

# Two Topologies of Balanced Dual-Band Bandpass Filters with Extended Common-Mode-Suppression Bandwidth

Roberto Gómez-García<sup>1</sup>, José-María Muñoz-Ferreras<sup>1</sup>, Wenjie Feng<sup>2</sup>, and Dimitra Psychogiou<sup>3</sup>

<sup>1</sup>Dept. Signal Theory and Commun., University of Alcalá, Alcalá de Henares 28871, Madrid, Spain

E-mails: roberto.gomez.garcia@ieee.org; jm.munoz@uah.es

<sup>2</sup>Dept. Commun. Eng., Nanjing Univ. of Science and Technology, 210094 Nanjing, China

E-mail: fengwenjie1985@163.com

<sup>3</sup>Dept. Electrical, Computer, and Energy Eng., Univ. of Colorado Boulder, Boulder, CO 80309 USA

E-mail: dimitra.psychogiou@colorado.edu

**Abstract**—Two architectures of fully-planar differential-mode dual-band bandpass filters (DB-BPFs) with enlarged common-mode-suppression bandwidth are reported. The first one, which aims at designs with broadly-separated wide passbands, exploits the loading of extra lines in its balanced symmetry plane. Thus, multiple common-mode transmission zeros (TZs) are created to make wider the DB-BPF common-mode-rejection range. The second one can be used for realizations with closely-spaced passbands and employs a properly-balanced quasi-bandpass-type DB-BPF topology. In this case, the common-mode-mitigation bandwidth broadening is performed by adequately selecting the type of implementation for the short-circuit terminations of its resonating lines—i.e., virtual or physical short circuits in the differential-mode operation—. For experimental-validation purposes, two microstrip DB-BPF prototypes are manufactured and tested.

## I. INTRODUCTION

RF balanced or differential-mode circuits feature higher robustness to common-mode noise, crosstalk, and electromagnetic interference when compared to their single-ended counterparts. As a result, they may be very desired in emerging RF wireless transceivers in which these problems become more prominent due to their progressive integration for lower-size/volume implementations. In the case of balanced planar filters, high-selectivity differential-mode filtering transfer functions with single/multi-band characteristics and spectrally-broad common-mode-suppression actions are essential requisites [1]–[3].

Despite several balanced single-passband planar filters have been reported in the past, less effort has been made in multi-band designs. Some examples to be highlighted are the dual-band bandpass filter (DB-BPF) in [4] that employs lumped elements in its symmetry plane with subsequent sensitivity issues or the triple-band configuration in [5] in which the common-mode suppression is only achieved throughout the differential-mode triple-passband range.

Two realizations of balanced DB-BPFs with broadened common-mode-suppression bandwidth and sharp-rejection differential-mode dual-passband response are presented. The first approach extrapolates the centrally-loaded-stub

