Compact Balanced Dual-Band Bandpass Filter Based on Modified Coupled-Embedded Resonators

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***Abstract*— A new compact balanced dual-band bandpass filter based on coupled-embedded resonators with modified ground plane is presented in this work. Common-mode is rejected within the two differential passbands by symmetrically introducing four coupled U-shaped defected ground structures below the resonators. Common-mode rejection is significantly improved when compared with the standard (solid ground plane) filter with similar geometry thanks to the introduction of four extra transmission zeros. Due to the symmetry, the differential mode is not significantly affected by the presence of the U-shaped resonators. Circuit-model data, full-wave simulations and measurements are provided to verify the benefits of the proposed dual-band filter.**

***Index Terms*— Balanced filter, common-mode suppression, dual-band filter.**

I. Introduction

RF/MICROWAVE balanced bandpass filters (BPFs) have attracted the interest of the microwave community in recent years due to their enhanced signal to noise ratio, noise immunity, low crosstalk and low electromagnetic interference (EMI) when compared with their classical single-ended counterparts. Nowadays, with the rapid growth of multiband wireless communication systems, multiband BPFs with very demanding specifications concerning both differential mode (DM) transmission and common-mode mode (CM) suppression are required. Several proposals regarding dual-band balanced BPFs can be found in the recent literature [1]–[9]. In [1]–[4], [7] balanced dual-band operation is obtained by means of electrically-coupled resonators. In such designs, CM suppression is improved by adding extra lumped capacitors, inductors, resistors and/or open-circuited stubs. Other recently proposed approaches to DM filter design with CM suppression make use of asymmetrical coupled lines [5] or substrate integrated waveguide (SIW) technology [8]. These designs provide good DM performance and CM rejection, but they suffer from the problem of having large electrical size and, moreover, the use of a large number of via-holes. In [6] balanced dual-band filtering is achieved by using coupled-embedded resonators. In this implementation the CM is rejected by cascading with the filter a pair of CM rejection differential-line stages based on the use of a low-pass DGS structure. Unfortunately, this solution increases the design complexity and the overall electrical size. Coupled complementary split-ring resonators (C-CSRR) have very recently been proposed [9] for the design of compact balanced dual-band filters with good CM rejection. In this letter, a new compact balanced dual-band BPF based on coupled-embedded resonators with a modified ground plane is proposed. Design methodology and experimental validation of the structure are illustrated with a specific filter example operating at two wireless local area network (WLAN) bands. Measured and simulated results show the benefit of the proposed configuration.

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II. Proposed DGS Structure

The layout of the proposed balanced dual-band BPF is shown in Fig.1. The top layer geometry is based on the single-ended and differential dual-band filters reported in [10] and [6] respectively. It consists of the combination of two different sub-filters that enable the generation of two different DM passbands. These bands can be independently tuned. The bottom layer is formed by four U-shaped slot resonators. These resonators have been used in [11], [12] to improve the CM rejection of differential lines. In this letter the DGS resonators are embedded within the printed filter area, thus yielding a more compact design. When operating in DM, the AA' symmetry plane (see Fig.1) is a virtual short-circuit. The DGS is then grounded at both ends and hence it hardly affects the response of this mode. On the contrary, for CM operation the AA' plane behaves as a virtual open-circuit. It is then expected a strong disturbance of the CM response.

Let us first focus our attention on the role of the U-shaped DGSs when used below a differential line pair [see Fig.2(a)]. Each resonator can be modeled (CM excitation) as a parallel LC-tank circuit with a couple of electrically short lines connected at both sides [11] (see Fig.2).

