Compact 4-pole BRF-based Directional Filter with Even-mode Matching Circuit for Sharp Cut-off

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Abstract — The directional filter structure using λ/2 strip resonators with better filtering performance has been the focus of recent research activities. The band-reject filter based directional filter structure has been demonstrated as an effective way to achieve this goal. However, the prototype reported is cascading resonators in the lateral direction. When the order of the filer gets higher, the lateral cascading leads to rapid oscillation in the stop-band of S_{41} and a lengthy structure. This paper demonstrated a 4-pole band-reject filter based DF using direct-coupled band-reject filter. It achieves the highest order of DF response reported without the rapid oscillation in the stop-band. Yet it is about 30% smaller compared to previous 3-pole directional filter prototypes.

Index Terms — directional filter, band-reject filter, multi-stage directional filter, compact directional filter, band-stop filter.

I. Introduction

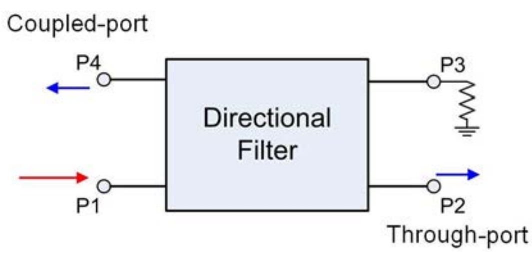


Fig. 1 The schematic of the directional filter.

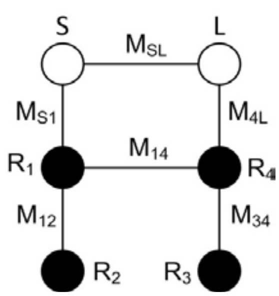
Multiplexers play an essential role in today's wireless or satellite communications. Directional filter (DF) is a promising candidate for multiplexers with many channels because it breaks down the multiplexer synthesis to the synthesis of individual modules without extra isolation circuits such as circulators or branch-line couplers [1].

The DF is a four-port device, of which the schematic is shown in Fig. 1. When the signal is input into DF from port P1, the coupled-port response S_{41} will have a band-pass response and the through-port response S_{21} will have the band-reject response complementary to S_{41}.

There are two main types of DFs. One uses traveling-wave loop resonators, the other one uses λ/2 strip resonators. The traveling-wave loop DFs are capable of synthesizing high-order band-pass filtering functions for the S_{41} response, such as Butterworth or Chebyshev, but its performance is very sensitive to manufacturing defects and is difficult to realize in practice [2]. The λ/2 strip resonator DFs are relatively more robust against manufacturing defects, but its S_{41} response is limited to first-order filter response.

With the goal of developing high-order DF with good tolerance to defects, recent research efforts have been focusing on improving the filtering performance of the DFs using λ/2 resonators [3]-[4]. In [4], the band-reject filter (BRF) based DF structure is studied in detail. It demonstrated prototypes with good S_{41} band-pass response with natural elliptic BRF prototype [5], and high isolation performance S_{31} using composite right/left handed (CRLH) transmission line (TL) for phase-matching.

However, there seems to be a potential drawback with the DF prototypes demonstrated in [4]. The resonators of the BRF have to be cascaded laterally. As the filter order becomes higher, the total structure becomes longer, which leads to large phase-shift in even-mode signal. This even-mode phase (S_{21e} in (1)) changes rapidly versus frequency as well, and will result in discrepancy between S_{41} and the designed BRF performance in close vicinity of center frequency, as can be inferred from (1) [4].



(a)

	S	1	2	3	4	L
S	0	1.5608	0	0	0	1
1	1.5608	0.0558	1.1647	0	1.2179	0
2	0	1.1647	0.5334	0	0	0
3	0	0	0	-0.9141	0.7625	0
4	0	1.2179	0	0.7625	0.0558	1.5608
L	1	0	0	0	1.5608	0

(b)

Fig. 2 The filter structure of the BRF (a) and the corresponding coupling matrix used in this work (b).