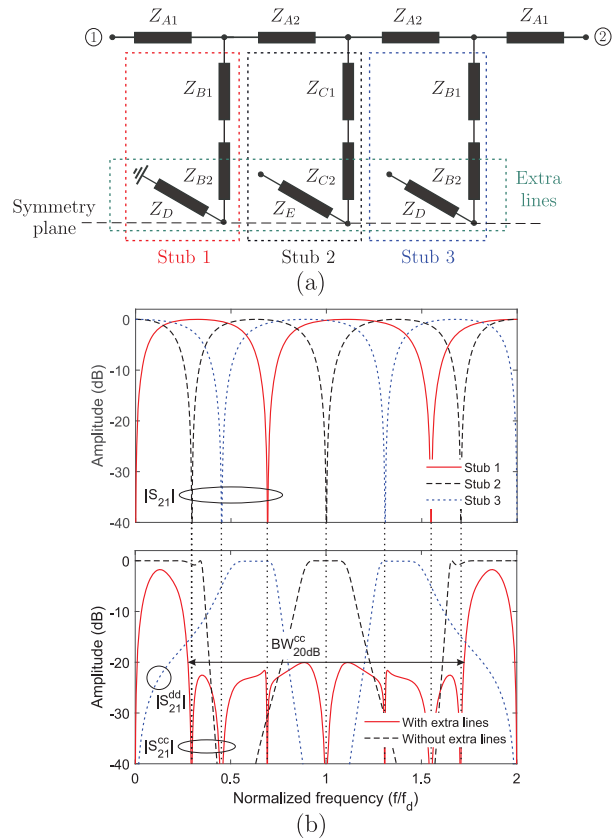


Fig. 1. Balanced DB-BPF with broadly-separated passbands (symmetrical half circuit). (a) Circuit detail ( $Z$  refers to the characteristic impedance of a transmission-line segment; all the lines segments have an electrical length of  $90^\circ$  at the design frequency  $f_d$  except from the extra lines whose lengths are  $45^\circ$  at  $f_d$ ). (b) Operational principle: composition of the enlarged common-mode power transmission ( $|S_{21}^{cc}|$ ) parameter—with/without extra lines—and differential-mode power transmission ( $|S_{21}^{dd}|$ ) parameter ( $Z_{A1} = 3Z_0/2$ ,  $Z_{A2} = 13Z_0/5$ ,  $Z_{B1} = Z_0$ ,  $Z_{B2} = Z_0$ ,  $Z_{C1} = 9Z_0/10$ ,  $Z_{C2} = 9Z_0/10$ ,  $Z_D = 12Z_0/5$ , and  $Z_E = 3Z_0/5$ ;  $Z_0$ : reference impedance).

technique used in [3] to fully-planar DB-BPF schemes with largely-separated wide passbands. The second technique is

based on the way to implement the short-circuit ends of the resonating lines—i.e., physical or virtual short circuits in the differential mode—of a dual-band quasi-bandpass filter as in [6] for a balanced arrangement. For practical-validation purposes, two microstrip DB-BPF prototypes are designed, constructed, and characterized.

## II. TOPOLOGY 1: BALANCED DB-BPF WITH BROADLY-SEPARATED PASSBANDS

The circuit detail of the first balanced DB-BPF with widely-spaced passbands—symmetrical half circuit for third-order realization—is depicted in Fig. 1(a). As shown, its symmetrical half is composed of a direct input-to-output transmission path with parallel-connected stepped-impedance-type resonating lines that are virtually short-ended in the differential-mode operation. These lines are loaded with extra line segments at the symmetry plane to control the locations of the created transmission zeros (TZs) by the overall stubs in the common-mode operation. Thus, through a proper TZ positioning, a broadened common-mode-suppression bandwidth can be produced. The aforementioned principle is illustrated in Fig. 1(b) for a particular design example. It reveals how common-mode suppression levels higher than 20 dB can be realized both throughout the differential-mode passbands and the stop-band regions below/above these transmission bands. Note also that some flexibility in the locations of the differential-mode dual passbands and their bandwidths is feasible through the line-impedance parameters of the symmetrical half circuit of the DB-BPF excluding the extra lines.

To demonstrate the practical viability of the previous differential-mode wide-band DB-BPF approach with broadly-spaced passbands, a microstrip prototype has been developed and characterized. It corresponds to the DB-BPF example in Fig. 1 for  $Z_0 = 50 \Omega$  and  $f_d = 2 \text{ GHz}$ . For its manufacturing, a RO4003C substrate with the following parameters was employed: relative dielectric permittivity  $\epsilon_r = 3.38 (\pm 0.05)$ , dielectric thickness  $H = 1.524 \text{ mm}$ , metal thickness  $t = 17.8 \mu\text{m}$ , and dielectric loss tangent  $\tan \delta_D = 0.0027$ . The ground connections of the extra lines were realized with 1-mm-diameter metallic via holes.

A photograph of the manufactured DB-BPF prototype is shown in Fig. 2(a). Its simulated—with Ansys HFSS—and measured—with a Keysight N5224A network analyzer—mixed-mode  $S$ -parameters are compared in Fig. 2(b). As observed, a fairly-close agreement between simulations and measurements is obtained. The measured characteristics for the fabricated DB-BPF circuit are as follows: lower and upper differential-mode transmission bands with center frequencies of 1.16 GHz and 2.69 GHz, 3-dB absolute bandwidths equal to 529 MHz and 470 MHz (i.e., 45.6% and 17.5% in relative terms), minimum in-band insertion-loss levels of 0.25 dB and 0.6 dB, in-band input-power-matching levels above 25 dB and 21 dB, and minimum in-band common-mode rejection levels of 17.9 dB and

