A balanced-to-balanced directional coupler based on branch-slotline coupled structure

Abstract: In this paper, a balanced-to-balanced (BTB) branch-slotline directional coupler (DC) is firstly presented, which can realize an arbitrary power division ratios (PDRs). The coupler is composed by microstrip-to-slotline (MS) transition structures and branch-slotline coupled structures. The single-ended to balanced-ended conversion is simplified and easy to implemented by the MS transition structures, which intrinsically leads to the differential-mode (DM) transmission and common-mode (CM) suppression. Moreover, the different PDRs which are controlled by the widths of branch-slotlines can be achieved. In order to verify the feasibility of the proposed design method, two prototype circuits of the proposed coupler with different PDRs are fabricated and measured. The return loss and the isolation of two designs are all better than 10 dB. Moreover, the CM suppressions are greater than 35 dB. A good agreement between the simulation and measurement results is observed.

Keywords: branch-slotline coupled structure; BTB directional coupler; MS transitions.

1 Introduction

Directional couplers (DCs) are used as power divider, hybrid junction, and most commonly used as a sampling device for measuring forward and backward waves on a transmission line. Recently, most of the reported works are single ended-to-single ended (SETSE). Paper [1] introduces a novel, compact and wideband coupled-line ring hybrid configuration that allowed for the easy realization of arbitrarily high power division ratios (PDRs) featuring significant miniaturization and wider bandwidths. Some balanced to single-ended (BTSE) or single-ended to balanced (SETB) couplers are also reported lately. In [2], the six-port quadrature and rat-race BTSE/SETB couplers with arbitrary PDRs and terminated resistances are proposed for the first time. In [3], a compact SETB four-section coupled-line coupler with inherent impedance matching and arbitrary PDRs is proposed. In [4], various types of six-port BTSE/SETB rat-race couplers with wideband common-mode (CM) suppression characteristics are presented. And the PDRs for the couplers can be flexibly adjusted by the characteristic-impedance parameters of their constituent transmission-lines. In [5], a new SETB impedance-transforming branch-line coupler composed of four quarter-wavelength and two half-wavelength microstrip lines with the arbitrary PDRs and arbitrary terminated impedances is presented. Recent years, several balanced-to-balanced (BTB) couplers are being studied and reported in some papers. In [6], a balanced branch-line coupler achieved wide bandwidth and low cost with arbitrary PDRs is proposed. In [7], a new BTB rat-race coupling network to achieve the differential-mode (DM) power division, DM impedance match, CM suppression, and port isolation is presented. In [8], a balanced coupler used only two varactors with improved phase balance and extended bandwidth for a wide range of tunable PDRs is proposed.

In this paper, a novel wideband BTB branch-slotline DC with an arbitrary PDRs is presented. The power distribution for DM signals and the CM suppression are integrated in one circuit. The couplers could achieve the arbitrary PDRs by employing branch-slotline structures. Furthermore, the circuit size of the BTB couplers is similar to single-ended ones. Two design prototypes with PDR of 1:1 and 2:1 are simulated and measured. The return losses and isolations of two designs are all better than 10 dB, and the CM suppressions are greater than 35 dB. The obtained measurement results are in a good agreement with the electromagnetic (EM) calculations, which shows good...
performance and proves the applicability of the proposed couplers.

2 Analysis and design

Figure 1 shows the schematic of a conventional branch-line DC. When power is input from port 1, the output power of the port 3 and port 4 can be distributed in a certain proportion. Ideally, port 2 is an isolated port which is no power to output.

For the balanced system, at least four baluns are needed to the single-ended (SE) branch-line DC, as shown in Figure 2 (a). However, the utilization of baluns and impedance transformers leads to design complexity and large in-band insertion loss. In comparison, the employment of SETB transitions has more advantages in terms of miniaturization and lower loss. Therefore, it is advantageous to develop a BTB branch-line DC. The circuit topology shown in Figure 2 (b) is symmetric with respect to the central line (A-A’).

The microstrip-to-slotline (MS) transition, which is composed of a U-type microstrip feed line crossing with a stepped impedance slotline resonator, is utilized in this design instead of SETB transition. It could separate the DM responses from the CM ones. The layout of the MS transition structure is shown in Figure 3. In order to achieve miniaturization of circuit devices, optimized slotline segment size (length is much less than λ/4) is utilized in the configuration of proposed BTB branch-line coupler. The larger the width of the slotline segment is, the better the open-circuit performance will be.

Because of the geometrical symmetry, the balanced circuit can be analyzed using the DM and CM methods, as shown in Figure 4 (a). Furthermore, the cross-views of electrical field distribution at S-S’ plane are used for demonstrating its working mechanism in Figures 4 (b) and (c). When a DM excitation is applied, a virtual electrical wall can be obtained at plane S-S’. A quasi-transverse electromagnetic slotline mode generates a virtual electrical wall at the same plane. Through the strong magnetic coupling, the DM signals along the U-type microstrip feedline can be converted successfully into the slotline mode propagating along the stepped impedance slotline resonator and be transferred to the next transition. Therefore, good DM transmission with a wideband response can be realized. The wideband transmission characteristic of the slotline resonator has been analyzed in [9]. Under CM operation, a virtual magnetic wall at S-S’ plane is formed.