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$$S_{41} = -\frac{1}{2} S_{11o}\{1 - e^{-j(2\theta+\Delta\theta)}[S_{21o}{}^2 \sin^2\frac{\Delta\theta}{2} + S_{21e}{}^2 \cos^2\frac{\Delta\theta}{2}]\} \quad (1)$$

In this paper, we demonstrate the adaption of the direct-coupled BRF [6] into the DF design. In this class of BRF, the resonators are cascaded in the vertical direction instead of lateral direction, which will be shown later. The advantage of this BRF structure in DF design is that the phase-shift between the two ends is maintained to be around 90° regardless of the number of the stages. Thus we can expect the rapid oscillatory behavior in the stop-band would be eliminated, and the incorporation of the CRLH phase-matching would be easier.

As a proof of concept, a four-pole DF based on the direct-coupled BRF is demonstrated with CRLH phase-matching for improved isolation. Compared to [4], this work achieved higher order filtering function without the side-effect of rapid oscillatory behavior in the stop-band. This BRF filter structure has been proven to be very compact as well. Compared to the prototype in the literature [4], this new DF realized a filtering function of higher order, yet it is 30% smaller in size.

II. 4-POLE BRF DESIGN

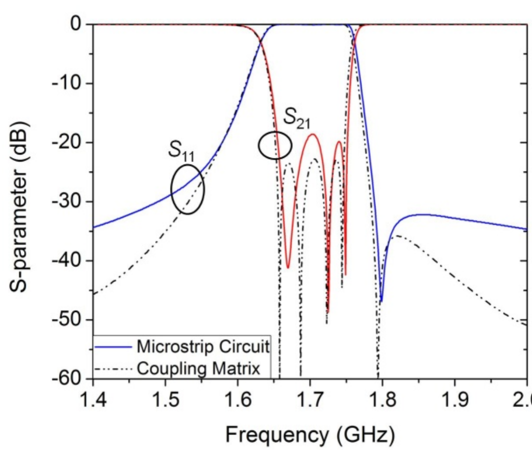


Fig. 3 BRF response from the coupling matrix (dotted) and the microstrip circuit (solid).

For compactness, better stop-band characteristics and easy incorporation of the CRLH phase-matching scheme, the structure of 4-pole BRF in Fig. 2(a) is adapted, where black solid circles stand for the four resonators R_1 though R_4, the connecting lines represents the coupling M_{ij}, and the hollowed circles represent the source and load. The corresponding coupling matrix synthesized for this demonstration is shown in Fig. 2(b). The filter is cascaded in the vertical direction and is designed to have one reflection zeros in the higher pass-band with S_{11} of -35dB and -23dB rejection in the stop-band. The resulting S-parameter is later shown in dotted line in Fig. 3.

The microstrip realization of this BRF is shown in Fig. 4 The source to load coupling M_{sL} is realized by a 90° transmission line, coupling M_{1s} and M_{4L} are realized by interdigital capacitors, and the rest of the coupling is realized by proximity coupling. The resonators are λ/4 resonators, and resonator R2 and R3 is meandered to fit in the available space.

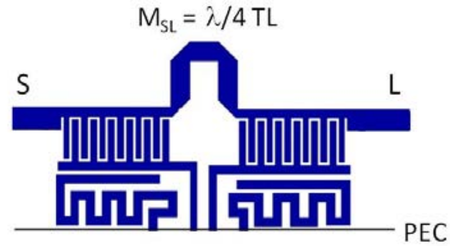


Fig. 4 The microstrip realization of the 4-pole BRF of Fig. 2(a).

The S-parameter of this microstrip BRF is also shown in Fig. 3 in solid line, with the ideal response from coupling matrix calculation in dotted line. The center frequency is designed to be at 1.7GHz with FBW ~5.7%. The responses are asymmetric and have a zero in S_{11} response at 1.8GHz. In the realized response, the lower two zeros in S_{21} merged together, the rejection level is about 20dB in the stop-band, and the cut-off rate is somewhat slower at frequencies away from the center frequency. These are caused by deviations of the real microwave circuits from the ideal elements used in the coupling matrix synthesis. However, the S_{11} response still resembles the ideal ones, and preserves the zeros and the sharp cut-off behavior.

