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Article

Balanced-to-Balanced Filtering Crossover with High Isolation and CM Suppression

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***Abstract*— A novel planar balanced-to-balanced (BTB) microstrip filtering crossover with high isolation and common-mode (CM) suppression is proposed in this paper. The circuit structure is based on microstrip transmission lines without coupling sections, which can reduce insertion loss and enhance isolation. Specific theoretical analysis of the BTB filtering crossover configuration using transfer matrix and mixed-mode scattering parameters is performed. In order to verify the validity of the theory analysis and design, a microstrip BTB filtering crossover prototype at the center frequency of 2.45 GHz is fabricated and measured with high isolation and excellent CM suppression.**

***Index Terms*—** BTB, filtering crossover, high isolation, CM suppression.

I. INTRODUCTION

Because of the ability to achieve cross-transmission of signals while maintaining high isolation, microwave crossovers have attracted a significant amount of interest and application in the Butler matrix of modern array antenna beam-forming technology. Compared to microwave crossovers implemented on 3-D configurations such as air bridges [1], underpasses [2], or substrate-integrated waveguides [3], planar crossovers based on microstrip structures have considerable advantages of low loss and simple manufacturing. Traditional microstrip crossovers can be achieved by ring-shaped configurations [4] or cascading multistage branch-line couplers [5]. In order to accomplish the function integration of microwave components, planar microstrip filtering crossovers with frequency selectivity are proposed in [6, 7]. However, the aforementioned microwave crossovers are limited to single-ended system applications.

With the rapid development of modern balanced RF transceiver systems, the balanced-to-balanced (BTB) microwave components, such as balanced filters [8] and balanced power dividers [9], have been emphasized because of their excellent common-mode suppression (CMS) and immunity to electromagnetic environmental interference than single-ended counterparts. Planar BTB microstrip crossovers [10-12] thus have very promising applications that are worth investigating. Fig. 1 illustrates two different implementations of the balanced filtering crossover. A composite balanced filtering crossover in Fig. 1(a) is composed of a single-ended crossover with four filtering networks and four Baluns. Fig. 1(b) demonstrates a type of BTB filtering crossover by co-design, which does

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not require an external cascaded filtering network to achieve band-pass responses and does not require the use of Baluns for connection between single-ended circuits and balanced circuits, and thus allows for a significant reduction in overall size compared to Fig. 1(a). In [13], a BTB filtering crossover with high selectivity is presented based on the square patch resonator. A planar balanced crossover with band-pass response is proposed in [14], which consists of a ring resonator and four half-wavelength resonators. However, both use the coupling method to excite the resonators, so the fabricated crossovers have a large measured insertion loss and suffer from insufficient isolation.

In order to achieve the bandpass filtering response of the BTB crossover and to solve the problems of excessive insertion loss and insufficient isolation of the previous BTB filtering crossovers, a novel planar BTB microstrip filtering crossover with high isolation and CMS is proposed in this paper. It is composed of microstrip transmission lines without coupling sections, which can reduce insertion loss and enhance isolation. The specific theory analysis of the proposed BTB filtering crossover is given and discussed. In order to verify the viability, a microstrip prototype has been fabricated and measured. The simulated results are in excellent agreement with the measured results.

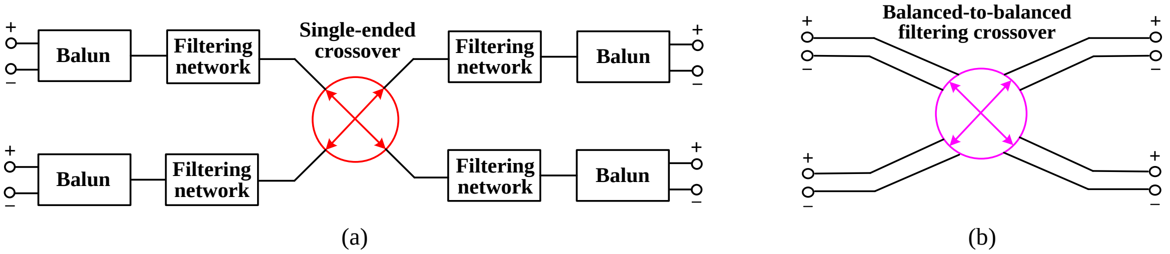

Fig. 1. Balanced filtering crossovers. (a) Composite balanced filtering crossover composed of a single-ended crossover with four filtering networks and four Baluns. (b) Balanced-to-balanced filtering crossover without filtering networks or Baluns.