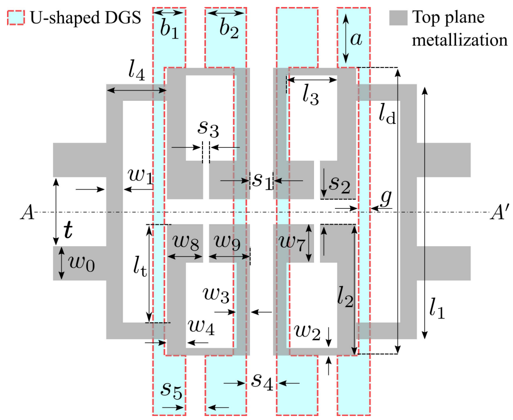

Fig. 1. Layout of the structure proposed for the implementation of a balanced dual-band bandpass filter. Dimensions (all in mm) are: (i) top plane: $t = 3.25$, $w_0 = 0.75$, $w_1 = 0.6$, $w_2 = 0.3$, $w_3 = 0.2$, $w_4 = 0.6$, $w_7 = 1.21$, $w_8 = 0.8$, $w_9 = 1.7$, $l_1 = 8.6$, $l_2 = 4.11$, $l_3 = 1.9$, $l_4 = 1.6$, $s_1 = 0.24$, $s_2 = 0.38$, and $s_3 = 0.2$; (ii) bottom plane: $b_1 = 1.13$, $b_2 = 1.56$, $a = 2.85$, $l_d = 9.6$, $g = 0.2$, $s_4 = 0.23$ and $s_5 = 0.2$.

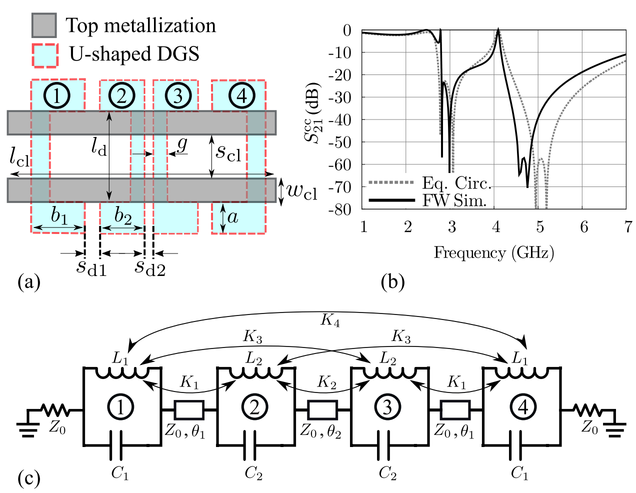

Fig. 2. (a) Differential lines with four coupled U-shaped DGSs (not to scale). (b) Full-wave and equivalent circuit simulations (CM operation). (c) Equivalent circuit for CM operation. Dimensions (mm): $l_{cl} = 12$, $w_{cl} = 0.75$, $s_{cl} = 4.05$, $b_1 = 1.53$, $b_2 = 1.06$, $a = 6.65$, $g = 0.2$, $l_d = 5.6$, $s_{d1} = 0.2$ and $s_{d2} = 0.1$. Extracted electrical parameters from [11] are: $C_1 = 0.68$pF, $C_2 = 0.409$pF, $L_1 = 2.74$nH, $L_2 = 3.95$nH, $K_1 = -0.228$, $K_2 = 0.05$, $K_3 = -0.0172$ and $K_4 = 0.0012$. $Z_0 = 50\Omega$, $\theta_1 = 11.02°$ and $\theta_2 = 0.69°$ (@ 1 GHz).

