Compact Balanced-to-Balanced Diplexer Based on Split-Ring Resonators Balanced Band-Pass Filters

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***Abstract*—A compact balanced-to-balanced diplexer composed of two balanced band-pass filters is proposed in this letter. The balanced filters are implemented using compact edge-coupled square split-ring resonators (SRR). The design methodology is based on the standard coupled-resonators filter synthesis procedure. First, each filter is independently designed. Then, they are connected to a common differential input port in order to achieve the desired diplexing operation, with the pertinent adjustments to take into account the loading effect of the second filter. Magnetic coupling inherently prevents common-mode transmission. An illustrative prototype example is provided with simulations and measurements to demonstrate the benefits of the proposed topology.**

***Index Terms*—Balanced-to-balanced diplexer, Split-ring resonators, Magnetic coupling, Inherent common-mode rejection.**

I. INTRODUCTION

THE interest in balanced/differential circuits has considerably increased along the last couple of decades [1]. In comparison with single-ended signals, differential signals offer enhanced electrical performance in terms of signal-to-noise ratio, noise immunity, crosstalk, and electromagnetic interference (EMI). In recent years, with the requirement for multi-band services, differential diplexers have attracted the interest of the microwave community [2]–[7]. A well designed balanced-to-balanced diplexer must simultaneously provide good differential-mode (DM) performance, strong common-mode (CM) rejection, and high isolation between the output ports. Several strategies have been proposed to achieve all those goals. For example, resonators with different DM and CM resonance frequencies are used in [2], [3]. The same approach is considered in [4], with the novelty of including via-holes in order to connect the resonators to ground. CM rejection is sacrificed in [5] by introducing mutual couplings between stub-loaded input/output lines in order to improve DM out-of-band performance. A modification of [5] is proposed in [6] to improve the CM rejection. The previous proposals provide good DM and CM performance at the expense of using complicated geometries and/or the presence of via-holes. Hybrid microstrip/slot-line resonators are used in [7], although this approach has some practical limitations since, in many situations, the integrity of the ground plane must be preserved. In this letter, a compact balanced-to-balanced (B-B) diplexer is proposed. The device is designed by using two different balanced band-pass filters (BBPF) based on magnetically coupled edge-coupled square split-ring resonators (EC-SRRs). The use of magnetic coupling reduces CM transmission [8], and the use of EC-SRRs leads to a very compact design.

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II. PROPOSED BALANCED DIPLEXER

A. Design methodology

The implementation of the balanced-to-balanced diplexer in this work starts with the design of the BBPFs for each balanced output port (or channel) (22' and 33' in Fig. 1). Each filter, being composed of two magnetically coupled EC-SRRs, is independently designed. The reasons behind the choice of EC-SRRs and magnetic coupling are: (i) EC-SRRs, consisting of a pair of tightly coupled concentric metallic split rings, are electrically small resonators yielding a higher level of compactness than other alternative printed resonators [9], [10]; (ii) common-mode transmission is reduced over a wide frequency range thanks to the use of magnetic coupling [8]. For the filters in Fig. 1, the coupled-resonators design procedure described in [11] has been used. Such method makes use of the external quality factors, Q_e, and the coupling coefficients, M. For given DM filter specifications both parameters can be theoretically calculated by means of the following expressions

$$M_{i,i+1} = \frac{\Delta}{\sqrt{g_i g_{i+1}}}, \quad \text{for} \quad i = 1, \ldots, n-1 \tag{1}$$

$$Q_{e1} = \frac{g_0 g_1}{\Delta} \qquad Q_{en} = \frac{g_n g_{n+1}}{\Delta} \quad , \tag{2}$$