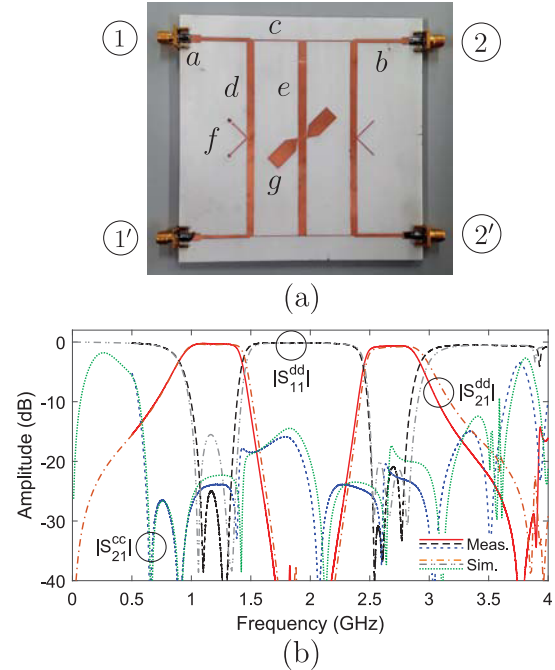


Fig. 2. Manufactured microstrip prototype of the balanced DB-BPF with broadly-separated passbands. (a) Photograph (dimensions, in mm, where “ $w$ ” and “ $l$ ” stand for width and length, respectively:  $w_a = 3.5$ ,  $l_a = 10$ ,  $w_b = 1.7$ ,  $l_b = 22$ ,  $w_c = 0.4$ ,  $l_c = 21.5$ ,  $w_d = 3.5$ ,  $l_d = 46.4$ ,  $w_e = 4.1$ ,  $l_e = 47$ ,  $w_f = 0.52$ ,  $l_f = 11.5$ ,  $w_g = 7.4$ , and  $l_g = 12.4$  with 5-mm taper length). (b) Simulated and measured differential-mode power transmission ( $|S_{21}^{dd}|$ ), differential-mode power reflection ( $|S_{11}^{dd}|$ ), and common-mode power transmission ( $|S_{21}^{cc}|$ ) parameters.

20.5 dB, respectively. The 10-dB-referred common-mode-suppression range is 0.55–3.65 GHz (i.e., 6.6:1 ratio).

## III. TOPOLOGY 2: BALANCED DB-BPF WITH CLOSELY-SPACED PASSBANDS

The second DB-BPF scheme, which is suitable for designs with closely-spaced differential passbands, is based on a dual-band quasi-bandpass approach. Its circuit detail—third-order case—is given in Fig. 3(a). As shown, only the second dual-band quasi-bandpass section is joined to the symmetry plane of the balanced DB-BPF through the ends of its resonating lines to create virtual short-circuits under differential-mode excitation. The resonating lines of the other sections are terminated in physical short-circuits. This allows wider common-mode-suppression bandwidth to be realized at the expense of lower minimum common-mode-rejection levels within the dual passbands. The previous design strategy is illustrated in Fig. 3(b) for a particular example. As can be seen, a broader common-mode-suppression bandwidth—but with reduced common-mode-rejection levels in the dual passbands—is obtained in the configuration of Fig. 3(a) when compared to that in which all the dual-band quasi-bandpass sections are connected to the symmetry plane—i.e., all the resonating lines are open ended in common-mode excitation—. In differential-mode operation, a sharp-rejection DB-BPF