The source to load coupling M_{sL} in the ideal coupling matrix is 1, which should translate to 50 Ohm quarter wave transmission line in microstrip circuit. However, in the actual realized circuit in Fig. 4 it is 55 Ohm instead. This is because the phase response of this quarter-wave transmission line is frequency dependent. In order to compensate for this effect, some increase in the characteristic impedance of the line and slight tuning in the resonators are necessary.

III. 4-POLE BRF-BASED DF PROTOTYPE

To use this BRF for a DF design, we first mirror the structure in Fig. 4 with respect to the PEC plane. In this way it

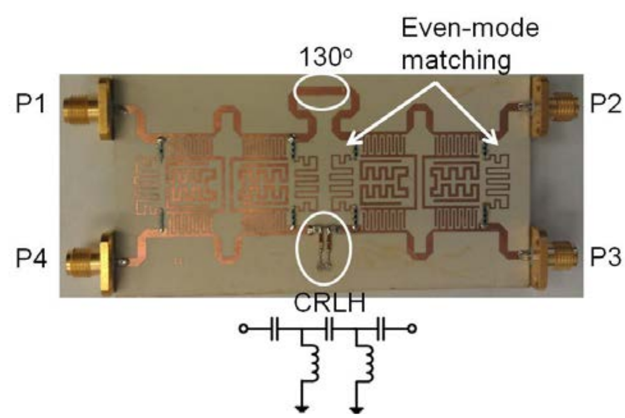
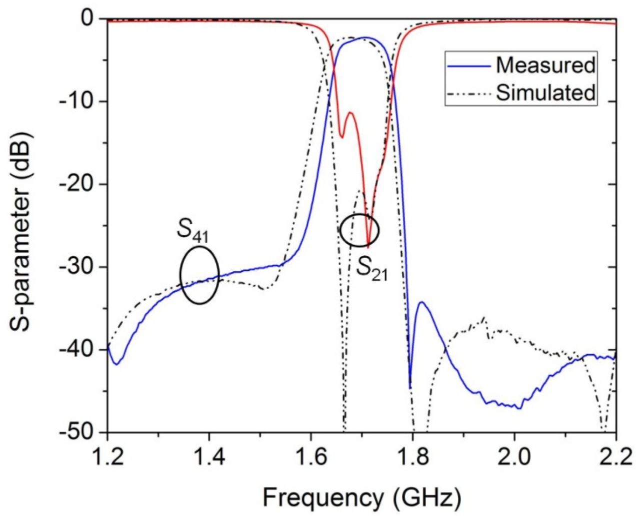
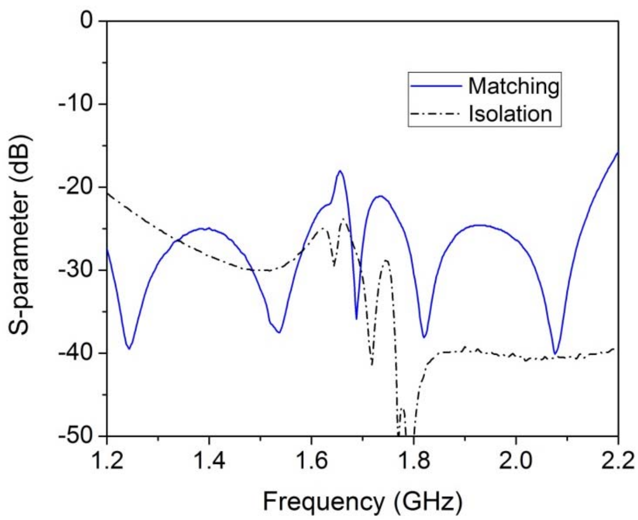


Fig. 5 The realized DF prototype using the 4-pole BRF in Fig. 4.



(a)



(b)

Fig. 6 The simulated and measured S41 and S21 response of the DF prototype (a), and its measured matching and isolation performance (b).

will preserve the BRF performance under odd-mode excitation, but will be an all-pass filter under even-mode excitation. This condition is necessary to construct a DF using the BRF. The proper delay line between the two mirrored BRFs is found to be 130^o. Notice this delay line is larger than 90^o and is ideal to work with CRLH phase-matching [4]. This is due to the fixed phase-shift (~90o) in the direct-coupled BRF structure regardless of the order of the filter.

