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Keywords:	Bandpass filter, crossover, filtering coupler

Design of Filtering Crossover Based on 180° Filtering Couplers

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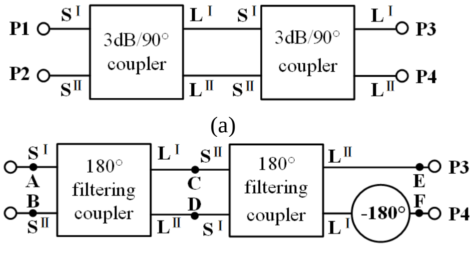
***Abstract*—This paper presents a novel crossover with an embedded bandpass filter function. The crossover is derived from the traditional crossover based on a tandem connection of two 3-dB 90° couplers by substituting them with 180° filtering couplers and introducing a filter function. In addition, a 180° phase shift realized by coupled resonators is added to keep the two cross paths in phase. The equivalent circuit of the crossover between the two diagonal ports have been treated as bandpass filters with coupled resonators. The design equations are derived to assist with the synthesis process for the filtering crossover. For verification, a filtering crossover with fifth-order filter characteristics, operating at 2.4 GHz, is designed, fabricated, and tested. The measured results match very well with the simulation, which verifies the proposed circuit concept.**

***Index Terms*—Bandpass filter, crossover, filtering coupler, stripline.**

I. INTRODUCTION

Multi-beam antennas have attracted more attention in the past few years as they help enhance the communication capacity and improve spectral efficiency. One of the typical topologies for a multi-beam antenna is to utilize the Butler matrix as the beam-forming network. In the design of a Butler matrix, the crossover is one key component that greatly reduces the complexity of wiring by crossing two independent signals with high isolation and low loss. Conventional crossovers were often implemented using air bridges [1], multilayer structures [2], or microstrip branch-line couplers [3]-[5]. As the demand for multifunction applications increases, crossovers of new capabilities such as multiband, multichannel, tunable frequency, wideband or with filter functions have been demonstrated [6]-[20]. In [6]-[11], branch-line structures with different electrical length and impedance were utilized in a dual-band crossover. In [12]-[14], crossovers with three and four channels were proposed based on double-ring structures. A crossover with continuously tunable frequency was first proposed in [15], where two fixed capacitors and one tunable capacitor were used to replace the coupled line. In [16]-[19], microstrip rings and coplanar waveguide structures were utilized in wideband crossovers. In [20]-[25], several filtering crossovers were proposed by utilizing orthogonal modes in substrate integrated waveguides (SIWs) and cavity resonators. In [26], a filtering crossover with extended channel number and controllable frequencies was proposed by utilizing square SIW cavities. In [27], a tunable filtering crossover with independently tuned channel passbands based on evanescent-mode cavity was reported. In [28], A single-layer planar wideband filtering crossover with excellent common-mode suppression was reported.



(a)
(b)

Fig. 1. (a) A typical schematic of crossover realized by a tandem connection of two 3-dB/90° couplers. (b) The proposed schematic of filtering crossover based on 180° filtering couplers.

In this paper, prototype of a filtering crossover realized by 180° filtering couplers is proposed. Compared with the previous filtering crossovers based on multimode resonators [20]-[27], the novelty of this work is that a novel design method of filtering crossover realized by 180° filtering couplers using single mode resonators is proposed, and the crossover is easier to be implemented in filtering Butler matrix for 5G communications [29]. The detailed design process and synthesis methods for the filtering crossover are presented. For validation, a stripline filtering crossover with fifth-order filter characteristic is designed, fabricated, and tested.

II. DESIGN

A. Analysis

Fig. 1(a) shows a typical schematic of a crossover realized by a tandem connection of two 3-dB 90° couplers [3]. In a similar way, Fig. 1(b) presents the new schematic of a filtering crossover based on 180° filtering couplers. The main difference between them is the replacement of the 3-dB/90° couplers with 180° filtering couplers, which introduce the filter function to the

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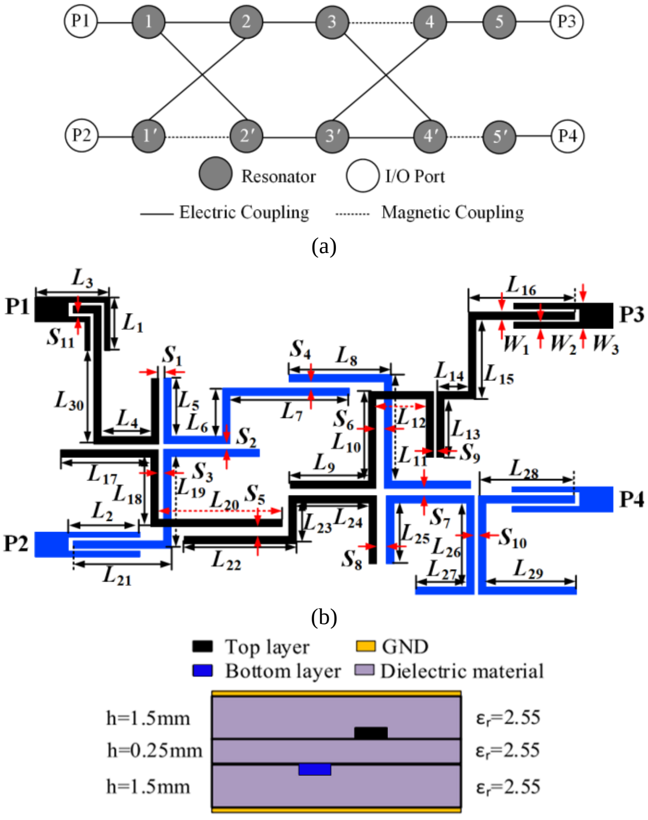
TABLE I
PHASE CHANGE OF EACH PATH WHEN DIFFERENT INPUT PORT ARE FED

Input port	Output port	Path ACE	Path ADE	Combined result
P1	P3	0°	-180°	CANCEL
	Output port	Path ACF	Path ADF	Combined result
	P4	-180°	-180°	-180°
Input port	Output port	Path BCE	Path BDE	Combined result
P2	P3	-180°	-180°	-180°
	Output port	Path BCF	Path BDF	Combined result
	P4	-180°	0°	CANCEL



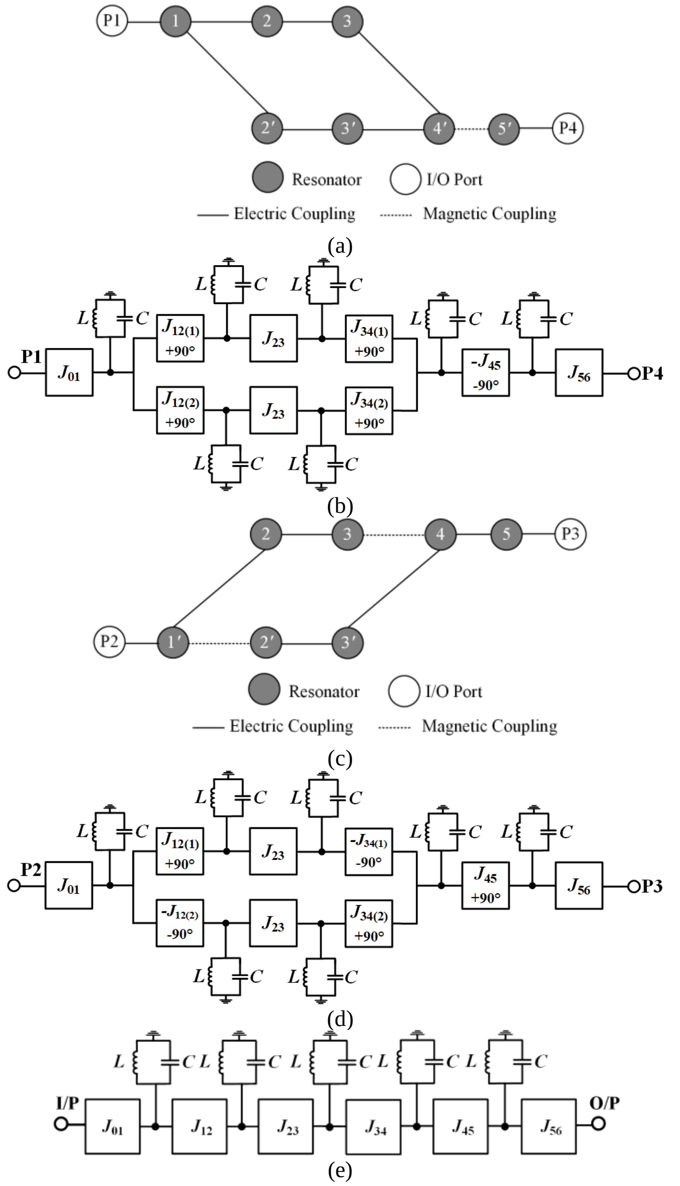
(a)

(b)

(c)

Fig. 2. (a) Coupling scheme of the filtering crossover. (b) Layout of the filtering crossover. (S_{11}=0.20, L_3=9.69, L_4=6.90, L_5=7.95, L_6=6.55, L_7=16.34, L_8=14.02, L_9=10.68, L_{10}=12.21 L_{11}=14.53, L_{12}=6.85, L_{13}=7.95, L_{14}=4.36, L_{15}=10.88, L_{16}=14.50, L_{17}=12.36, L_{18}=9.50, L_{19}=12.50, L_{20}=16.89, L_{21}=13.34, L_{22}=15.30, L_{23}=5.54, L_{24}=10.00, L_{25}=8.32, L_{26}=11.50, L_{27}=7.03, L_{28}=13.14, L_{29}=12.36, L_{30}=12.75, W_1=1.00, W_2=0.50, W_3=2.40, all in millimeters.) (c) The three-layer stripline structure.

crossover. In addition, the input and output ports (S^{I}, S^{II}, L^{I}, and L^{II}) of 180° coupler connected with output ports P3 and P4 are reversed compared with the 180° coupler connected with input ports P1 and P2. Finally, in order to keep the same phase shift of the two crossing paths in the crossover, a 180° phase shifter is connected before the output port P4. Based on the phase response of the 180° coupler, Table I shows the phase change of the two crossing paths when different input ports are excited. It can be concluded that when port P1(P2) is fed, the signal is output from port P4(P3) while port P3(P4) is isolated.