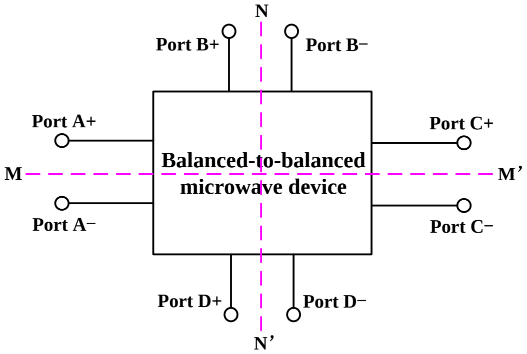

Fig. 2. Schematic of a typical balanced-to-balanced four-port crossover.

II. THEORY ANALYSIS AND DESIGN

Fig. 2 shows a typical balanced-to-balanced four-port crossover, which has two symmetry planes MM' and NN' consisting of balanced ports denoted as A, B, C, and D. Each balanced port consists of two single-ended ports with positive and negative polarity. The mixed-mode *S*-parameter matrix of a BTB four-port crossover is

$$[S_{\mathrm{mix}}]=\begin{bmatrix} S_{\mathrm{dd}} & S_{\mathrm{dc}} \\ S_{\mathrm{cd}} & S_{\mathrm{cc}} \end{bmatrix} \tag{1}$$

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where S_{dd}, S_{dc}, S_{cd}, and S_{cc} are all 4×4 submatrices. The letters d and c identify the differential mode (DM) and common mode (CM), respectively. For example, the conversion of the CM wave into the DM wave is denoted by the symbol dc. Each of the four submatrices can be written as

$$[S_{pq}]=\begin{bmatrix} S_{pq\mathrm{AA}} & S_{pq\mathrm{AB}} & S_{pq\mathrm{AC}} & S_{pq\mathrm{AD}} \\ S_{pq\mathrm{BA}} & S_{pq\mathrm{BB}} & S_{pq\mathrm{BC}} & S_{pq\mathrm{BD}} \\ S_{pq\mathrm{CA}} & S_{pq\mathrm{CB}} & S_{pq\mathrm{CC}} & S_{pq\mathrm{CD}} \\ S_{pq\mathrm{DA}} & S_{pq\mathrm{DB}} & S_{pq\mathrm{DC}} & S_{pq\mathrm{DD}} \end{bmatrix} \tag{2}$$

where *pq* could be dd, dc, cd, or cc. Specifically, the proposed BTB filtering crossover that features DM pass-through, CM suppression and prohibition of cross-mode conversion between DM and CM can be described by using the mixed-mode *S*-parameters in the following analysis.

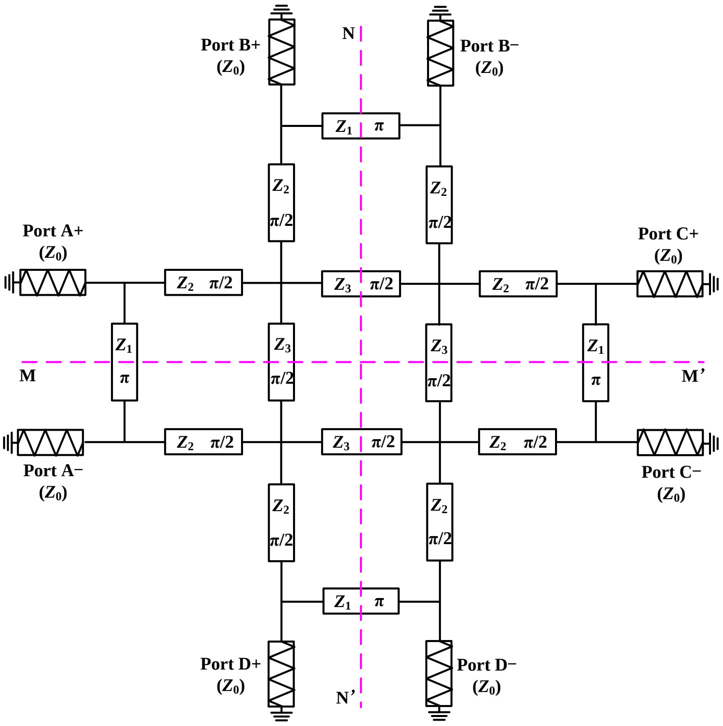

Fig. 3. Configuration of the proposed BTB filtering crossover.