The fabricated prototype is shown in Fig. 5. We can see that the two mirrored BRFs are connected by 130^o microstrip line and the CRLH TL. It is fabricated on RO3003 substrate with ε_r=3 and thickness of 30mil. The size of the DF is about 89mm x 32mm. The CRLH line part has two unit cells, and consists of three series capacitors and two shunt inductors, as also shown in the Fig. 5. The shunt inductance consists of two 2.2nH inductors and a 3.3mm shorted stub connected in series. The series capacitors at the two ends consist of one 2.2pF and one 2.4pF capacitor in parallel, and the capacitor in the center is 2.2pF. This CRLH TL is designed to achieve phase-matching with the corresponding 130^o microstrip line.

The band-pass S_{41} response and the band-stop S_{21} response of the DF from 1.2 to 2.2 GHz are shown in Fig. 6(a) where solid lines are measured results and dotted line is simulated results. The insertion loss at 1.7GHz is about 2.4dB. By comparing to the designed BRF response in Fig. 3, we can see that the zeros at 1.8GHz and the sharp cut-off in the S_{11} of the BRF are preserved in the S_{41} of the DF. However, the band-reject level in S_{21} of the DF is only about 10dB, higher than the simulated case. This is possibly due to the manufacturing tolerance, the lumped element value variation and extra loss introduced by the lumped elements. The S_{11} and S_{31} are shown in Fig. 6(b). For clarity, only measured responses are shown. Wide-band matching and isolation are achieved, which is the typical characteristic of the DF.

Notice that there are extra even-mode matching circuits being added at the two sides of the mirrored BRF, as indicated in Fig. 5. It is consists of three 10nH inductors in series at the two ends, connected by a transmission line close to 180^o. It has been pointed out that the out-of-band rejection level of S_{41} will be affected by the matching of the mirrored BRF under even-mode excitation [4]. Since the rejection level we are realizing is deep (~35dB), extra care is taken by adding the matching circuits to improve the even-mode matching to be better than 30dB without disturbing the odd-mode operation.

IV. Conclusion

This work demonstrated that by using direct-coupled BRF prototype in the DF design, we can avoid oscillatory behavior in the stop-band of S_{41} with a more compact structure, and we can incorporate the CRLH phase-matching easily for better isolation performance. The prototype demonstrated a 4-pole DF with CRLH phase-matching. This is the highest order of DF reported using $\lambda/2$ resonator structure, yet it is 30% smaller than the 3-pole elliptic DF in the literature [4]. The stop-band rejection is about 30dB in the lower frequency and 35dB in the higher frequency, without any rapid oscillation behavior.

References

[1] R. J. Cameron, and M. Yu, "Design of manifold-coupled multiplexers," *IEEE Microwave Magazine.,* vol. 8, no. 5, pp. 46-59, 2007.

[2] G. Matthaei, E.M.T. Jones, and L. Young, *Microwave filters, impedance-matching networks, and coupling structures,* Artech House Publishers, 1980.

[3] J. P. Kim, "Improved design of single-section and cascaded planar directional filters," *IEEE Trans. Microwave Theory & Tech.,* vol. 59, no. 9, pp. 2206-2213, 2011.

[4] J. S. Sun, H. Lobato-Morales, J. H. Choi, A. Corona-Chavez, T. Itoh "Multi-stage directional filter based on band-reject filter with isolation improvement using composite right-/left handed

transmission lines," *IEEE Trans. Microwave Theory & Tech.,* vol. 60, no. 12, part 2, pp. 3950-3958, 2012.

[5] J. D. Rhodes, "Waveguide bandstop elliptic function filters," *IEEE Trans. Microwave Theory & Tech*, vol. 20, no. 11, pp. 715-718, 1972.

[6] R. J. Cameron, M. Yu, Y. Wang, "Direct-coupled microwave filters with single and dual stopbands," *IEEE Trans. Microwave Theory & Tech*, vol. 53, no. 11, pp. 3288-3297, 2005.

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