where n is the filter order, Δ is the fractional bandwidth and g_j ($j = 1, \ldots, n+1$) are the low-pass prototype element values for the desired filter response. For the following specifications: Butterworth response, $n = 2$, fractional bandwidth $\Delta^{\mathrm{l}} = 11.5\,\%$, $\Delta^{\mathrm{u}} = 7.2\,\%$, and center frequencies $f_{0d}^{\mathrm{l}} = 1.5\,\mathrm{GHz}$ and $f_{0d}^{\mathrm{u}} = 2.2\,\mathrm{GHz}$, the theoretical values for the M's and Q's calculated from (1) and (2) are: $M_{1,2}^{\mathrm{l}} = 0.081$, $M_{1,2}^{\mathrm{u}} = 0.051$, $Q_{e1}^{\mathrm{l}} = Q_{e2}^{\mathrm{l}} = Q_{e}^{\mathrm{l}} = 12.29$, and $Q_{e1}^{\mathrm{u}} = Q_{e2}^{\mathrm{u}} = Q_{e}^{\mathrm{u}} = 19.64$. The superscripts "l" and "u" stand for the lower (l) and

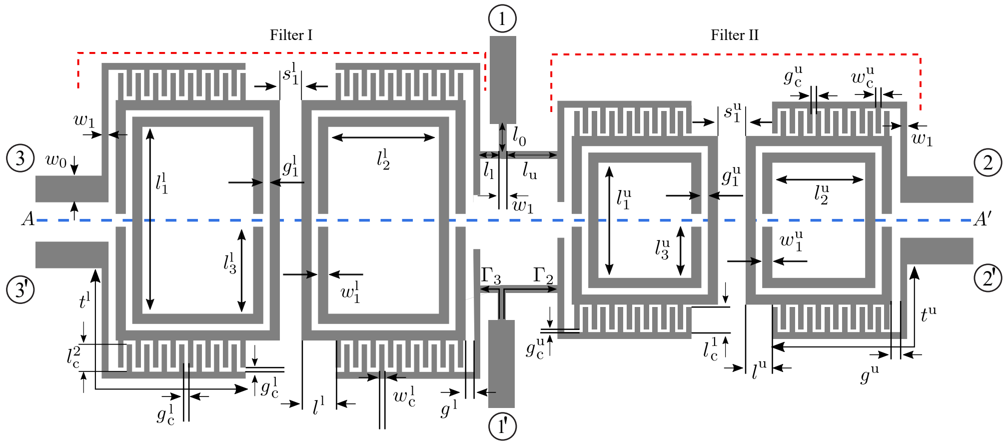

Fig. 1. Layout of the proposed balanced diplexer (not to scale). Dimensions in mm are: $w_0 = 2.54$, $w_1 = w_\mathrm{c}^\mathrm{l} = g_\mathrm{c}^\mathrm{l} = g_1^\mathrm{l} = 0.2$, $g^\mathrm{l} = 0.4$, $w_1^\mathrm{l} = 0.3$, $l_\mathrm{c}^2 = 1.3$, $l^\mathrm{l} = 2.8$, $l_1^\mathrm{l} = 12.7$, $l_2^\mathrm{l} = 8$, $l_3^\mathrm{l} = 6.2$, $s_1^\mathrm{l} = 0.9$, $t^\mathrm{l} = 11.96$, $w_\mathrm{c}^\mathrm{u} = g_\mathrm{c}^\mathrm{u} = g_1^\mathrm{u} = 0.2$, $g^\mathrm{u} = 0.4$, $w_1^\mathrm{u} = 0.3$, $l_\mathrm{c}^1 = 1$, $l^\mathrm{u} = 2$, $l_1^\mathrm{u} = 7.7$, $l_2^\mathrm{u} = 6$, $l_3^\mathrm{u} = 3.7$, $s_1^\mathrm{u} = 1.1$, $t^\mathrm{u} = 8.46$, $l_\mathrm{l} = 1.47$, $l_\mathrm{u} = 3.2$ and $l_0 = 3.2$.