The configuration of the proposed BTB filtering crossover is illustrated in Fig. 3. It is composed of three types of microstrip lines with different characteristic impedances and electrical wavelengths, where the microstrip line with characteristic impedance Z_1 corresponds to the electrical wavelength of π at the center frequency of f_0, denoted (Z_1, π), and similarly (Z_2, π/2), (Z_3, π/2). Since the structure of the proposed BTB filtering crossover is perfectly symmetric (horizontally symmetric about MM’ and vertically symmetric about NN’), the simplified equivalent sub-circuit of the proposed BTB filtering crossover is obtained in Fig. 4, which can be considered as a cascade of five microstrip sections. Because of the even- and odd-mode analysis method, four different modes of the simplified equivalent sub-circuit (e, e), (e, o), (o, e), and (o, o) are shown in Table I. Denote S^{ee}, S^{eo}, S^{oe}, and S^{oo} as two-port *S*-parameters of the equivalent sub-circuit corresponding to (e, e), (e, o), (o, e), and (o, o) modes, respectively.

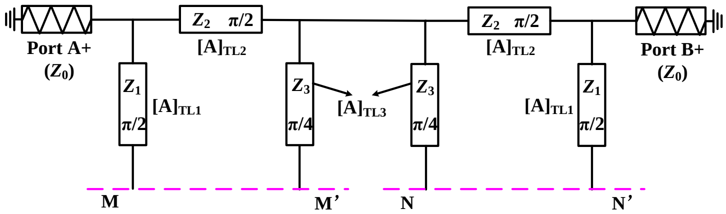

Fig. 4. Simplified equivalent sub-circuit of the proposed BTB filtering crossover.

TABLE I. FOUR DIFFERENT MODES OF THE REDUCED EQUIVALENT SUB-CIRCUIT.

Mode	MM'	NN'
(e, e)	Open-circuited	Open-circuited
(e, o)	Open-circuited	Short-circuited
(o, e)	Short-circuited	Open-circuited
(o, o)	Short-circuited	Short-circuited

According to transmission line and microwave network theory, the transfer matrix of two-port equivalent sub-circuit $[A]^{uv}$ at the center frequency of f_0 can be deduced as

$$\begin{aligned} A^{uv} &= [A]_{\mathrm{TL1}} \times [A]_{\mathrm{TL2}} \times [A]_{\mathrm{TL3}} \times [A]_{\mathrm{TL2}} \times [A]_{\mathrm{TL1}} \\ &= \begin{bmatrix} 1 & 0 \\ Y_{1\_m} & 1 \end{bmatrix} \times \begin{bmatrix} 0 & \mathrm{j}Z_2 \\ \frac{\mathrm{j}}{Z_2} & 0 \end{bmatrix} \times \begin{bmatrix} 1 & 0 \\ Y_{3\_m} + Y_{3\_n} & 1 \end{bmatrix} \times \begin{bmatrix} 0 & \mathrm{j}Z_2 \\ \frac{\mathrm{j}}{Z_2} & 0 \end{bmatrix} \times \begin{bmatrix} 1 & 0 \\ Y_{1\_n} & 1 \end{bmatrix} \\ &= \begin{bmatrix} -1 - Z_2^2 (Y_{3\_m} + Y_{3\_n}) Y_{1\_n} & -Z_2^2 (Y_{3\_m} + Y_{3\_n}) \\ -Y_{1\_m} - Y_{1\_n} - Z_2^2 Y_{1\_m} (Y_{3\_m} + Y_{3\_n}) Y_{1\_n} & -1 - Z_2^2 Y_{1\_m} (Y_{3\_m} + Y_{3\_n}) \end{bmatrix} \end{aligned} \tag{3}$$

where uv could be ee, eo, oe, or oo corresponding to (e, e), (e, o), (o, e), or (o, o) modes, respectively. Similarly, m and n could be e or o corresponding to the varying input admittance of the stubs in different modes.