Figure 1: Schematic diagram of the conventional branch-line directional coupler (DC).

Figure 2: (a) Cascade of a single-ended DC and four baluns; (b) balanced-to-balanced (BTB) DC.

Figure 3: Configuration of the microstrip-to-slotline (MS) transition structure.
Due to the magnetic wall perpendicular to the electric field of the slotline mode, which conflicts with the magnetic wall's boundary condition, the CM signals are blocked and hence a better CM suppression is achieved. In the end, balanced MS transition structures are employed to transformation between the slotline modes and the microstrip line modes. Therefore, the structure is very simple and suitable for designing extended wideband microwave components.

In a SE circuit, a second-order matrix can represent a two-port network. In a balanced system, since a pair of DM signals are transmitted, a pair of parallel transmission lines must be used. Therefore, the fourth-order $S$-parameter matrix would be used to represent a two-port network in the balanced system. For the convenience of analysis, the balanced two-port network can be regarded as a four-port network, as shown in Figure 5.

The incident and reflected waves in the DM can be expressed as:

$$[S_{mm}] = [M][S][M]^{-1}$$  \hspace{1cm} (1)

where:

From the above analysis, the traditional SE $S$-parameters can be converted into mixed-mode $S$-parameters when the decisive condition ($Z_{0d} = Z_{0e} = Z_0$) holds.

Explanation of the superscript of the mixed-mode $S$-parameters matrix in Formula (2):
- $S_{dd}$ sub-matrix: $S$ parameters of the mode transmission from DM signal to DM signal,
- $S_{dc}$ sub-matrix: $S$ parameters of the mode conversion from CM signal to DM signal,
- $S_{cd}$ sub-matrix: $S$ parameters of the mode conversion from DM signal to CM signal,
- $S_{cc}$ sub-matrix: $S$ parameters of the mode transmission from CM signal to CM signal.

Since the slotline is narrower than the microstrip line, it is easy to be bent and the miniaturization can be realized. Therefore, the branch-line of the conventional coupler can be replaced by the branch-slotline. Moreover, the four balanced ports are achieved by the MS transition structures. As shown in Figure 6, the energy is converted into slotline-transmission mode by MS transition, and then transferred along the slotline.

### 3 Simulation and measurement results

The configuration of the proposed BTB branch-line coupler is shown in Figure 6. The substrate is Rogers
RT/duriod 5880 with a dielectric constant of 2.2 and a thickness of 0.8 mm. The effective dimension of the proposed coupler is only 56.5 × 43 mm (0.54λg × 0.41λg, where λg is the guide wavelength at the center frequency), in which all the dimensions are selected as follows: \( W_{d1} = 2.5 \) mm, \( W_{d2} = 3.0 \) mm, \( L_{d1} = 12.5 \) mm, \( L_{d2} = 13.0 \) mm, \( L_{s1} = 9.8 \) mm, \( L_{s2} = 3.4 \) mm, \( L_{s3} = 9 \) mm, \( L_{s4} = 10 \) mm, and \( L_{s5} = 3.6 \) mm.

The PDR, isolation and other parameters of the proposed branch-line coupler are influenced by the widths of branch-slotlines. Under the precondition of the qualified return loss and isolation, the variable range of \( W_1 \) is 0.15–0.45 mm, and the variable range of \( W_2 \) is 0.4–1.4 mm. PDR would be larger when \( W_1 \) decreases or \( W_2 \) increases as shown in Figure 7. It can be known that PDR range of the coupler is 0.8–3.3 by simulation. After simulation and optimization, the simulated and measured results of the couplers with PDRs of 1:1 and 2:1 are given below.

### 3.1 Design results of the proposed coupler with PDR of 1:1

The input power would be contributed equally to through port and coupled port of the proposed coupler when...
$W_1 = 0.3$ mm and $W_2 = 0.55$ mm. Figure 8 shows the frequency responses of the proposed coupler with equal power division. It can be seen that the isolation $|S_{21}^{dd}|$ and the return loss $|S_{11}^{dd}|$ are all better than 10 dB. In addition, the insertion loss of through port $|S_{41}^{dd}|$ and the coupling $|S_{31}^{dd}|$ are about 4.7 dB in the operating bandwidth (1.7~3.2 GHz).

Also, the S parameters under CM excitation is shown in Figure 8 (c) to demonstrate the good CM rejection, such as $|S_{21}^{cc}|$, $|S_{31}^{cc}|$, $|S_{41}^{cc}|$ are all greater than 40 dB. The measured results of the proposed coupler agree well with the simulated results.