A series-connected LC-tank resonator introduces a transmission zero (TZ) at its resonance frequency. This frequency can be allocated by selecting the values of L and C which, in turn, depend on the physical dimensions of the resonator, i.e., b, a, g, and l_d in Fig.2. The proposed slotted ground pattern is aimed to reject the CM within the two DM passbands. Hence, it is necessary to introduce several CM TZs in the proper locations. Several coupled U-shaped slot–like resonators are etched in the ground plane with this purpose. From network theory it is well known that any transmission line loaded with n coupled resonators presents n transmission zeros (even if the only considered couplings are those between adjacent resonators). Such zeros can be allocated in the frequencies of interest by properly choosing the values L_i and C_i $(i = 1, 2)$ and the couplings between resonators. To illustrate this fact, Fig.2 depicts an example of CM response when four U-shaped resonators are introduced below a simple pair of differential lines (CM rejection filtering). In this example, the substrate parameters are: dielectric constant $\varepsilon_r = 5.8$, loss tangent $\tan\delta = 0.0022$, and substrate thickness $h = 0.508$ mm. The value of the lumped-elements, L_i and C_i $(i = 1, 2)$, and the inductive coupling between resonators, K_i $(i = 1 \ldots 4)$, for the configuration in Fig.2(a) have been extracted using the procedure reported in [11]. The simulated performance (full-wave and circuit-model simulations) is shown in Fig.2(b), where two CM rejection bands clearly appear due to the presence of the four U-shaped coupled resonators. It is important to mention that the nature of the coupling between resonators (i.e., electric, magnetic or mixed) has been determined following the methodology described in [14] and [15]. An example of the application of this DGS structure to the design of a balanced dual-band filter is given in the next section.

III. Example of Dual-Band Filter Design

A. Conventional Filter

Let us first consider the design of a dual-band balanced filter without the DGS structure (the same layout as in Fig.1 but with a solid ground plane). The guidelines given in [14] are followed. The procedure makes use of the external quality factors, Q_j, and the coupling coefficients, $M^j_{(1,2)}$ $(j = 1, 2)$. For the proposed topology, the filter specs are: Butterworth of order $N = 2$; center frequencies $f_{\mathrm{DM}^{(1)}} = 2.5$ GHz and $f^{(2)}_{\mathrm{DM}} = 5.6$ GHz; fractional bandwidths $\Delta^{(1)}_{\mathrm{DM}} = 8\%$ and $\Delta^{(2)}_{\mathrm{DM}} = 5\%$. The same substrate as in the previous section is used. The required external quality factors and coupling coefficients result to be: $Q_1 = 17.67$, $Q_2 = 28.28$, $M^{(1)}_{1,2} = 0.056$ and $M^{(2)}_{1,2} = 0.035$. For the conventional filter, the external quality factor and coupling coefficient of the first DM passband are controlled by the tapping position, t, and the gap distance, s_1, respectively. Once t and s_1 are obtained for the first passband, the external quality factor of the second passband is adjusted by choosing the appropriate value of l_t. The required coupling coefficient is achieved by tuning the ratio w_3/w_4 [6], [10]. The obtained final dimensions (in mm) are: $t = 3.11$, $w_0 = 0.75$, $w_1 = 0.6$, $w_2 = 0.43$, $w_3 = 0.35$, $w_4 = 0.6$, $w_7 = 0.91$, $w_8 = 1.29$, $w_9 = 1.68$, $l_1 = 8.6$, $l_2 = 4.44$, $l_3 = 2.22$, $l_4 = 2.11$, $s_1 = 0.28$, $s_2 = 1.08$, and $s_3 = 0.2$.

B. Filter With Embedded U-Shaped DGS Structure

Once the conventional filter has been designed, the proposed DGS designed in section II, consisting of four U-shaped coupled resonators, is introduced in the ground plane, just below the filter layout. Since the CM signal must be rejected within the two differential passbands, the DGS pattern has been optimized so as to avoid CM propagation in the 2-3 GHz and 5-6 GHz bands. The physical parameters of the DGSs in section II have been used as initial guesses for the final optimization step. This process has been carried out with the help of *ADS Momentum* [13] (See Fig.1 for dimensions. Note please that some dimensions of the conventional filter have been slightly modified in the new structure in order to compensate for the small perturbations introduced by the DGS on the DM response).