$$Y_{1\_\mathrm{e}} = \frac{\mathrm{j}\tan(\pi/2)}{Z_1}, \quad Y_{1\_\mathrm{o}} = \frac{-\mathrm{j}\cot(\pi/2)}{Z_1} \tag{4}$$

$$Y_{3\_\mathrm{e}} = \frac{\mathrm{j}\tan(\pi/4)}{Z_3}, \quad Y_{3\_\mathrm{o}} = \frac{-\mathrm{j}\cot(\pi/4)}{Z_3} \tag{5}$$

After that, based on the conversion relationship between the transfer matrix and the scattering matrix, the simplified scattering matrix of two-port equivalent sub-circuit $[S]^{uv}$ at f_0 can be obtained in Equation (6).

$$\begin{cases} S_{\mathrm{A+A+}}^{\mathrm{ee}} \to -1, \quad S_{\mathrm{B+A+}}^{\mathrm{ee}} \to 0 \\ S_{\mathrm{A+A+}}^{\mathrm{eo}} \to -1, \quad S_{\mathrm{B+A+}}^{\mathrm{eo}} \to 0 \\ S_{\mathrm{A+A+}}^{\mathrm{oe}} \to -1, \quad S_{\mathrm{B+A+}}^{\mathrm{oe}} \to 0 \\ S_{\mathrm{A+A+}}^{\mathrm{oo}} = 1 + \dfrac{Z_0 Z_3}{\mathrm{j}Z_2^2 - Z_0 Z_3}, \quad S_{\mathrm{B+A+}}^{\mathrm{oo}} = \dfrac{Z_0 Z_3}{\mathrm{j}Z_2^2 - Z_0 Z_3} \end{cases} \tag{6}$$

Using the two-port S-parameters of the equivalent sub-circuit in each mode, the mixed-mode S-parameters of the proposed BTB filtering crossover for the input port A in Equation (2) can be derived as [10]

$$\begin{cases} S_{\mathrm{ddAA}} = \dfrac{S_{\mathrm{A+A+}}^{\mathrm{oe}} + S_{\mathrm{A+A+}}^{\mathrm{oo}}}{2}, & S_{\mathrm{ccAA}} = \dfrac{S_{\mathrm{A+A+}}^{\mathrm{ee}} + S_{\mathrm{A+A+}}^{\mathrm{eo}}}{2} \\ S_{\mathrm{ddBA}} = -S_{\mathrm{ddDA}} = \dfrac{S_{\mathrm{B+A+}}^{\mathrm{oo}}}{2}, & S_{\mathrm{ccBA}} = S_{\mathrm{ccDA}} = \dfrac{S_{\mathrm{B+A+}}^{\mathrm{ee}}}{2} \\ S_{\mathrm{ddCA}} = \dfrac{S_{\mathrm{A+A+}}^{\mathrm{oe}} - S_{\mathrm{A+A+}}^{\mathrm{oo}}}{2}, & S_{\mathrm{ccCA}} = \dfrac{S_{\mathrm{A+A+}}^{\mathrm{ee}} - S_{\mathrm{A+A+}}^{\mathrm{eo}}}{2} \end{cases} \tag{7}$$

The mixed-mode *S*-parameters of the proposed BTB filtering crossover for the input port A are expected to satisfy the matching condition, DM pass-through, excellent CM suppression, and good isolation between adjacent output ports, the following conditions at the center frequency of f_0 should be met

$$\begin{cases} \left|S_{\mathrm{ddAA}}\right| \to 0, & \left|S_{\mathrm{ccAA}}\right| \to 1 \\ \left|S_{\mathrm{ddBA}}\right| = \left|S_{\mathrm{ddDA}}\right| \to 0, & \left|S_{\mathrm{ccBA}}\right| = \left|S_{\mathrm{ccDA}}\right| \to 0 \\ \left|S_{\mathrm{ddCA}}\right| \to 1, & \left|S_{\mathrm{ccCA}}\right| \to 0 \end{cases} \tag{8}$$