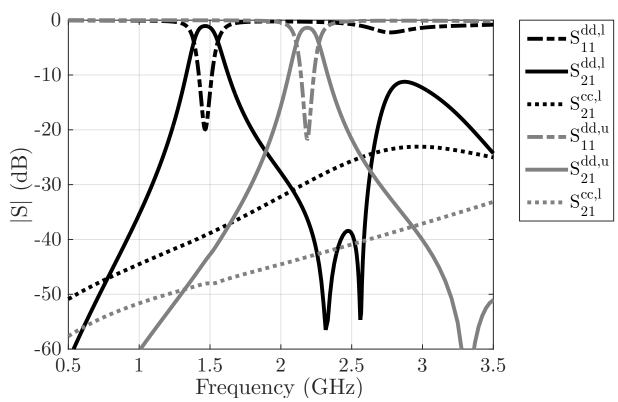

Fig. 2. Simulated (EM) differential- and common-mode responses for the designed lower and upper balanced bandpass filters. Simulations have been carried out with *ADS Momentum* software.

upper (u) differential pass-bands (channels 33' and 22' in Fig. 1). The parameters of the used substrate are $\varepsilon_r = 3.0$, thickness $h = 1.016\,\mathrm{mm}$, and $\tan\delta = 0.0022$. The filters are independently designed to fulfill the theoretical requirements for Q_e and $M_{1,2}$. Design curves similar to those reported in [8] have been generated (not included here to save space). Note that interdigital capacitors have to be used in order to achieve the desired value of Q_e [8]. The simulated responses for both filters are depicted in Fig. 2. The two transmission zeros in the upper stop-band of each channel filter are an intrinsic feature of the EC-SRR structure. They correspond to those frequencies at which the even or odd electrical lengths of the resonators is π. Good DM performance and a high CM rejection can be observed in both differential pass-bands. The diplexing operation can be now obtained by joining the filters to a common differential input port (see Fig. 1). The key point in designing the T-junction that connects both filters is that the external quality factors at the filters inputs must be those imposed by the design specifications. This means that the T-junction must be designed accounting for the loading effect of the accompanying filter so as to preserve the required external Q's, thus ensuring low return loss level at both output channels, i.e., $|\Gamma_3| \approx 0$ at f_{0d}^l= 1.5 GHz while $|\Gamma_2| \approx 0$ at f_{0d}^u= 2.2 GHz [3]. We have proceeded as follows: (i) first, the T-junction with arbitrarily chosen values of w_1, l_0, l_l and l_u has been introduced; (ii) second, the lengths of the branch feeding lines, l_l and l_u, have been used as adjustable parameters to fit the required external quality factors at the filters input ports such that $Q_\mathrm{e1}^\mathrm{l} = Q_\mathrm{e1}^\mathrm{l} = 12.29$ and $Q_\mathrm{e1}^\mathrm{u} = Q_\mathrm{e1}^\mathrm{u} = 19.64$ (i.e., two physical parameters for two electrical parameters). The final dimensions of the proposed B-B diplexer are detailed in Fig. 1.

B. Experimental Results

In order to validate our proposal, the B-B diplexer in Fig. 1 has been fabricated and measured using the *Agilent PNA-N5221A* four-port network analyzer. Simulated and measured DM and CM responses are shown in Fig. 3(a) and (b), where a photograph of the fabricated prototype has been included. Good agreement between simulations and measurements can be observed. Measured results exhibit passband center frequencies at 1.47 GHz and 2.19 GHz, with fractional bandwidths of 11.5% and 7% and insertion loss (IL) level of 0.94 dB and 2.2 dB, respectively. The experimental DM isolation (Iso) is better than 40 dB for the lower band and about 40 dB for the upper band. In addition, the measured CM rejection is about 40 dB and 45 dB for the lower and upper-band channels, respectively. Note that a third TZ appears in the transmission response when the two differential filters are assembled to build up the diplexer. This is a natural consequence of the imposed design goals of the T-junction.

A comparison with previous contributions is included in Table I. This table demonstrates that the proposed structure provides the most compact design, thanks to the use of EC-SRRs to implement the filters by halving the area of the smallest previous contributions. In addition, in terms of CMRR, the proposed diplexer is found to be very competitive. Moreover, high DM isolation is observed in both passbands.