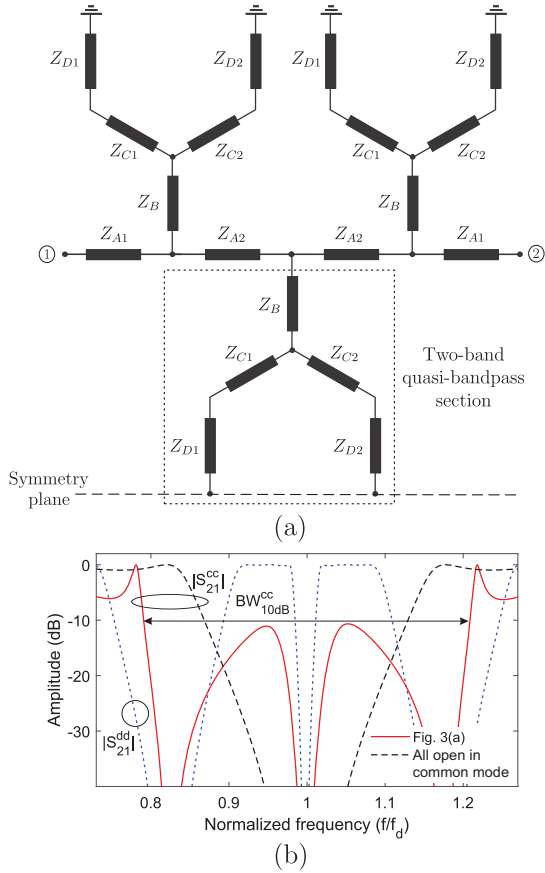


Fig. 3. Balanced DB-BPF with broadly-separated passbands (symmetrical half circuit). (a) Circuit detail ( $Z$  refers to the characteristic impedance of a transmission-line segment; all the line segments have an electrical length of  $90^\circ$  at the design frequency  $f_d = (f_1 + f_2)/2 - f_1$  and  $f_2$  are the center frequencies of the lower and upper passbands—except from those of  $Z_{C1}$  and  $Z_{D1}$ —at  $f_1$ —and  $Z_{C2}$  and  $Z_{D2}$ —at  $f_2$ —). (b) Operational principle: common-mode power transmission ( $|S_{21}^{cc}|$ ) parameter—Fig. 3(a) and case with all the stubs open ended for common-mode operation—and differential-mode power transmission ( $|S_{21}^{dd}|$ ) parameter ( $f_1 = 0.85f_d$ ,  $f_2 = 1.15f_d$ ,  $Z_{A1} = Z_0$ ,  $Z_{A2} = Z_0$ ,  $Z_B = Z_0$ ,  $Z_{C1} = 5Z_0/2$ ,  $Z_{C2} = 5Z_0/2$ ,  $Z_{D1} = 0.46Z_0$ , and  $Z_{D2} = 0.46Z_0$ ;  $Z_0$ : reference impedance).

response with TZs at both sides of the two passbands is derived from the dual-band quasi-bandpass approach.

A microstrip prototype of the DB-BPF example in Fig. 3 has been constructed for  $Z_0 = 50 \Omega$  and  $f_d = 3$  GHz. In this case, an RO5880 substrate with the following parameters was employed: relative dielectric permittivity  $\epsilon_r = 2.2 (\pm 0.05)$ , dielectric thickness  $H = 1$  mm, metal thickness  $t = 35 \mu\text{m}$ , and dielectric loss tangent  $\tan \delta_D = 0.0009$ . The ground connections in the physically-shortened stubs were realized as in the previous prototype.

A photograph of the built DB-BPF circuit is shown in Fig. 4(a), whereas its simulated and measured mixed-mode  $S$ -parameters are plotted in Fig. 4(b). As can be seen, apart from a minor frequency shifting, the agreement obtained between simulations and measurements is reasonable. The measured characteristics of the manufactured DB-BPF