It can be observed that the mixed-mode S_{cc} parameters obtained according to Equation (6) all satisfy the conditions listed in Equation (8). And if the mixed-mode S_{dd} parameters solved based on Equation (6) want to meet the qualification of Equation (8), the characteristic impedance relationship needs to be satisfied as

$$\left| \frac{Z_0 Z_3}{\mathrm{j} Z_2^2 - Z_0 Z_3} \right| \to 0 \tag{9}$$

Although the case of Equation (9) cannot be realized ideally, the mixed-mode S_{dd} parameters acquired by choosing a large value of Z_2 and a small value of Z_3 can still satisfy the application requirements of the BTB filtering crossover. In order to consider the fabrication limitation of the width of the microstrip lines, the characteristic impedances of the microstrip line are eventually selected as $Z_1 = 12\ \Omega$, $Z_2 = 130\ \Omega$, and $Z_3 = 15\ \Omega$.

Furthermore, it should be noted that due to the symmetry and reciprocity of the proposed BTB filtering crossover, the situation when the other ports are served as input ports is the same as that of input port A, and thus has the same analysis process as described above.

The simulated electric field distributions on the proposed BTB filtering crossover prototype operating at the center frequency f_0 are shown in Fig. 5. It can be observed from Fig. 5(a), when the energy is input from the differential ports A+ and A−, under the DM excitation, the majority of the energy is able to achieve cross-transmission to the differential output ports C+ and C− and cannot enter the adjacent ports, thus ensuring high isolation. For CM excitation, due to the symmetry of the circuit structure, the CM noise is basically completely reflected back, resulting in excellent CM suppression characteristics, as shown in Fig. 5(b). Therefore, with the proposed design concept, the desired performance of the BTB crossover has indeed been achieved in a simple structure.

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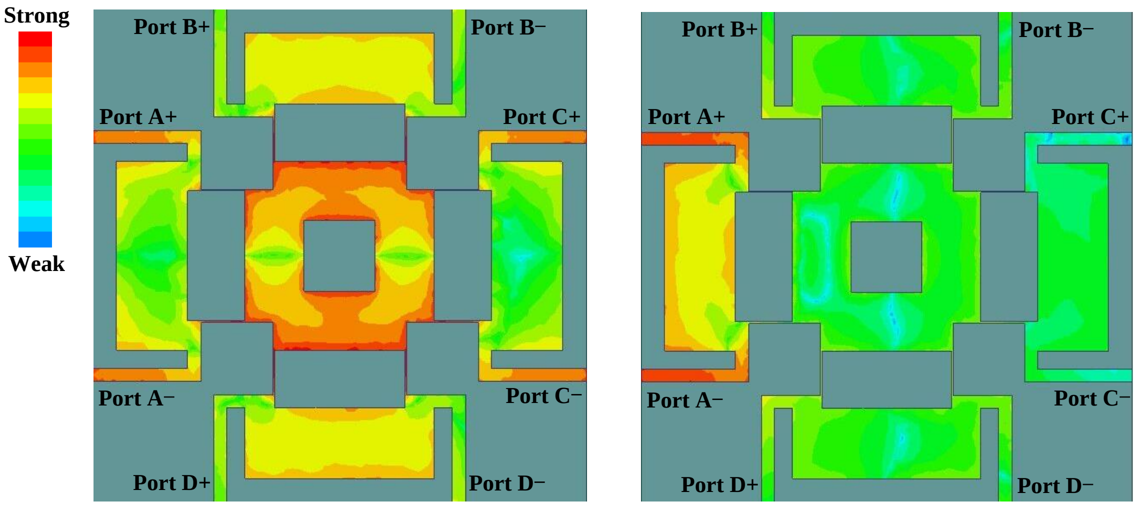
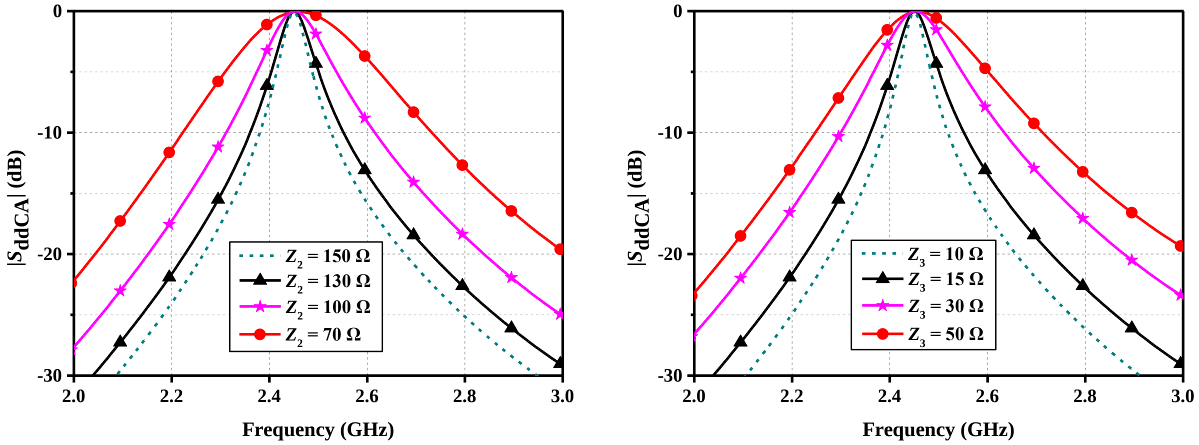