TABLE I

COMPARISON OF SEVERAL DUAL-BAND BALANCED FILTERS

Ref.	$f_{\rm DM}^{1,2}$ (GHz)	IL (dB)	Size ($\lambda_g \times \lambda_g$)	CMRR @ $f_{\rm DM}^{1,2}$ (dB)
[1]	2.44 / 5.57	1.78 / 2.53	0.258 $\times$ 0.592	36.2 / 30.5
[2]	2.44 / 5.25	2.4 / 2.82	0.420 $\times$ 0.380	52.6 / 39.2
[3]	1.84 / 2.45	2.20 / 2.60	0.187 $\times$ 0.285	20.5 / 20.0
[4]	2.46 / 5.56	0.96 / 1.9	0.314 $\times$ 0.413	36.2 / 31.1
[5]	2.40 / 3.57	0.87 / 1.90	0.50 $\times$ 0.20	27.1 / 29.1
[6]	2.50 / 5.27	1.46 / 2.22	0.262 $\times$ 0.637	38.5 / 22.8
[7]	2.50 / 5.80	0.77 / 1.56	0.343 $\times$ 0.133	41.2 / 36.4
[8]	9.23 / 14.05	2.90 / 2.70	2.70 $\times$ 1.27	45.3 / 38.7
[9]	1.57 / 2.47	0.53 / 0.72	0.14 $\times$ 0.23	54.5 / 42.3
This	2.50 / 5.60	1.29 / 1.97	0.153 $\times$ 0.268	34.7 / 24.1

Fig. 3. Photograph of the fabricated prototype (top and bottom sides).

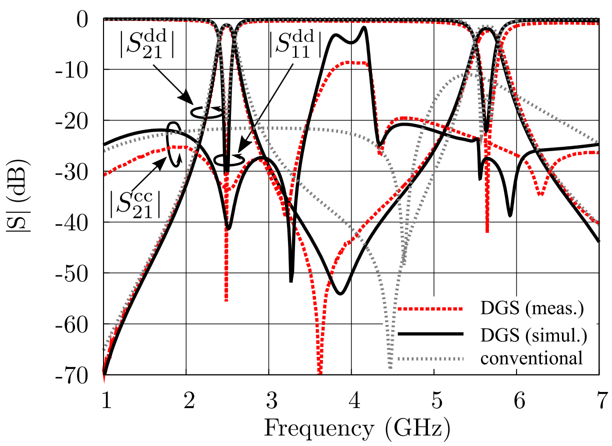

Fig. 4. Measured DM and CM responses for the DGS-based filter. DM and CM responses of the conventional filter have been included for comparison purposes. Simulations have been carried out with *ADS-Momentum* [13].

C. Experimental Results

In order to validate our proposal, a prototype of the DGS-based designed filter has been fabricated (see photo in Fig.3) and measured using an Agilent PNA-E8363B with a N4420B test-set extension. Simulated and measured DM and CM responses are shown in Fig.4. The CM and DM responses of the conventional filter (with solid ground plane) have been included for comparison. This figure clearly shows the CM rejection improvement as well as the good agreement between simulations and measurements for the novel filter. It can be appreciated the absence in the measurements of the simulated CM transmission zero located at approximately 5.5 GHz (DGS filter). It has been verified that this TZ is very sensitive to the fabrication tolerances. However, even without that TZ, CM rejection has been improved in about 15 dB when compared with the conventional case. A comparison with other contributions is given in Table I. Common-mode rejection ratio (CMRR) and electrical size are found to be competitive when compared with the other designs.

IV. CONCLUSION

A new balanced dual-band bandpass filter based on embedded resonators and U-shaped DGS has been presented. An easy-to-follow step-by-step design procedure is described. The first step consists on the design of the conventional filter with solid ground plane. Next, four coupled U-shaped DGS resonators are introduced, which are symmetrically located below the filter area. The parameters of the U-shaped slots are set in order to get good CM rejection over the frequency ranges of interest, namely, the two differential passbands. Finally, some physical dimensions of the top-layer resonators are slightly tuned to compensate for the small effect of the ground plane slots. The proposed structure provides a significant improvement of the CMRR while does not deteriorate the integrity of the differential-mode response and does not increase the filter size.

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