(a)

(b)

(c)

(d)

(e)

Fig. 3. (a) Coupling scheme of the filtering crossover for the input port P1. (b) Equivalent circuit of the filtering crossover for the input port P1. (c) Coupling scheme of the filtering crossover for the input port P2. (d) Equivalent circuit of the filtering crossover for the input port P2. (e) Equivalent circuit of the standard coupled resonator bandpass filter.

The design method of the 180° filtering coupler has been proposed in our previous work [29]. To achieve the filtering function as well as the required phase response of the crossover, the 180° phase shifter can be realized by utilizing different types of coupling between resonators 4 and 5 (4’ and 5’) as shown in the coupling scheme in Fig. 2(a). Fig. 2(b) shows the circuit layout based on a three-layer stripline structure, consisting of one thin and two thick dielectric layers with the dielectric constant of 2.55, as shown in Fig. 2(c).

As in [24], the input and output couplings are equivalent to the +90° admittance inverters *J*. The couplings between resonators dominated by electric or magnetic coupling are represented by the +90° or -90° admittance inverter, respectively. The parallel *LC* circuits are used to model the resonators. Using an analytical method, when the port P1 is

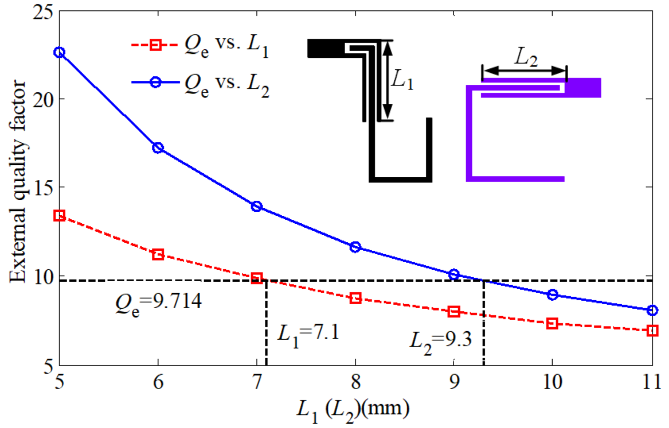


Fig. 4. Extracted external quality factor versus the corresponding design parameters.

the input, the ports P2 and P3 are isolated. Fig. 3(a) shows the coupling scheme of the filtering crossover for the input port P1. Therefore, the equivalent circuit of the filtering crossover when the port P1 is fed can be reduced to Fig. 3(b). Similarly, when the port P2 is fed, the coupling scheme and equivalent circuit can be reduced to Fig. 3(c) and (d).

As the 180° coupler is a uniform power splitter, the admittance inverters J can be expressed as

$$J^2_{12(1)} = J^2_{12(2)},\quad J^2_{34(1)} = J^2_{34(2)} \tag{1}$$

Comparing the admittance inverters in Fig. 3(b) and (d) with those in a standard filter (Fig. 3(e)), we have

$$J^2_{12(1)} + J^2_{12(2)} = J^2_{12},\quad J^2_{34(1)} + J^2_{34(2)} = J^2_{34} \tag{2}$$

where J_{12} and J_{45} are the inverters in the standard filter.

From (1) and (2), it can be found that

$$\begin{aligned} J_{12(1)} &= J_{12(2)} = \pm\frac{\sqrt{2}}{2}J_{12} \\ J_{34(1)} &= J_{34(2)} = \pm\frac{\sqrt{2}}{2}J_{34} \end{aligned} \tag{3}$$

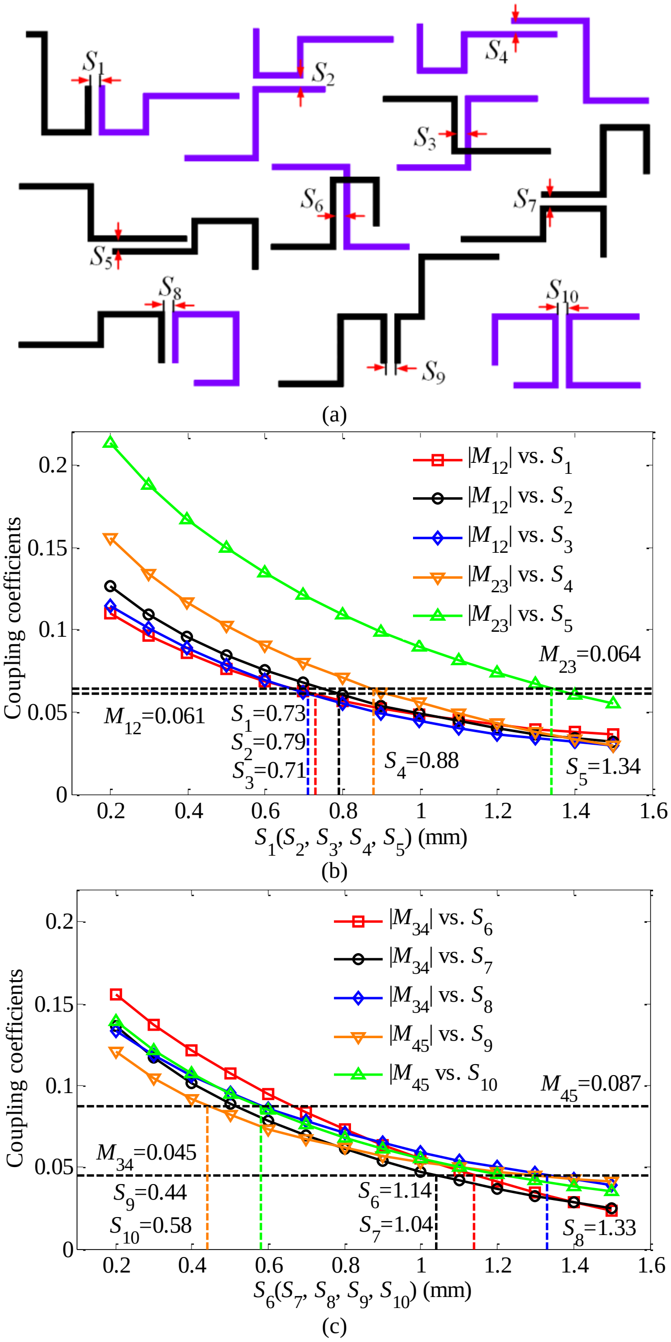
Therefore, different paths of the crossover from input to output can be equivalent to the circuits in Fig. 3(e), which is regarded as the fundamental bandpass filter. If the design specifications such as the ripple level, center frequency (f_0) as well as fractional bandwidth (FBW) are prescribed, the parameters of the prototype filter (g_1, g_2, g_3, g_4 and g_5) can be obtained, and the external quality factors (Q_{e1} and Q_{e2}) and coupling coefficients (M_{12}, M_{23}, M_{34} and M_{45}) of the bandpass filter can be obtained as [30]

$$Q_{e1} = \frac{g_0 g_1}{FBW}, Q_{e2} = \frac{g_5 g_6}{FBW} \tag{4}$$

$$\begin{aligned} M_{12(1)} &= M_{12(2)} = \pm\frac{\sqrt{2}FBW}{2\sqrt{g_1 g_2}}, M_{23} = \frac{FBW}{\sqrt{g_2 g_3}} \\ M_{34(1)} &= M_{34(2)} = \pm\frac{\sqrt{2}FBW}{2\sqrt{g_3 g_4}}, M_{45} = \pm\frac{FBW}{\sqrt{g_4 g_5}} \end{aligned} \tag{5}$$

where “+” and “-” denote the coupling which is dominated by electric and magnetic field, respectively.

B. Design Example



(a)

(b)

(c)

Fig. 5. (a) Circuit layout for extracting coupling coefficients. (b) and (c) Extracted coupling coefficients versus the corresponding design parameters.