(a) (b)

Fig. 5. Simulated electric field distributions on the crossover prototype operating at f_0. (a) DM excitation. (a) CM excitation.

For the control of filtering bandwidth, Fig. 6 displays the effects of the characteristic impedances Z_2 and Z_3 of the microstrip lines with electrical lengths π/2 on the mixed-mode cross-transmission *S*-parameters of the proposed BTB filtering crossover. It can be seen from Fig. 6(a) that when the characteristic impedance Z_2 is decreased from 150 to 50 Ω with Z_3 = 15 Ω, the filtering bandwidth of the proposed BTB crossover is increased. Similarly, as the characteristic impedance Z_3 is increased from 10 to 50 Ω with Z_2 = 130 Ω, the filtering bandwidth is also increased, as shown in Fig. 6(b).



(a) (b)

Fig. 6. Effects of the characteristic impedances Z_2 and Z_3 on the mixed-mode cross-transmission *S*-parameters.
(a) Different Z_2 with Z_3 = 15 Ω. (b) Different Z_3 with Z_2 = 130 Ω.

III. IMPLEMENTATION AND PERFORMANCE

To validate the theory analysis of the proposed BTB filtering crossover, a planar microstrip prototype is fabricated on the F4B substrate (ε_r = 3.5, tanδ = 0.003, *h* = 1.0 mm) with the center frequency of f_0 = 2.45 GHz. Fig. 7 displays the photograph of the proposed balanced-to-balanced filtering crossover. Fig. 6 shows the simulated (solid line) and measured (short dash line) mixed-mode *S*-parameter results.

