as a 3-order bandpass filter with three shunt resonators and two \(J\)-inverters as shown in Fig. 4(b).

By using (3), the susceptances of shunt resonators can be obtained as follows,

\[
\begin{align*}
B_1 &= -(Y_1 + Y_{12}) \cot \theta + \omega C_1 \\
B_2 &= -(\frac{1}{2}Y_1 + 2Y_{12}) \cot \theta + \omega C_2
\end{align*}
\]

\[(4)\]

where \(Y_1=1/Z_1, Y_{12}=1/Z_{12}\). \(\omega\) is angle frequency.
At center angle frequency of \( \omega_0 \), the susceptance of each resonator is equal to zero (i.e., \( B_1 = B_2 = 0 \)). Then the values of shunt capacitors and \( J \)-inverter can be calculated as

\[
\begin{align*}
C_1 &= \frac{(Y_1 + Y_{12})\cot \theta}{\omega_0} \\
C_2 &= \frac{(1/2 Y_1 + 2 Y_{12})\cot \theta}{\omega_0} \\
J_{12} &= \frac{Y_{12}}{\sin \theta} \quad (6)
\end{align*}
\]

The susceptance slope parameters of shunt resonators are obtained by using (4) as follows

\[
\begin{align*}
b_1 &= \frac{\omega_0}{2} \frac{d B_1}{d \omega_{\text{ref}}} 
&= \frac{(Y_1 + Y_{12})}{2} \left( \cot \theta + \theta \csc^2 \theta \right) \\
b_2 &= \frac{\omega_0}{2} \frac{d B_2}{d \omega_{\text{ref}}} 
&= \frac{(Y_1 + Y_{12})}{4} \left( \cot \theta + \theta \csc^2 \theta \right) \\
\end{align*}
\]

Substituting (6) and (7) into (8) and (9), it can be obtained as (10).

\[
\begin{align*}
Z_0 \frac{b_1 \cdot \Delta}{g_0 \cdot g_1} &= 1 \\
\frac{b_1 \cdot \Delta}{b_2 \cdot \Delta} &= 1 \\
\frac{g_1}{g_2} \cdot \frac{J_{12}^2}{\theta} &= 1 \\
\end{align*}
\]

where \( \Delta \) is the fractional bandwidth (FBW). \( g_0, g_1, \) and \( g_2 \) are the 3-order low-pass prototype value, respectively.

Fig. 5 shows the calculated characteristic impedances \( Z_1 \) and \( Z_{12} \) versus the electrical length \( \theta \) for specific FBW \( \Delta \), where the 3-order Chebyshev low-pass prototype values are given as \( g_0 = 1.0, g_1 = g_3 = 0.6291, \) and \( g_2 = 0.9702 \) [16] with \( Z_0 = 50 \Omega \). It is seen from Fig. 5 that the required values of \( Z_1 \) and \( Z_{12} \) become larger with the decrease of electrical length \( \theta \) from 90° to 0°. When FBW is increased from 20% to 50%, the required value of \( Z_1 \) is increased sharply. For the FBW of 50%, when \( \theta \) is less than 35°, the characteristic impedance \( Z_1 \) even becomes unacceptable. Therefore, there needs a tradeoff between the miniaturized electrical length and the FBW.

**B. Odd-Mode Analysis**

The odd-mode equivalent circuit is shown in Fig. 6, its block diagram of the equivalent odd-mode circuit is given in Fig. 7(a). Since the shunt stubs with shunt capacitors resonate at the center frequency \( (B_1 = B_2 = 0) \), therefore, Fig. 7(a) can be simplified as Fig. 7(b). Considering impedance matching at the center frequency (i.e., \( |S_{\text{odd}}| = |S_{\text{even}}| = 0 \), the value of \( R \) can be obtained as

\[
R = 2Z_0 \quad (13)
\]
TABLE 1. Dimensions of the proposed miniaturized BTU filtering power divider (unit: mm).

| W12 | Wc | W2 | W01 | W02 | S  | Wf | Wc |
|-----|-----|-----|------|------|----|------|-----|
| 1.27| 4.87| 1.31| 1.20 | 0.50 | 2.00| 1.85 |

| L12 | Lc | L2 | L01 | L02 | S1 | S2 |
|-----|----|----|-----|-----|----|-----|
| 14.3| 9.13| 25.7| 20.5 | 17.6 | 0.79| 4.14 |

FIGURE 8. Layout of the proposed miniaturized BTU filtering power divider.

FIGURE 9. Photographs of the fabricated miniaturized BTU filtering power divider. (a) Top view. (b) Bottom view.

Based on the foregoing analysis, the following procedures are suggested to design the proposed BTU filtering power divider.