TABLE I
COMPARISON BETWEEN BALANCED AND BALUN DIPLEXERS BASED ON COUPLED RESONATORS

	Type	Area (λ_g^2)†	Differential-mode				Common-mode
			$f_{0d}^{l,u}$ (GHz)	3-dB $\Delta^{l,u}$(%)	IL $f_{0d}^{l,u}$ (dB)	Iso (dB)	CMRR @$f_{0d}^{l,u}$ (dB)
[2]	U-B*	0.315	1 / 1.2	10.5 / 10.4	2.2 / 2.35	46.5 / 46.5	55 / 50
[3]	U-B	0.202	1.847 / 2.467	11.6 / 8.7	1.48 / 1.78	≈ 45 / 45	38.5 / 38.22
[4]	U-B	0.225	1.93 / 2.46	7.2 / 4.5	0.67 / 1.07	42.1 / 39.5	36.7 / 42.9
[4]	B-B	0.225	1.94 / 2.46	6.7 / 4.5	0.88 / 0.98	42.1 / 40.1	26.4 / 46.9
[7]	U-B	0.544	2.41 / 3.57	4.6 / 8.7	1.56 / 1.66	41.3 / 44.5	55.7 / 53.6
[7]	B-B	0.550	2.45 / 3.55	6.7 / 8.2	1.95 / 2.11	39.5 / 44.5	50.2 / 47.7
[5]	B-B	0.099	2.46 / 3.65	8.1 / 4.9	1.5 / 2	33 / 42	28.5 / 30
[6]	B-B	N/A	2.45 / 3.6	6 / 3	1.3 / 1.8	≈ 35 / 55	≈ 56.7 / 48.2
Fig. 1	B-B	**0.046**	1.47 / 2.19	11.5 / 7	0.94 / 2.2	**43.3 / 40**	39.06 / 42.8

λ_g †: Guided wavelength @ f_{0d}^{l}; U-B*: Unbalanced-to-balanced; N/A: substrate characteristics not provided.

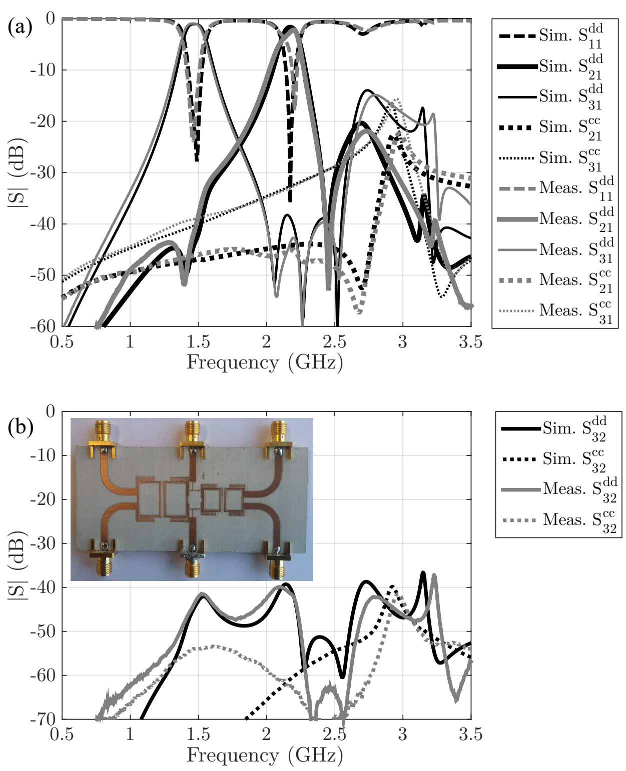

Fig. 3. DM and CM simulated and measured responses (both channels) of the designed diplexer (see Fig. 1). (a) Reflection and transmission. (b) Isolation.

These results prove that the use of EC-SRRs with magnetic coupling leads to compact diplexer design with high levels of CM rejection and DM isolation.

III. CONCLUSION

A compact B-B diplexer has been presented in this letter. It consists of two balanced band-pass filters based on magnetically coupled EC-SRRs. Both filters have been straightforwardly designed by means of a well-known approach based on the coupling coefficients and external quality factors. High common-mode rejection for both channels is achieved by virtue of the magnetic coupling between EC-SRRs, providing significant inter-resonator distance and hence efficiently blocking the common mode up to high frequencies. DM and CM isolation are also very good. Nevertheless, the main competitive advantage of the proposed diplexer is its small size, achieved thanks to the use of EC-SRRs. The lack of vias and defected ground structures are additional beneficial aspects for the application of the proposed diplexer in real scenarios.

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