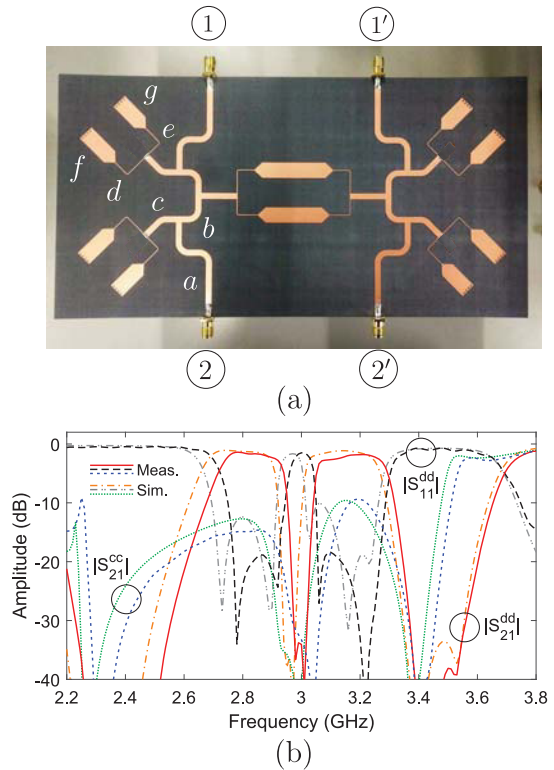


Fig. 4. Manufactured microstrip prototype of the balanced DB-BPF with closely-spaced passbands. (a) Photograph (dimensions, in mm, where “ $w$ ” and “ $l$ ” stand for width and length, respectively:  $w_a = 3$ ,  $l_a = 57.7$ ,  $w_b = 3$ ,  $l_b = 15.6$ ,  $w_c = 3$ ,  $l_c = 17.9$ ,  $w_d = 0.38$ ,  $l_d = 19.9$ ,  $w_e = 0.38$ ,  $l_e = 18$ ,  $w_f = 7.8$ ,  $l_f = 15.2$ ,  $w_g = 7.8$ , and  $l_g = 13.4$  with 4-mm taper length). (b) Simulated and measured differential-mode power transmission ( $|S_{21}^{dd}|$ ), differential-mode power reflection ( $|S_{11}^{dd}|$ ), and common-mode power transmission ( $|S_{21}^{cc}|$ ) parameters.

prototype are as follows: lower and upper differential-mode transmission bands with center frequencies equal to 2.83 GHz and 3.17 GHz, 3-dB absolute bandwidths of 215 MHz and 240 MHz (i.e., 7.6% for both bands in relative terms), minimum in-band insertion-loss levels of 1.4 dB and 1.8 dB, in-band input-power-matching levels above 18.8 dB and 18.4 dB, and minimum in-band common-mode rejection levels equal to 14.7 dB and 9.4 dB, respectively. The 9.4-dB-referred common-mode-suppression range is 2.25–3.52 GHz (i.e., 1.57:1 ratio).

#### IV. CONCLUSION

Two fully-planar realizations of balanced DB-BPFs with broadened common-mode-suppression bandwidth have been presented. These two DB-BPF configurations, which are respectively suitable for designs with broadly- and closely-spaced dual passbands, exploit two different strategies for the common-mode-mitigation range enlargement. The engineered differential-mode DB-BPF approaches have been experimentally validated through the construction and measurement of two microstrip prototypes.

## ACKNOWLEDGMENT

This work was financially supported in part by the Spanish Ministry of Economy, Industry and Competitiveness (State Research Agency) under Project TEC2017-82398-R, in part by the National Science Foundation under Award 1731956, and in part by the National Natural Science Foundation of China under Grant 6182200033.

## REFERENCES

- [1] W. J. Feng, W. Q. Che, and Q. Xue, "The proper balance: Overview of microstrip wideband balanced circuits with wideband common mode suppression," *IEEE Microw. Mag.*, vol. 16, no. 5, pp. 55–68, Jun. 2015.
- [2] F. Martín, J. Naqui, A. Fernández-Prieto, P. Velez, J. Bonache, J. Martel, and F. Medina, "The beauty of symmetry: Common-mode rejection filters for high-speed interconnects and band microwave circuits," *IEEE Microw. Mag.*, vol. 18, no. 1, pp. 42–55, Jan. 2017.
- [3] T. B. Lim and L. Zhu, "A differential-mode wideband bandpass filter on microstrip line for UWB application," *IEEE Microw. Wireless Compon. Lett.*, vol. 19, no. 10, pp. 632–634, Oct. 2009.
- [4] J. Shi and Q. Xue, "Balanced bandpass filters using center-loaded half-wavelength resonator," *IEEE Trans. Microw. Theory Techn.*, vol. 58, no. 4, pp. 970–977, Apr. 2010.
- [5] R. Gómez-García, R. Loeches-Sánchez, D. Psychogiou, and D. Peroulis, "Multi-stub-loaded differential-mode multi-band bandpass planar filters," *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 65, no. 3, pp. 271–275, Mar. 2018.
- [6] R. Gómez-García and A. C. Guyette, "Reconfigurable multi-band microwave filters," *IEEE Trans. Microw. Theory Techn.*, vol. 63, no. 4, pp. 1294–1307, Apr. 2015.