1) Determine the FBW and center angle frequency $\omega_0$ according to the design requirements. Obtain the values of relative dielectric constant $\varepsilon_r$ and thickness $h$ of the substrate.

2) According to the required FBW, select a proper electrical length $\theta$ referring to Fig. 5. Then calculate $Z_1$ and $Z_{12}$ using (11) and (12).

3) Calculate the capacitances $C_1$ and $C_2$ using (5).

4) Calculate the even- and odd- characteristic impedance of the short-circuited coupled lines $Z_e$ and $Z_o$ using (1).

5) So far, all the needed circuit parameters can be determined, then convert all the circuit parameters to the physical dimensions using the TL synthesis tool.

6) Optimize the physical dimensions using a full-wave electromagnetic simulator.

III. IMPLEMENTATION AND PERFORMANCE

To validate the proposed method, a miniaturized BTU filtering power divider is designed with a center frequency of $f_0 = 1.0$ GHz and an FBW of 37%. The chosen Chebyshev low-pass prototype values are $g_0 = 1.0$, $g_1 = g_3 = 0.6291$, and $g_2 = 0.9702$ with $Z_0 = 50$ $\Omega$. Based on Section II, the circuit parameters are calculated as $Z_1 = Z_e = 97.9$ $\Omega$, $Z_{12} = 95.9$ $\Omega$, $Z_0 = 32.2$ $\Omega$, $\theta = 35.2^\circ$, $C_1 = 4.65$ pF, $C_2 = 5.84$ pF, and $R = 2Z_0 = 100$ $\Omega$. Using the TL synthesis tool, the physical dimensions of TLs are calculated. However, the optimal dimensions must take the discontinuous interface into consideration. Thus, the final dimensions are obtained by using the HFSS EM simulation and given in Table 1. The
layout is depicted in Fig. 8. A floating conductor strip is inserted in the ground plane under the coupled lines [17] to enhance the level of coupling and achieve the low odd-mode impedance. As shown in Fig. 8, C1, C2, and C3 are chosen as 3.6 pF, 3.6 pF, and 3.9 pF, respectively. The prototype is implemented on a PTFE/woven-glass substrate with a relative dielectric constant of 2.65 and thickness of 1.5 mm. Photographs of the fabricated BTU filtering power divider are shown in Fig. 9. The circuit size of the prototype is 41 mm × 32 mm (0.20λg × 0.16λg).

Fig. 10 gives the simulated and measured results of the proposed miniaturized BTU filtering power divider. It is seen from Fig. 10(a) that the measured differential return loss (|S_{d11}|) is better than 15 dB from 0.82 to 1.22 GHz (FBW of 39.2%), in which the measured differential-mode to single-ended transmission coefficients |S_{d21}| remain −3.6 ± 0.2 dB. The upper stopband rejection is better than 20 dB from 1.41 to 3.57 GHz (up to 3.57f0). Fig. 10(b) depicts the common-mode performance. The common mode signals (including the measured |S_{d21}| and |S_{d11}|) are suppressed by more than 20 dB from 0 to 3.7 GHz. Fig. 10(c) exhibits the return loss (|S_{a22}|) and the isolation (|S_{a32}|) of unbalanced ports. The measured |S_{a22}| is less than −10 dB from 0.795 to 1.246 GHz. The measured isolation between the two unbalanced output ports at f0 is better than 32 dB. As shown in Fig. 10(d), the measured amplitude and phase imbalances between S_{a21} and S_{a31} are less than 0.3 dB and 1° from 0.5 to 1.25 GHz, respectively.

The comparisons of the proposed BTU filtering power divider with previous works are summarized in Table 2. It can be found that the proposed BTU filtering power divider has smaller size and wider upper stopband than the existing BTU filtering power divider designs [12]–[14], [18]–[25]. Furthermore, wideband CMS, large isolation, good DRL, and in-phase output characteristics are also obtained.

### IV. CONCLUSION

In this paper, a miniaturized BTU in-phase filtering power divider with wide upper stopband and wideband CMS has been presented. The coupled/non-coupled lines are used to realize in-phase outputs of unbalanced ports. The stub with shunt-capacitor is used to realize the function of filtering and circuit miniaturization. A 1.0-GHz prototype has been designed, fabricated, and measured. The measurement results are consistent with the EM simulation ones. The proposed BTU filtering power divider has wider upper stopband (up to 3.57f0) and smaller size than the previous BTU FPD designs. In addition, it also has good impedance matching, isolation, and in-phase output characteristics with wideband CMS (larger than 20 dB from DC to 3.7f0), which can be applied in various differential microwave circuits and systems.

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