To test the validity of the design approach, a filtering crossover is devised, manufactured and measured. It is designed to have a fractional bandwidth of 10% at a midband frequency f_0 = 2.4 GHz. The passband ripple level is chosen to be 0.0432 dB with respect to a 20 dB return loss. The lowpass prototype parameters can be obtained as $g_1 = 0.9714$, $g_2 = 1.3721$, $g_3 = 1.8014$, $g_4 = 1.3721$ and $g_5 = 0.9714$ from a lookup table [30]. From equations (4) to (5), the bandpass design parameters can be calculated as $Q_{e1} = Q_{e2} = 9.714$, $M_{12(1)} = M_{12(2)} = \pm 0.061$, $M_{23} = 0.064$, $M_{34(1)} = M_{34(2)} = \pm 0.045$, $M_{45} = \pm 0.087$. By using the extraction approach in [30], the external quality factor and coupling coefficients with

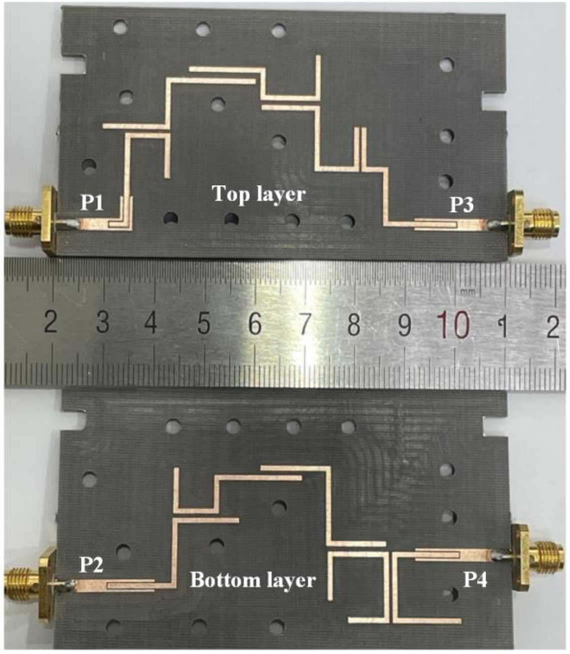
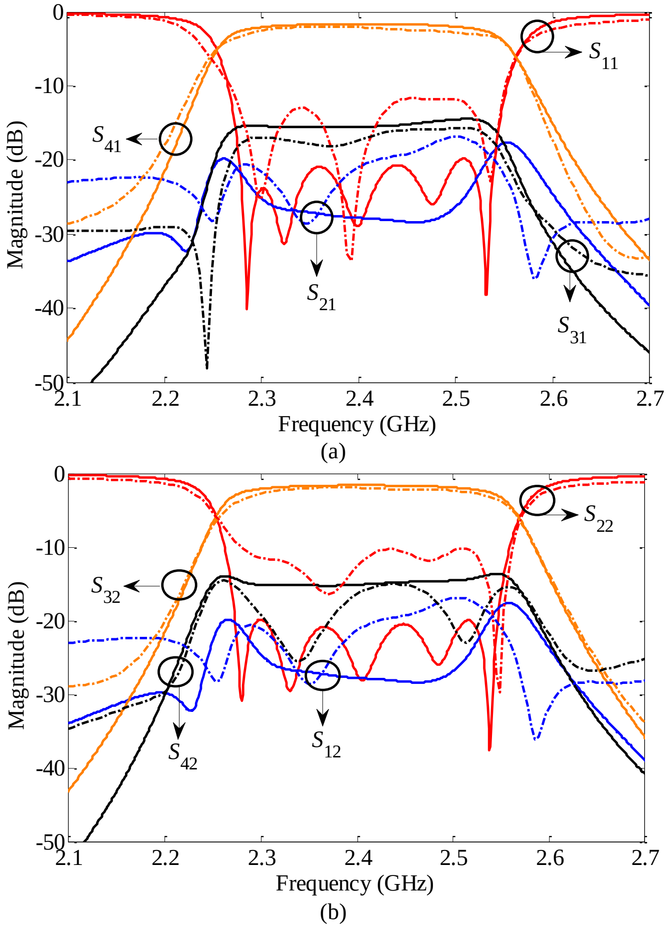


Fig. 6. Photo of the manufactured crossover.



(a)

(b)

Fig. 7. Simulated and measured *S*-parameters (dash-dotted lines: measurement results, solid lines: simulation results).

respect to the design parameters are shown in Fig. 4 and Fig. 5. The initial values of the filtering crossover can be obtained as L_1 = 7.10, L_2 = 9.30, S_1 = 0.73, S_2 = 0.79, S_3 = 0.71, S_4 = 0.88, S_5 = 1.34, S_6 = 1.14, S_7 = 1.04, S_8 = 1.33, S_9 = 0.44, S_{10} = 0.58, all in millimeters. Then, the filtering crossover is optimized by using IE3D software and its final dimensions are L_1 = 6.80, L_2 = 9.29, S_1 = 0.71, S_2 = 0.78, S_3 = 0.71, S_4 = 0.87, S_5 = 1.30, S_6 = 1.13, S_7 = 1.00, S_8 = 1.35, S_9 = 0.46, S_{10} = 0.60, all in millimeters.

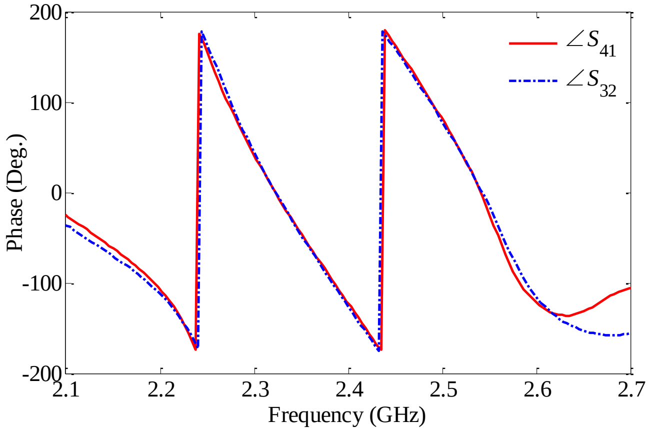


Fig. 8. Measured phase of the two cross paths.

TABLE II
COMPARISON WITH PREVIOUS WORK

Ref.	CF (GHz)	Iso. (dB)	Loss (dB)	FBW (%)	Filter	Techn.	Type of realized resonator	Size (λ_g^2)
[3]	6.0	20	1.0	NG	No	ML	NA	NG
[20]	2/2.4	23	1.6/1.5	6.7/4.4	Yes	ML	Multi-mode	0.08
[21]	20	30	1.63	2.41	Yes	SIW	Multi-mode	6.29
[22]	18.68	18.5	2.03	3.72	Yes	SIW	Multi-mode	1.23
[23]	12	21.8	1.61	7.17	Yes	SIW	Multi-mode	6.35
	12	18.3	2.1	5.08				7.55
	12/12	21.9	1.3/1.7	7.9/5.2				6.15
	12/13.5	29	1.2/1.4	6.9/6.1				5.47
[24]	3	45	0.6	24	Yes	WG	Multi-mode	NG
[25]	9.7/10/10.3	29.6	0.2/0.36/0.21	2.1/2/1.9	Yes	WG	Multi-mode	NG
[26]	8.83	23	2.29	3.74	Yes	SIW	Multi-mode	10.9
	8.83	22	1.8/2.3	4.5/4.4				7.27
	8/8.8	21	1.4/1.8	4.5/5				3.98
This work	**2.4**	**15**	**1.8**	**10**	**Yes**	**SL**	**Single mode**	**0.93**

CF: Center frequency; Iso.: Isolation; Techn.: Technology; NG: not given; ML: Microstrip; WG: Waveguide; SL: Stripline.

C. Measurement Results

Photo of the manufactured filtering crossover is shown in Fig. 6. Fig. 7(a) shows the simulation and measurement *S*-parameters when the input is at port P1. The measured minimum insertion loss is 1.8 dB, and the measured return loss is better than 11 dB. The isolation between port P1 and port P2 and P4 are larger than 15 dB. In the same way, Fig. 7(b) shows the simulation and measurement results when the input is at port P2. The measured minimum insertion loss is

1.8 dB, and the measured return loss is better than 11 dB. The isolation between port P2 and port P1 and P4 are larger than 15 dB. The measured phases for the two crossing paths are shown in Fig. 8. It can be clearly observed that the two cross paths have the same phase in the passband of the filter. Table II compares the proposed filtering crossover with previous work in the field. It can be seen that this work provides a higher order filter function by utilizing single mode resonators, which would be easier to be implemented in the filtering Butler matrix.

III. CONCLUSION

This paper presents a design method for the filtering crossover based on 180° couplers. It is comprised of 180° filtering couplers and coupled resonators, providing two crossing paths with isolation larger than 15 dB, the same phase shift as well as a bandpass filtering characteristic with an insertion loss of 1.8 dB. The measurement results are consistent with the simulation, which confirms the validity of the design approach.

REFERENCES

[1] T.-S. Horng, “A rigorous study of microstrip crossovers and their possible improvements,” *IEEE Trans. Microw. Theory Techn.*, vol. 42, no. 9, pp. 1802–1806, Sep. 1994.

[2] D. Jaisson, “Multilayer microstrip directional coupler with discrete coupling,” *IEEE Trans. Microw. Theory Techn*., vol. 48, no. 9, pp. 1591–1595, Sep. 2000.

[3] J. S. Wight, W. J. Chudobiak, and V. Makios, “A microstrip and stripline crossover structure (letters),” *IEEE Trans. Microw. Theory Techn.*, vol. 24, no. 5, p. 270, May 1976.

[4] J. J. Yao, “Nonstandard hybrid and crossover design with branchline structures,” *IEEE Trans. Microw. Theory Techn.*, vol. 58, no. 12, pp. 3801–3808, Dec. 2010.

[5] J. Yao, C. Lee, and S. P. Yeo, “Microstrip branch-line couplers for crossover application,” *IEEE Trans. Microw. Theory Techn.*, vol. 59, no. 1, pp. 87–92, Jan. 2011.

[6] J. Shao, H. Ren, B. Arigong, C. Li, and H. Zhang, “A fully symmetrical crossover and its dual-frequency application,” *IEEE Trans. Microw. Theory Techn.*, vol. 60, no. 8, pp. 2410–2416, Aug. 2012.

[7] H. Ren, M. Zhou, H.-X. Zhang, and B. Arigong, “A novel dual-band zero-phase true crossover with arbitrary port impedance,” *IEEE Microw. Wireless Compon. Lett.*, vol. 29, no. 1, pp. 29–31, Jan. 2019.

[8] F.-L. Wong and K.-K. M. Cheng, “A novel, planar, and compact crossover design for dual-band applications,” *IEEE Trans. Microw. Theory Techn.*, vol. 59, no. 3, pp. 568–573, Mar. 2011.

[9] F. Lin, Q.-X. Chu, and S.-W. Wong, “Dual-band planar crossover with two-section branch-line structure,” *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 6, pp. 2309–2316, June. 2013.