As shown in Figure 8 (d), the output phase difference between the output ports of the coupler is 75 degrees in order to meet the requirements of our project. However, the output phase difference of the proposed coupler can also be 90 degrees by employing the following method.

As shown in Figure 9, different output phase differences can be obtained by changing the length of the U-type slotline. The simulation results of the phase parameters are different with the different slotline lengths (SLs). We optimized the simulation model to get the following results (Figure 10).

### 3.2 Design results of the proposed coupler with PDR of 2:1

The unequal PDR of the proposed coupler would be achieved when $W_1 = 0.3$ mm and $W_2 = 1.2$ mm. Figures 11 (a) and (b) show the in-band magnitude response under DM excitation, respectively. In the operating bandwidth (1.7~3.2 GHz), $|S_{31}^{dd}|$ and $|S_{41}^{dd}|$ are unequal to 7.0 and 3.5 dB. The isolation and the return loss are all greater than 10 dB, and the fractional bandwidth (FBW) is 61.2%. Figure 11 (c)
Figure 11: Simulated and measured results of the proposed coupler with 2:1 PDR about (a) $\left| S_{dd}^{11} \right|$ and $\left| S_{dd}^{21} \right|$, (b) $\left| S_{dd}^{31} \right|$ and $\left| S_{dd}^{41} \right|$, (c) $\left| S_{cc}^{11} \right|$, $\left| S_{cc}^{31} \right|$ and $\left| S_{cc}^{41} \right|$, (d) simulated results about the phase parameters.

Table 1: Comparison with some reported couplers.

| Ref. | Type         | $f_0$ (GHz)/FBW | PDR | CMS | Size ($\lambda_0^{-1}$) |
|------|--------------|-----------------|-----|-----|------------------------|
| [4]-Design 1 | SETB | 2/7.6% | 1:1 | >25 dB | 0.2139 |
| [4]-Design 2 | SETB | 2/8.5% | 3:1 | >20 dB | 0.14 |
| [7]-Single-stage 1 | BTB | 1.86/4.3% | 1:1 | >20 dB | 0.26 |
| [7]-Single-stage 2 | BTB | 1.86/7.3% | 2:1 | >20 dB | 0.26 |
| [7]-Single-stage 3 | BTB | 1.86/10.2% | 4:1 | >20 dB | 0.26 |
| [8]-Circuit 1 | BTSE/SETB | 0.9/91% | 1:1 | >15 dB | 0.045 |
| [8]-Circuit 2 | BTSE/SETB | 0.9/84.4% | 7:1 | >15 dB | 0.045 |
| [9]-Design 1 | SETB | 1/47.3% | 1:1 | >20 dB | 0.146 |
| [9]-Design 2 | SETB | 2.5/12% | 3:1 | >20 dB | 0.234 |
| [9]-Design 3 | SETB | 2.5/20% | 6:1 | >20 dB | 0.225 |
| [9]-Design 3 | SETB | 2.5/17.6% | 6:1 | >20 dB | 0.312 |
| This work | BTB | 2.45/61.2% | 0.8–3.3 | >35 dB | 0.1365 |

FBW = Fractional bandwidth.
PDR = Power division ratio.
CMS = Common-mode suppression.
shows the results under CM excitation. $|S_{11}|$ is about 0 dB, and $|S_{21}|$, $|S_{31}|$, $|S_{41}|$ are better than 35 dB. It shows the good CM rejection can be obtained. The measured results are in agreement with the simulated ones.

Compared to the reported works in Table 1, the contributions of proposed coupler are as follows: Firstly, overall better performance has been achieved over many reported designs. For example, the CM suppression is better than 35 dB in working bandwidth. The size of proposed coupler is smaller than most reported couplers. The center frequency is 2.45 GHz, and a wide 3 dB bandwidth is obtained covering from 1.7 to 3.2 GHz (FBW = 61.2%). Secondly, the proposed coupler is BTB, which could be more adapted to the balanced systems to improve the CM suppression. Finally, the proposed structure has a great flexibility to tune the PDR of the proposed coupler to meet different system requirements. Therefore, the proposed balanced coupler is competitive in the applications for balanced communication systems.

4 Conclusion

A BTB coupler based on the branch-slotline coupled structure is presented, which can achieve an arbitrary PDRs. The key concept to fulfill the design is the coupled structure, which can influence the PDR if the width of branch-slotline changes. The simulated and measured results of the four-balanced-port S-parameters are illustrated. In the operating bandwidth of coupler, the DM return losses and the DM isolations are greater than 10 dB, and a good CM rejection can also be obtained. The simulated results are in a good agreement with the measured ones. Its application to balanced circuits will be an interesting topic worthy of future study.

Author contribution: All the authors have accepted responsibility for the entire content of this submitted manuscript and approved submission.

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