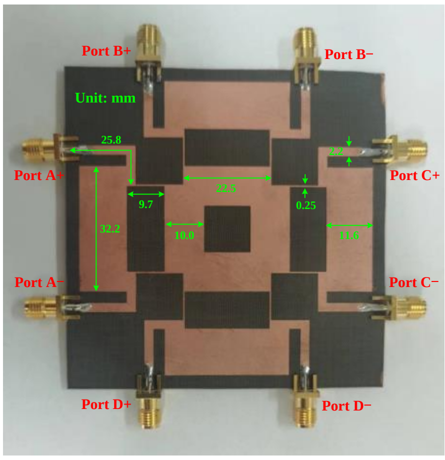
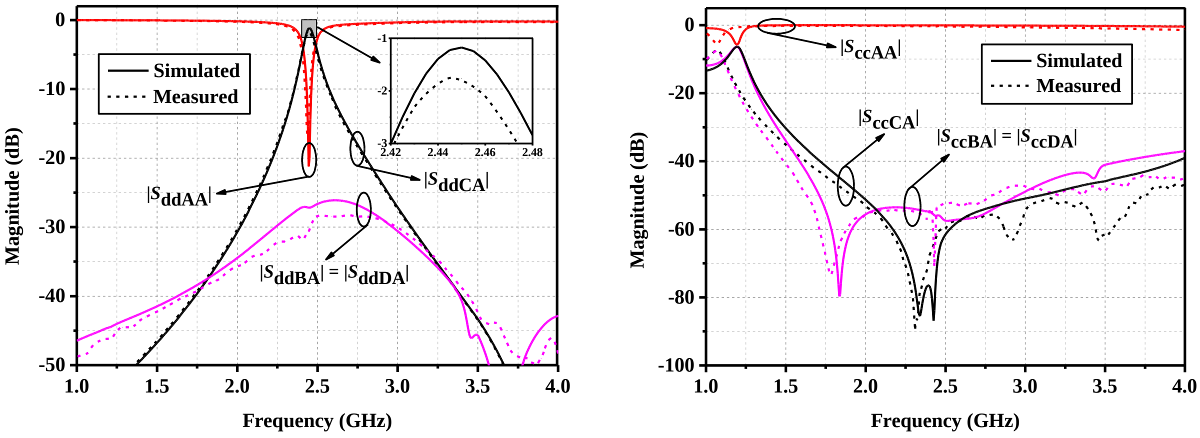


Fig. 7. Photograph of the fabricated balanced-to-balanced filtering crossover.



(a) (b)

Fig. 8. Simulated and measured results of the proposed BTB filtering crossover. (a) DM mode. (b) CM mode.

It can be seen from Fig. 8(a) that the proposed BTB filtering crossover has an insertion loss (IL) of 1.77 dB and a return loss (RL) of 18.2 dB at the center frequency f_0 = 2.45 GHz under DM excitation. The DM isolation is greater than 28.4 dB over the all measurement frequencies from 1.0 to 4.0 GHz. Furthermore, the proposed BTB crossover has a bandpass filtering characteristic. Under CM excitation, the proposed BTB filtering crossover exhibits excellent CM suppression and CM isolation (both better than 50.0 dB) throughout a wide frequency range as shown in Fig. 8(b).

To further demonstrate the performances of the proposed BTB filtering crossover, the comparisons between with previous works are shown in Table II. The proposed balanced-to-balanced crossover not only has great common-mode suppression, but also has a bandpass filtering characteristic compared to the previous BTB crossovers [10-12], which enables the function integration of the BTB crossovers. Compared with the reported BTB filtering crossovers [13, 14], which both use the coupling method to excite the resonators, the fabricated BTB filtering crossover suffers from excessive insertion loss as well as insufficient isolation. This design is composed of the microstrip transmission lines without coupling sections, which has a much smaller insertion loss and enhanced isolation. In addition, the proposed BTB filtering crossover has the most excellent DM isolation as shown in Table II.

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TABLE II. COMPARISONS BETWEEN THE PROPOSED BTB FILTERING CROSSOVER AND PREVIOUS WORKS.

Ref.	**f_0 (GHz)**	**IL (dB)**	**DM Isolation (dB)**	**CMS (dB)**	**Filtering**
[10]	2.45	0.86	20.8	> 50.0	No
[11]	2.00	0.81	25.3	> 40.0	No
[12]	2.40	0.96	15.1	> 30.0	No
[13]	5.10	3.38	20.0	> 35.0	Yes
[14]	2.41	2.56	21.5	> 50.0	Yes
Proposed	**2.45**	**1.77**	**28.4**	**> 50.0**	**Yes**

IV. CONCLUSION

In this paper, a novel planar balanced-to-balanced microstrip filtering crossover with high isolation and common-mode suppression characteristics has been proposed. Compared with the previous balanced-to-balanced crossovers, the proposed BTB filtering crossover not only realizes excellent common-mode suppression but also enhances the isolation between adjacent output ports. The frequency selectivity characteristic is achieved in the proposed BTB crossover for function integration. In addition, this design is composed of the microstrip transmission lines without coupling sections, which can further reduce insertion loss and enhance isolation.

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