[10] W. Feng, T. Zhang, W. Che, and Q. Xue, “Compact single-/dual-band planar crossovers based on strong coupled lines,” *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 6, no. 6, pp. 854-863, June 2016.

[11] M. A. Maktoomi, M. S. Hashmi, and F. M. Ghannouchi, “Systematic design technique for dual-band branch-line coupler using T- and Pi-networks and their application in novel wideband-ratio crossover,” *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 6, no. 5, pp. 784-795, May 2016

[12] L. S. Wu, Y. X. Guo, and J. F. Mao, “A planar microstrip crossover with lumped inductors for three intersecting channels,” *IEEE Trans. Microw. Theory Techn.*, vol. 62, no. 4, pp. 851–860, Apr. 2014.

[13] C. W. Tang and W. M. Chuang, “Design of the planar six-port crossover with double rings,” *IEEE Microw. Wireless Compon. Lett.*, vol. 25, no. 10, pp. 651–653, Oct. 2015.

[14] P.-C. Chu and C.-W. Tang, “Design of a compact planar crossover with four intersecting channels,” *IEEE Microw. Wireless Compon. Lett.*, vol. 28, no. 4, pp. 293–295, Apr. 2018.

[15] F. Lin, S.-W. Wong, and Q.-X. Chu, “Compact design of planar continuously tunable crossover with two-section coupled lines,” *IEEE Trans. Microw. Theory Techn.*, vol. 62, no. 3, pp. 408–415, Mar. 2014.

[16] Y.-H. Pang and J.-J. Li, “A planar wideband balanced crossover,” *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 8, no. 10, pp. 1807-1814, Oct. 2018.

[17] Y. Wang, A. M. Abbosh, and B. Henin, “Broadband microwave crossover using combination of ring resonator and circular microstrip patch,” *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 3, no. 10, pp. 1771-1777, Oct. 2013.

[18] W.-D. Liu, Z.-J. Zhang, Z.-H. Feng, and M. F. Iskander, “A compact wideband microstrip crossover,” *IEEE Microw. Wireless Compon. Lett.*, vol. 22, no. 5, pp. 254–256, May 2012.

[19] A. Abbosh, S. Ibrahim, and M. Karim, “Ultra-wideband crossover using microstrip-to-coplanar waveguide transitions,” *IEEE Microw. Wireless Compon. Lett.*, vol. 22, no. 10, pp. 500–502, Oct. 2012.

[20] Q.-Y. Guo, X.-Y. Zhang, and L. Gao, “Novel compact planar crossover with bandpass response based on cross-shaped resonator,” *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 7, no. 12, pp. 2018-2026, Dec. 2017.

[21] S.-Q. Han, K. Zhou, J.-D. Zhang, C.-X. Zhou, and W. Wu, “Novel substrate integrated waveguide filtering crossover using orthogonal degenerate modes,” *IEEE Microw. Wireless Compon. Lett.*, vol. 27, no. 9, pp. 803–805, Sep. 2017.

[22] B.-N. Yao, G. Zhang, X. Zhou, N. Li, W.-C. Tang, and J.-Q. Yang, “Substrate-integrated waveguide filtering crossover based on 3-D assembly,” *IEEE Microw. Wireless Techn. Lett.*, vol. 33, no. 5, pp. 523–526, May 2023.

[23] K. Zhou and K. Wu, “Wide-stopband substrate-integrated waveguide filtering crossovers with flexibly allocated channel frequencies and bandwidths,” *IEEE Trans. Microw. Theory Techn.*, vol. 69, no. 7, pp. 3264–3274, Mar. 2021.

[24] J.-Y. Lin, S.-W. Wong, Y.-M. Wu, Y. Yang, L. Zhu, and Y.-J He, “Three-way multiple-mode cavity filtering crossover for narrowband and broadband applications,” *IEEE Trans. Microw. Theory Techn.*, vol. 67, no. 3, pp. 896–905, Mar. 2019.

[25] Y. Zhang, J. Xu, and X.-B. Shang, “3-D printed filtering crossover using ellipsoidal cavities,” *IEEE Microw. Wireless Techn. Lett.*, vol. 33, no. 2, pp. 153–156, Feb. 2023.

[26] W.-L. Zhan, J.-X. Xu, X.-L. Zhao, B.-J. Hu, and X.-Y. Zhang, “Substrate integrated waveguide multi-channel filtering crossover with extended channel number and controllable frequencies,” *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 67, no. 12, pp. 2858–2862, Dec. 2020.

[27] J.-C. Lai, T. Yang, P.-L. Chi, and R.-M. Xu, “A novel 1.7–2.85 GHz filtering crossover with independently tuned channel passbands and reconfigurable filtering power-dividing function,” *IEEE Trans. Microw. Theory Techn.*, vol. 69, no. 5, pp. 2458–2469, May 2021.

[28] Y.-N. Zheng, W.-M. Wang, Y.-L. Wu, and W.-J. Che, “A single-layer planar wideband filtering single-ended-to-balanced crossover with excellent common-mode suppression,” *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 69, no. 2, pp. 364–368, Feb. 2022.

[29] Q. Shao, F. C. Chen, Y. Wang, and Q. X. Chu, “Design of 4 × 4 and 8 × 8 filtering Butler matrices utilizing combined 90° and 180° couplers,” *IEEE Trans. Microw. Theory Techn.*, vol. 69, no. 8, pp. 3842–3852, Aug. 2021.

[30] J. S. Hong and M. J. Lancaster, *Microstrip Filters for RF/Microwave Applications*. New York, NY, USA: Wiley, 2001.

Design of Filtering Crossover Based on 180° Filtering Couplers

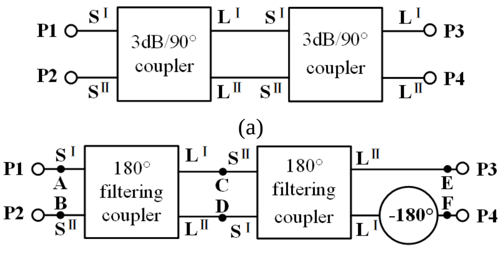
Qiang Shao, *Member*, *IEEE*, Ning Yang, Rui-Sen Chen, *Member*, *IEEE*, Guang-Long Huang, *Senior Member*, *IEEE*, Fu-Chang Chen, *Senior Member*, *IEEE* and Yi Wang, *Senior Member*, *IEEE*

Abstract**—This paper presents a novel crossover with an embedded bandpass filter function. The crossover is derived from the traditional crossover based on a tandem connection of two 3-dB 90° couplers by substituting them with 180° filtering couplers and introducing a filter function. In addition, a 180° phase shift realized by coupled resonators is added to keep the two cross paths in phase. The equivalent circuit of the crossover between the two diagonal ports have been treated as bandpass filters with coupled resonators. The design equations are derived to assist with the synthesis process for the filtering crossover. For verification, a filtering crossover with fifth-order filter characteristics, operating at 2.4 GHz, is designed, fabricated, and tested. The measured results match very well with the simulation, which verifies the proposed circuit concept.**

Index Terms**—Bandpass filter, crossover, filtering coupler, stripline.**

I. INTRODUCTION

Multi-beam antennas have attracted more attention in the past few years as they help enhance the communication capacity and improve spectral efficiency. One of the typical topologies for a multi-beam antenna is to utilize the Butler matrix as the beam-forming network. In the design of a Butler matrix, the crossover is one key component that greatly reduces the complexity of wiring by crossing two independent signals with high isolation and low loss. Conventional crossovers were often implemented using air bridges [1], multilayer structures [2], or microstrip branch-line couplers [3]-[5]. As the demand for multifunction applications increases, crossovers of new capabilities such as multiband, multichannel, tunable frequency, wideband or with filter functions have been demonstrated [6]-[20]. In [6]-[11], branch-line structures with different electrical length and impedance were utilized in a dual-band crossover. In [12]-[14], crossovers with three and four channels were proposed based on double-ring structures. A crossover with continuously tunable frequency was first proposed in [15], where two fixed capacitors and one tunable capacitor were used to replace the coupled line. In [16]-[19], microstrip rings and coplanar waveguide structures were utilized in wideband crossovers. In [20]-[25], several filtering crossovers were proposed by utilizing orthogonal modes in substrate integrated waveguides (SIWs) and cavity resonators. In [26], a filtering crossover with extended channel number and controllable frequencies was proposed by utilizing square SIW cavities. In [27], a tunable filtering crossover with independently tuned channel passbands based on evanescent-mode cavity was reported. In [28], A single-layer planar wideband filtering crossover with excellent common-mode suppression was reported.



(a)
(b)

Fig. 1. (a) A typical schematic of crossover realized by a tandem connection of two 3-dB/90° couplers. (b) The proposed schematic of filtering crossover based on 180° filtering couplers.

In this paper, prototype of a filtering crossover realized by 180° filtering couplers is proposed. Compared with the previous filtering crossovers based on multimode resonators [20]-[27], the novelty of this work is that a novel design method of filtering crossover realized by 180° filtering couplers using single mode resonators is proposed, and the crossover is easier to be implemented in filtering Butler matrix for 5G communications [29]. The detailed design process and synthesis methods for the filtering crossover are presented. For validation, a stripline filtering crossover with fifth-order filter characteristic is designed, fabricated, and tested.

II. DESIGN

A. Analysis

Fig. 1(a) shows a typical schematic of a crossover realized by a tandem connection of two 3-dB 90° couplers [3]. In a similar way, Fig. 1(b) presents the new schematic of a filtering crossover based on 180° filtering couplers. The main difference between them is the replacement of the 3-dB/90° couplers with 180° filtering couplers, which introduce the filter function to the

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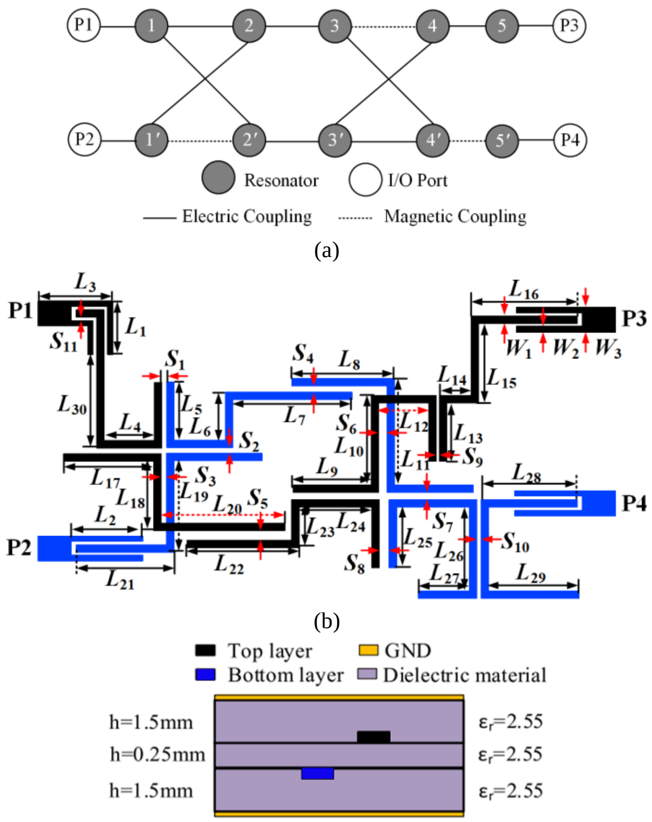
TABLE I
PHASE CHANGE OF EACH PATH WHEN DIFFERENT INPUT PORT ARE FED

Input port	Output port	Path ACE	Path ADE	Combined result
P1	P3	0°	-180°	CANCEL
	Output port	Path ACF	Path ADF	Combined result
	P4	-180°	-180°	-180°
Input port	Output port	Path BCE	Path BDE	Combined result
P2	P3	-180°	-180°	-180°
	Output port	Path BCF	Path BDF	Combined result
	P4	-180°	0°	CANCEL



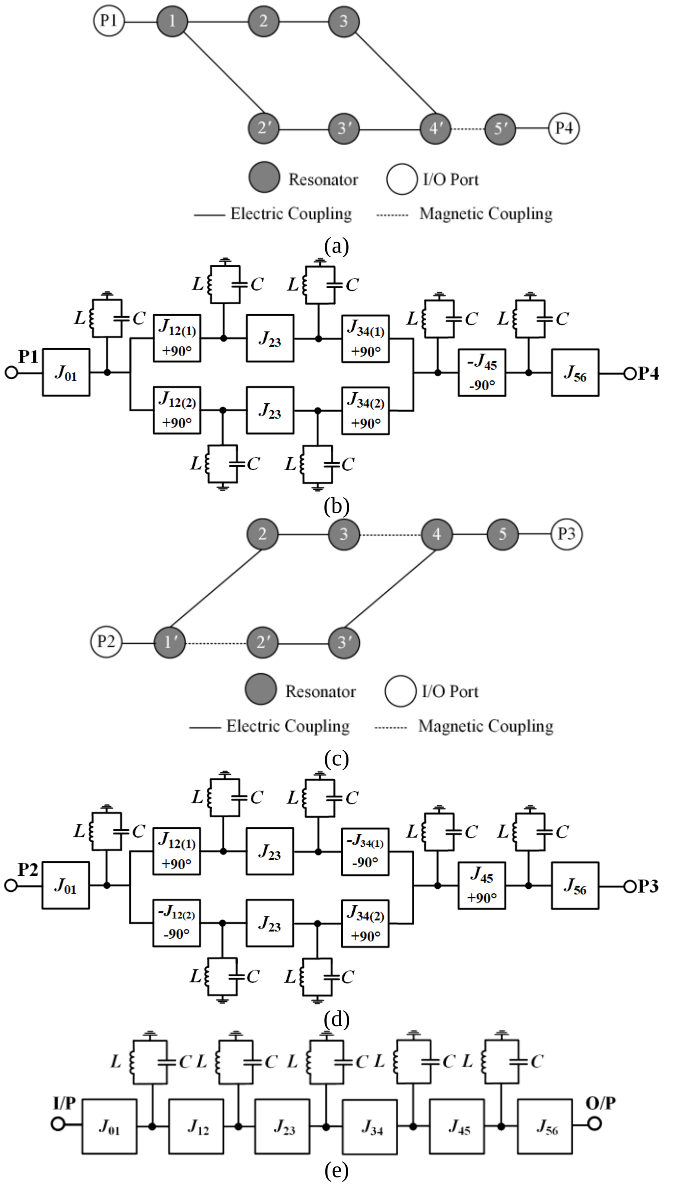
(a)

(b)

(c)

Fig. 2. (a) Coupling scheme of the filtering crossover. (b) Layout of the filtering crossover. (S_{11}=0.20, L_3=9.69, L_4=6.90, L_5=7.95, L_6=6.55, L_7=16.34, L_8=14.02, L_9=10.68, L_{10}=12.21 L_{11}=14.53, L_{12}=6.85, L_{13}=7.95, L_{14}=4.36, L_{15}=10.88, L_{16}=14.50, L_{17}=12.36, L_{18}=9.50, L_{19}=12.50, L_{20}=16.89, L_{21}=13.34, L_{22}=15.30, L_{23}=5.54, L_{24}=10.00, L_{25}=8.32, L_{26}=11.50, L_{27}=7.03, L_{28}=13.14, L_{29}=12.36, L_{30}=12.75, W_1=1.00, W_2=0.50, W_3=2.40, all in millimeters.) (c) The three-layer stripline structure.

crossover. In addition, the input and output ports (S^I, S^{II}, L^I, and L^{II}) of 180° coupler connected with output ports P3 and P4 are reversed compared with the 180° coupler connected with input ports P1 and P2. Finally, in order to keep the same phase shift of the two crossing paths in the crossover, a 180° phase shifter is connected before the output port P4. Based on the phase response of the 180° coupler, Table I shows the phase change of the two crossing paths when different input ports are excited. It can be concluded that when port P1(P2) is fed, the signal is output from port P4(P3) while port P3(P4) is isolated.



(a)

(b)

(c)

(d)

(e)

Fig. 3. (a) Coupling scheme of the filtering crossover for the input port P1. (b) Equivalent circuit of the filtering crossover for the input port P1. (c) Coupling scheme of the filtering crossover for the input port P2. (d) Equivalent circuit of the filtering crossover for the input port P2. (e) Equivalent circuit of the standard coupled resonator bandpass filter.

The design method of the 180° filtering coupler has been proposed in our previous work [29]. To achieve the filtering function as well as the required phase response of the crossover, the 180° phase shifter can be realized by utilizing different types of coupling between resonators 4 and 5 (4’ and 5’) as shown in the coupling scheme in Fig. 2(a). Fig. 2(b) shows the circuit layout based on a three-layer stripline structure, consisting of one thin and two thick dielectric layers with the dielectric constant of 2.55, as shown in Fig. 2(c).

As in [24], the input and output couplings are equivalent to the +90° admittance inverters *J*. The couplings between resonators dominated by electric or magnetic coupling are represented by the +90° or -90° admittance inverter, respectively. The parallel *LC* circuits are used to model the resonators. Using an analytical method, when the port P1 is

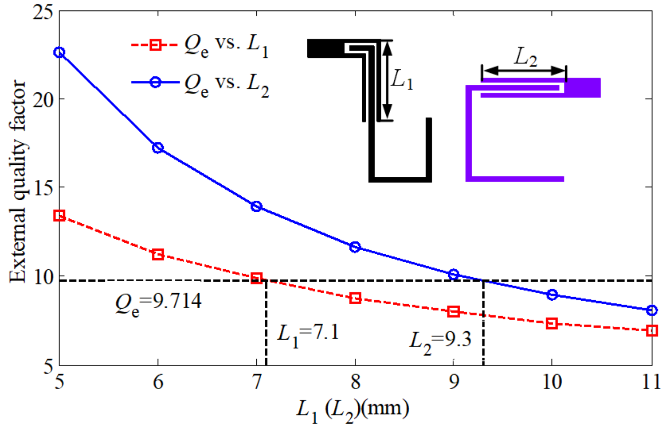


Fig. 4. Extracted external quality factor versus the corresponding design parameters.

the input, the ports P2 and P3 are isolated. Fig. 3(a) shows the coupling scheme of the filtering crossover for the input port P1. Therefore, the equivalent circuit of the filtering crossover when the port P1 is fed can be reduced to Fig. 3(b). Similarly, when the port P2 is fed, the coupling scheme and equivalent circuit can be reduced to Fig. 3(c) and (d).

As the 180° coupler is a uniform power splitter, the admittance inverters J can be expressed as

$$J^2_{12(1)} = J^2_{12(2)},\quad J^2_{34(1)} = J^2_{34(2)} \tag{1}$$

Comparing the admittance inverters in Fig. 3(b) and (d) with those in a standard filter (Fig. 3(e)), we have

$$J^2_{12(1)} + J^2_{12(2)} = J^2_{12},\quad J^2_{34(1)} + J^2_{34(2)} = J^2_{34} \tag{2}$$

where J_{12} and J_{45} are the inverters in the standard filter.

From (1) and (2), it can be found that

$$\begin{aligned} J_{12(1)} &= J_{12(2)} = \pm\frac{\sqrt{2}}{2}J_{12} \\ J_{34(1)} &= J_{34(2)} = \pm\frac{\sqrt{2}}{2}J_{34} \end{aligned} \tag{3}$$

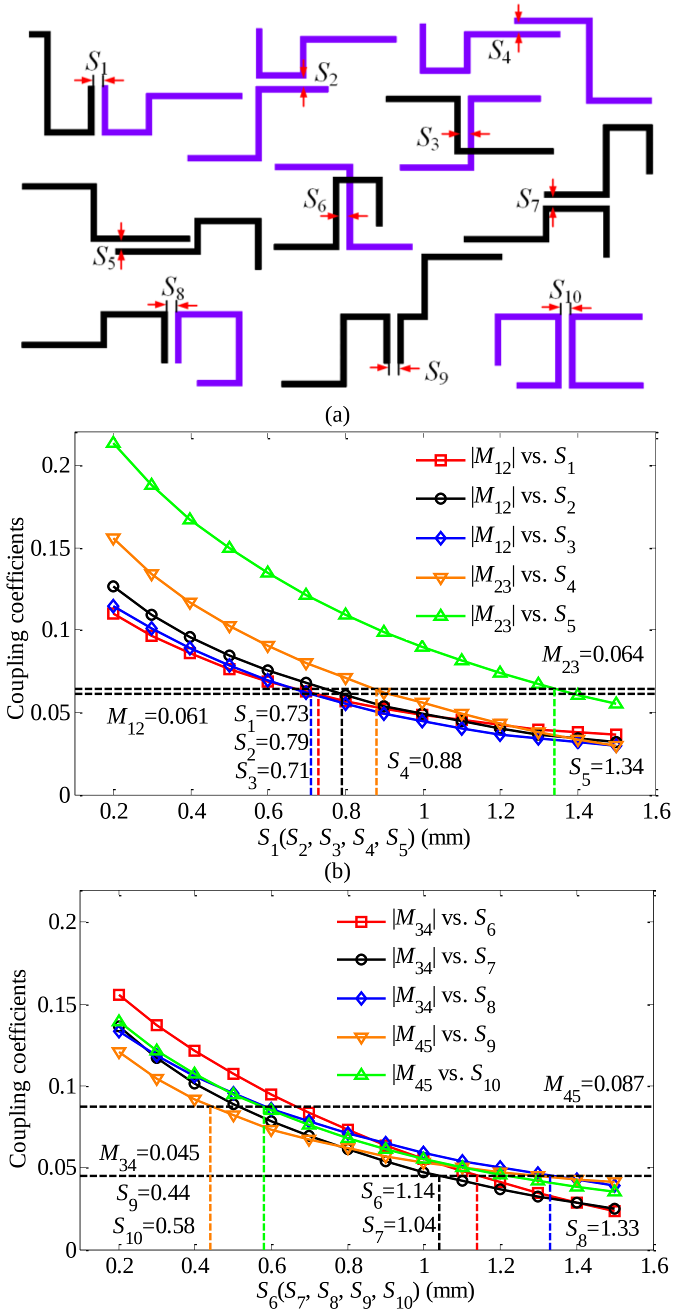
Therefore, different paths of the crossover from input to output can be equivalent to the circuits in Fig. 3(e), which is regarded as the fundamental bandpass filter. If the design specifications such as the ripple level, center frequency (f_0) as well as fractional bandwidth (FBW) are prescribed, the parameters of the prototype filter (g_1, g_2, g_3, g_4 and g_5) can be obtained, and the external quality factors (Q_{e1} and Q_{e2}) and coupling coefficients (M_{12}, M_{23}, M_{34} and M_{45}) of the bandpass filter can be obtained as [30]

$$Q_{e1} = \frac{g_0 g_1}{FBW},\ Q_{e2} = \frac{g_5 g_6}{FBW} \tag{4}$$

$$\begin{aligned} M_{12(1)} &= M_{12(2)} = \pm\frac{\sqrt{2}FBW}{2\sqrt{g_1 g_2}},\ M_{23} = \frac{FBW}{\sqrt{g_2 g_3}} \\ M_{34(1)} &= M_{34(2)} = \pm\frac{\sqrt{2}FBW}{2\sqrt{g_3 g_4}},\ M_{45} = \pm\frac{FBW}{\sqrt{g_4 g_5}} \end{aligned} \tag{5}$$

where "+" and "-" denote the coupling which is dominated by electric and magnetic field, respectively.

B. Design Example



(a)

(b)

(c)

Fig. 5. (a) Circuit layout for extracting coupling coefficients. (b) and (c) Extracted coupling coefficients versus the corresponding design parameters.

To test the validity of the design approach, a filtering crossover is devised, manufactured and measured. It is designed to have a fractional bandwidth of 10% at a midband frequency f_0 = 2.4 GHz. The passband ripple level is chosen to be 0.0432 dB with respect to a 20 dB return loss. The lowpass prototype parameters can be obtained as g_1 = 0.9714, g_2 = 1.3721, g_3 = 1.8014, g_4 = 1.3721 and g_5 = 0.9714 from a lookup table [30]. From equations (4) to (5), the bandpass design parameters can be calculated as Q_{e1} = Q_{e2} = 9.714, $M_{12(1)}$ = $M_{12(2)}$ = ±0.061, M_{23} = 0.064, $M_{34(1)}$ = $M_{34(2)}$ = ±0.045, M_{45} = ±0.087. By using the extraction approach in [30], the external quality factor and coupling coefficients with

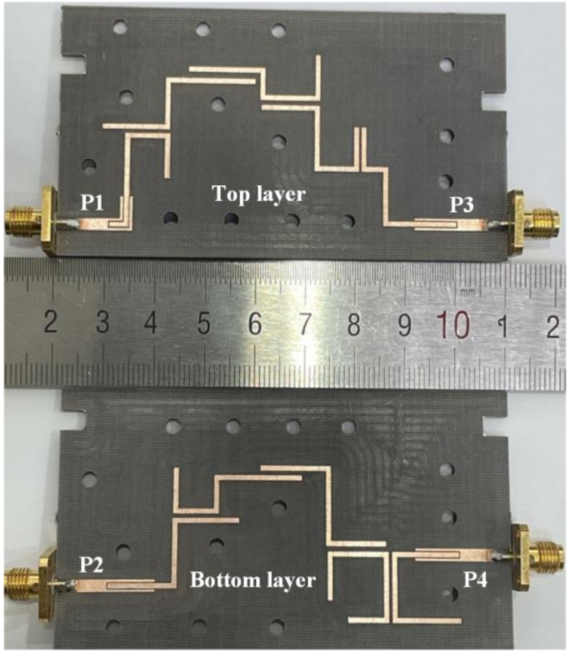
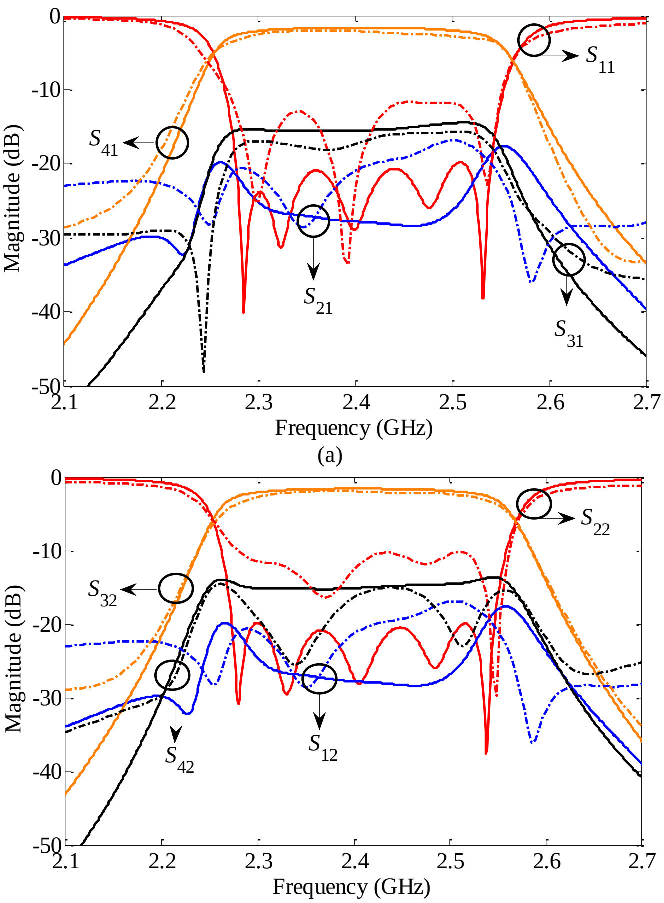


Fig. 6. Photo of the manufactured crossover.



(a)

(b)

Fig. 7. Simulated and measured *S*-parameters (dash-dotted lines: measurement results, solid lines: simulation results).

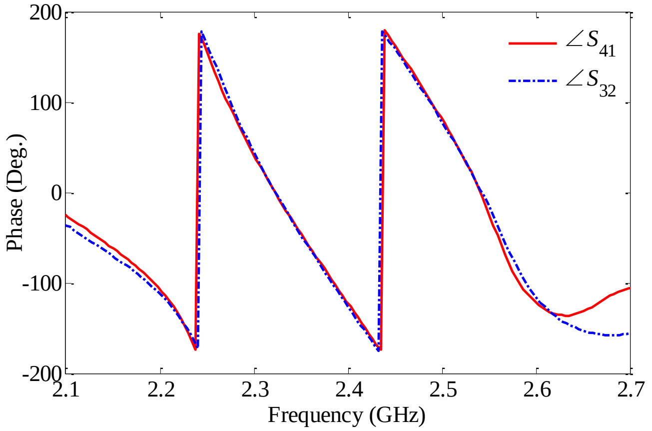


Fig. 8. Measured phase of the two cross paths.

TABLE II
COMPARISON WITH PREVIOUS WORK

Ref.	CF (GHz)	Iso. (dB)	Loss (dB)	FBW (%)	Filter	Techn.	Type of realized resonator	Size (λ_g^2)
[3]	6.0	20	1.0	NG	No	ML	NA	NG
[20]	2/2.4	23	1.6/1.5	6.7/4.4	Yes	ML	Multi-mode	0.08
[21]	20	30	1.63	2.41	Yes	SIW	Multi-mode	6.29
[22]	18.68	18.5	2.03	3.72	Yes	SIW	Multi-mode	1.23
[23]	12	21.8	1.61	7.17	Yes	SIW	Multi-mode	6.35
	12	18.3	2.1	5.08				7.55
	12/12	21.9	1.3/1.7	7.9/5.2				6.15
	12/13.5	29	1.2/1.4	6.9/6.1				5.47
[24]	3	45	0.6	24	Yes	WG	Multi-mode	NG
[25]	9.7/10/10.3	29.6	0.2/0.36/0.21	2.1/2/1.9	Yes	WG	Multi-mode	NG
[26]	8.83	23	2.29	3.74	Yes	SIW	Multi-mode	10.9
	8.83	22	1.8/2.3	4.5/4.4				7.27
	8/8.8	21	1.4/1.8	4.5/5				3.98
This work	**2.4**	**15**	**1.8**	**10**	**Yes**	**SL**	**Single mode**	**0.93**

CF: Center frequency; Iso.: Isolation; Techn.: Technology; NG: not given; ML: Microstrip; WG: Waveguide; SL: Stripline.

respect to the design parameters are shown in Fig. 4 and Fig. 5. The initial values of the filtering crossover can be obtained as L_1 = 7.10, L_2 = 9.30, S_1 = 0.73, S_2 = 0.79, S_3 = 0.71, S_4 = 0.88, S_5 = 1.34, S_6 = 1.14, S_7 = 1.04, S_8 = 1.33, S_9 = 0.44, S_{10} = 0.58, all in millimeters. Then, the filtering crossover is optimized by using IE3D software and its final dimensions are L_1 = 6.80, L_2 = 9.29, S_1 = 0.71, S_2 = 0.78, S_3 = 0.71, S_4 = 0.87, S_5 = 1.30, S_6 = 1.13, S_7 = 1.00, S_8 = 1.35, S_9 = 0.46, S_{10} = 0.60, all in millimeters.

C. Measurement Results

Photo of the manufactured filtering crossover is shown in Fig. 6. Fig. 7(a) shows the simulation and measurement *S*-parameters when the input is at port P1. The measured minimum insertion loss is 1.8 dB, and the measured return loss is better than 11 dB. The isolation between port P1 and port P2 and P4 are larger than 15 dB. In the same way, Fig. 7(b) shows the simulation and measurement results when the input is at port P2. The measured minimum insertion loss is

1.8 dB, and the measured return loss is better than 11 dB. The isolation between port P2 and port P1 and P4 are larger than 15 dB. The measured phases for the two crossing paths are shown in Fig. 8. It can be clearly observed that the two cross paths have the same phase in the passband of the filter. Table II compares the proposed filtering crossover with previous work in the field. It can be seen that this work provides a higher order filter function by utilizing single mode resonators, which would be easier to be implemented in the filtering Butler matrix.

III. CONCLUSION

This paper presents a design method for the filtering crossover based on 180° couplers. It is comprised of 180° filtering couplers and coupled resonators, providing two crossing paths with isolation larger than 15 dB, the same phase shift as well as a bandpass filtering characteristic with an insertion loss of 1.8 dB. The measurement results are consistent with the simulation, which confirms the validity of the design approach.

REFERENCES

[1] T.-S. Horng, “A rigorous study of microstrip crossovers and their possible improvements,” *IEEE Trans. Microw. Theory Techn.*, vol. 42, no. 9, pp. 1802–1806, Sep. 1994.

[2] D. Jaisson, “Multilayer microstrip directional coupler with discrete coupling,” *IEEE Trans. Microw. Theory Techn*., vol. 48, no. 9, pp. 1591–1595, Sep. 2000.

[3] J. S. Wight, W. J. Chudobiak, and V. Makios, “A microstrip and stripline crossover structure (letters),” *IEEE Trans. Microw. Theory Techn.*, vol. 24, no. 5, p. 270, May 1976.

[4] J. J. Yao, “Nonstandard hybrid and crossover design with branchline structures,” *IEEE Trans. Microw. Theory Techn.*, vol. 58, no. 12, pp. 3801–3808, Dec. 2010.

[5] J. Yao, C. Lee, and S. P. Yeo, “Microstrip branch-line couplers for crossover application,” *IEEE Trans. Microw. Theory Techn.*, vol. 59, no. 1, pp. 87–92, Jan. 2011.

[6] J. Shao, H. Ren, B. Arigong, C. Li, and H. Zhang, “A fully symmetrical crossover and its dual-frequency application,” *IEEE Trans. Microw. Theory Techn.*, vol. 60, no. 8, pp. 2410–2416, Aug. 2012.

[7] H. Ren, M. Zhou, H.-X. Zhang, and B. Arigong, “A novel dual-band zero-phase true crossover with arbitrary port impedance,” *IEEE Microw. Wireless Compon. Lett*., vol. 29, no. 1, pp. 29–31, Jan. 2019.

[8] F.-L. Wong and K.-K. M. Cheng, “A novel, planar, and compact crossover design for dual-band applications,” *IEEE Trans. Microw. Theory Techn.*, vol. 59, no. 3, pp. 568–573, Mar. 2011.

[9] F. Lin, Q.-X. Chu, and S.-W. Wong, “Dual-band planar crossover with two-section branch-line structure,” *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 6, pp. 2309–2316, June. 2013.

[10] W. Feng, T. Zhang, W. Che, and Q. Xue, “Compact single-/dual-band planar crossovers based on strong coupled lines,” *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 6, no. 6, pp. 854-863, June 2016.

[11] M. A. Maktoomi, M. S. Hashmi, and F. M. Ghannouchi, “Systematic design technique for dual-band branch-line coupler using T- and Pi-networks and their application in novel wideband-ratio crossover,” *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 6, no. 5, pp. 784-795, May 2016

[12] L. S. Wu, Y. X. Guo, and J. F. Mao, “A planar microstrip crossover with lumped inductors for three intersecting channels,” *IEEE Trans. Microw. Theory Techn.*, vol. 62, no. 4, pp. 851–860, Apr. 2014.

[13] C. W. Tang and W. M. Chuang, “Design of the planar six-port crossover with double rings,” *IEEE Microw. Wireless Compon. Lett.*, vol. 25, no. 10, pp. 651–653, Oct. 2015.

[14] P.-C. Chu and C.-W. Tang, “Design of a compact planar crossover with four intersecting channels,” *IEEE Microw. Wireless Compon. Lett.*, vol. 28, no. 4, pp. 293–295, Apr. 2018.

[15] F. Lin, S.-W. Wong, and Q.-X. Chu, “Compact design of planar continuously tunable crossover with two-section coupled lines,” *IEEE Trans. Microw. Theory Techn.*, vol. 62, no. 3, pp. 408–415, Mar. 2014.

[16] Y.-H. Pang and J.-J. Li, “A planar wideband balanced crossover,” *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 8, no. 10, pp. 1807-1814, Oct. 2018.

[17] Y. Wang, A. M. Abbosh, and B. Henin, “Broadband microwave crossover using combination of ring resonator and circular microstrip patch,” *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 3, no. 10, pp. 1771-1777, Oct. 2013.

[18] W.-D. Liu, Z.-J. Zhang, Z.-H. Feng, and M. F. Iskander, “A compact wideband microstrip crossover,” *IEEE Microw. Wireless Compon. Lett.*, vol. 22, no. 5, pp. 254–256, May 2012.

[19] A. Abbosh, S. Ibrahim, and M. Karim, “Ultra-wideband crossover using microstrip-to-coplanar waveguide transitions,” *IEEE Microw. Wireless Compon. Lett.*, vol. 22, no. 10, pp. 500–502, Oct. 2012.

[20] Q.-Y. Guo, X.-Y. Zhang, and L. Gao, “Novel compact planar crossover with bandpass response based on cross-shaped resonator,” *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 7, no. 12, pp. 2018-2026, Dec. 2017.

[21] S.-Q. Han, K. Zhou, J.-D. Zhang, C.-X. Zhou, and W. Wu, “Novel substrate integrated waveguide filtering crossover using orthogonal degenerate modes,” *IEEE Microw. Wireless Compon. Lett.*, vol. 27, no. 9, pp. 803–805, Sep. 2017.

[22] B.-N. Yao, G. Zhang, X. Zhou, N. Li, W.-C. Tang, and J.-Q. Yang, “Substrate-integrated waveguide filtering crossover based on 3-D assembly,” *IEEE Microw. Wireless Techn. Lett*., vol. 33, no. 5, pp. 523–526, May 2023.

[23] K. Zhou and K. Wu, “Wide-stopband substrate-integrated waveguide filtering crossovers with flexibly allocated channel frequencies and bandwidths,” *IEEE Trans. Microw. Theory Techn.*, vol. 69, no. 7, pp. 3264–3274, Mar. 2021.

[24] J.-Y. Lin, S.-W. Wong, Y.-M. Wu, Y. Yang, L. Zhu, and Y.-J He, “Three-way multiple-mode cavity filtering crossover for narrowband and broadband applications,” *IEEE Trans. Microw. Theory Techn.*, vol. 67, no. 3, pp. 896–905, Mar. 2019.

[25] Y. Zhang, J. Xu, and X.-B. Shang, “3-D printed filtering crossover using ellipsoidal cavities,” *IEEE Microw. Wireless Techn. Lett.*, vol. 33, no. 2, pp. 153–156, Feb. 2023.

[26] W.-L. Zhan, J.-X. Xu, X.-L. Zhao, B.-J. Hu, and X.-Y. Zhang, “Substrate integrated waveguide multi-channel filtering crossover with extended channel number and controllable frequencies,” *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 67, no. 12, pp. 2858–2862, Dec. 2020.

[27] J.-C. Lai, T. Yang, P.-L. Chi, and R.-M. Xu, “A novel 1.7–2.85 GHz filtering crossover with independently tuned channel passbands and reconfigurable filtering power-dividing function,” *IEEE Trans. Microw. Theory Techn.*, vol. 69, no. 5, pp. 2458–2469, May 2021.

[28] Y.-N. Zheng, W.-M. Wang, Y.-L. Wu, and W.-J. Che, “A single-layer planar wideband filtering single-ended-to-balanced crossover with excellent common-mode suppression,” *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 69, no. 2, pp. 364–368, Feb. 2022.

[29] Q. Shao, F. C. Chen, Y. Wang, and Q. X. Chu, “Design of 4 × 4 and 8 × 8 filtering Butler matrices utilizing combined 90° and 180° couplers,” *IEEE Trans. Microw. Theory Techn.*, vol. 69, no. 8, pp. 3842–3852, Aug. 2021.

[30] J. S. Hong and M. J. Lancaster, *Microstrip Filters for RF/Microwave Applications*. New York, NY, USA: Wiley, 2001.

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Manuscript No.: TCPMT-2023-533

Dear Editors and Reviewers,

Thank you very much for your constructive comments on our manuscript entitled with " Design of Filtering Crossover Based on 180° Filtering Couplers". We have revised our manuscript based on the comments. The changes made in the revised manuscript had been highlighted in blue color. The followings are the replies to the reviewers comments.

Sincerely,
Qiang Shao, Ning Yang, Rui-Sen Chen, Guang-Long Huang, Fu-Chang Chen, and Yi Wang

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Reply to the Reviewer's comments:

Reviewer: 1

There is no novelty in the presented work. This type of structure is old.

Response of authors

Thanks for your comment. In recent years, there are many work about the filtering crossover. However, nearly all of them are designed based on the multimode resonator, in which two cross path will excite different mode of the resonator and realize a crossover with filter function. In this paper, based on the typical schematic of crossover realized by a tandem connection of two 3-dB/90° couplers, a novel schematic of crossover based on 180° couplers was proposed. In addition, we introduce the filter function into the crossover by replacing the 180° couplers with the 180° filtering couplers realized by single mode resonators. Hence， compared with the previous filtering crossovers based on multimode resonators, the novelty of this work is that a novel design method of filtering crossover realized by 180° filtering couplers using single mode resonators is proposed, and the crossover is easier to be implemented in filtering Butler matrix for 5G communications.

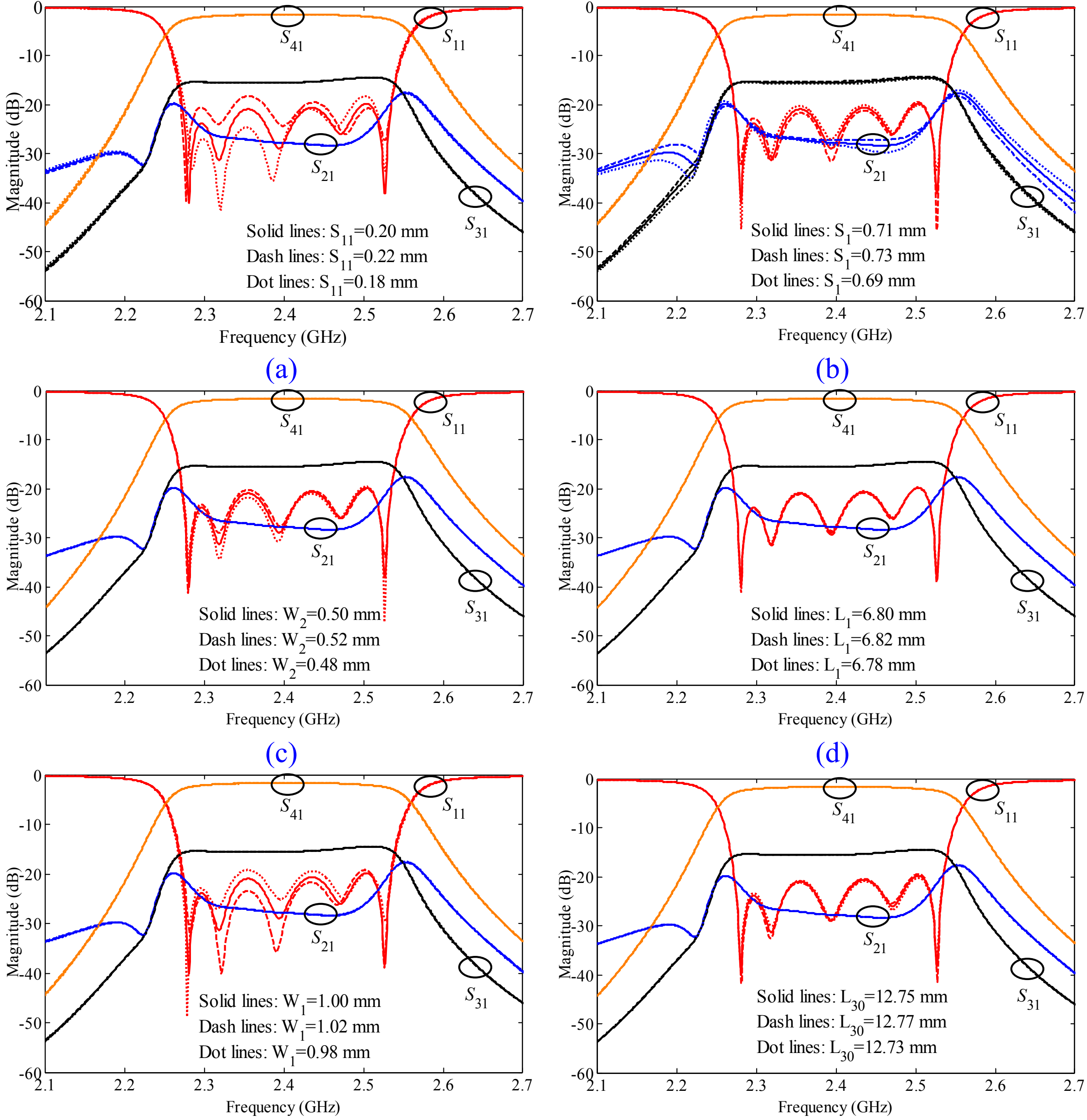
Reviewer: 2

This paper proposes the design of filtering crossover based on 180° filtering couplers. General speaking, this manuscript is well written. There are two comments should be properly addressed.

(1) The visible discrepancies between the simulated and measured results can be observed in Fig. 7. Please provide the sensitivity analysis of this proposed crossover based on the three-layer stripline structure.

Response of authors

Thanks for your useful comments. As for a sensitivity test, we think it is no need to take all the variables into consideration, so we just pick some important variables to test the sensitivity. Take the input port P1 as example, we choose the gap between the input feeding line with the first resonator (S_{11}), the gap between the adjacent resonators (S_1), the width and length of the input feeding line (W_2, L_1), the width and length of first resonator (W_1, L_{30}) to conduct a sensitivity test and the manufacturing tolerances is set to 0.02mm corresponding to machining error for device in our lab. Fig. A shows the simulated results of S parameters under different conditions. It can conclude that when taken manufacturing tolerances into consideration, there is nearly no influence on the performance of filtering crossover which means it can pass a sensitivity test.



(a) (b) (c) (d) (e) (f)

Fig. A Simulated results of S parameters under different conditions. (a)S_{11}. (b)S_1. (c)W_2. (d) L_1. (e)W_1. (f)L_{30}.

(2) The circuit size is the key parameter of the microwave component. Please add the circuit size in the comparison table.

Response of authors

Thanks for your useful comments. We have added the circuit size in the comparison table in the revised manuscript.

TABLE II
COMPARISON WITH PREVIOUS WORK

Ref.	CF (GHz)	Iso. (dB)	Loss (dB)	FBW (%)	Filter	Techn.	Type of realized resonator	Size (λ_g^2)
[3]	6.0	20	1.0	NG	No	ML	NA	NG
[20]	2/2.4	23	1.6/1.5	6.7/4.4	Yes	ML	Multi-mode	0.08
[21]	20	30	1.63	2.41	Yes	SIW	Multi-	6.29

							mode	
[22]	18.68	18.5	2.03	3.72	Yes	SIW	Multi-mode	1.23
[23]	12	21.8	1.61	7.17	Yes	SIW	Multi-mode	6.35
	12	18.3	2.1	5.08				7.55
	12/12	21.9	1.3/1.7	7.9/5.2				6.15
	12/13.5	29	1.2/1.4	6.9/6.1				5.47
[24]	3	45	0.6	24	Yes	WG	Multi-mode	NG
[25]	9.7/10/10.3	29.6	0.2/0.36/0.21	2.1/2/1.9	Yes	WG	Multi-mode	NG
[26]	8.83	23	2.29	3.74	Yes	SIW	Multi-mode	10.9
	8.83	22	1.8/2.3	4.5/4.4				7.27
	8/8.8	21	1.4/1.8	4.5/5				3.98
This work	**2.4**	**15**	**1.8**	**10**	**Yes**	**SL**	**Single mode**	**0.93**

CF: Center frequency; Iso.: Isolation; Techn.: Technology; NG: not given; ML: Microstrip; WG: Waveguide; SL: Stripline.

Finally, thanks Editors and Reviewers again for your constructive comments on our manuscript.