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Miniaturized dual-band branch-line coupler with enhanced bandwidth

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Abstract: In this letter, a miniaturized hybrid dual-band branch-line coupler (BLC) with enhanced fractional bandwidths is proposed. Compact size and bandwidth enhancement are obtained using meandered transmission line sections with broken symmetry between cross-coupling branches. The circuit is designed at a low numerical cost using surrogate-assisted techniques. The optimized design features small size of only 0.25 λ_g × 0.19 λ_g (28% miniaturization with respect to conventional single-band structure), as well as fractional bandwidths of 16% and 9% for 2.5 GHz and 5.4 GHz center frequencies, respectively. The proposed structure is compared against state-of-the-art dual-band couplers and validated experimentally.

Keywords: dual-band couplers, EM-driven design, computer-aided design, bandwidth enhancement, coupler miniaturization.

1. Introduction

Hybrid branch-line couplers (BLCs) are important components of antenna feeding networks, balanced mixers, and amplifiers. Their conventional realizations are characterized by single-band operation and relatively large footprints, which limits their usefulness for compact multi-band systems. From this perspective, replacement of conventional BLCs with dual-band couplers is interesting alternative.

The available literature indicates that design of dual-band (DB) BLCs is a challenging problem where an appropriate trade-off between structure size and its performance has to be sought [1], [4]-[5]. Although DB operation can be obtained by modification of a single-band coupler using stub lines [1], cross-coupled branches [2], or stepped impedance feeds [3], the resulting structures are characterized by narrow fractional bandwidths and increased dimensions w.r.t. conventional couplers. On one hand, bandwidth-enhanced DB operation can be achieved using multi-section topologies with stepped impedance stubs [1], but such structures are characterized by large footprints. On the other hand, meandered [4], or dual transmission lines [5], although proved to be useful for size reduction, results in degradation of coupler electrical performance. So far, design of compact DB BLCs featuring bandwidth-enhanced operation has not been considered in the literature.

In this letter, a miniaturized equal-split dual-band BLC is proposed. Bandwidth of the structure is enhanced by breaking the symmetry between its cross-coupled branches, which results in increase of the number of degrees of freedom. At the same time, its compact size is ensured using meandered transmission line sections. The circuit is designed at low computational cost using surrogate-based optimization (SBO). The bandwidths of the proposed BLC are from 2.39 GHz to 2.6 GHz and from 5.2 GHz to 5.6 GHz, respectively. The structure features a footprint of only 255 mm^2 which represents 61% and 28% miniaturization w.r.t. a reference DB coupler with cross-coupler branches and conventional single-band BLC, respectively. The proposed circuit is compared to state-of-the-art BLCs. Simulation results are supported by measurements of fabricated coupler prototype.

2. Structure Description

Consider a compact dual-band hybrid branch-line coupler shown in Fig. 1a. The structure is implemented in microstrip technology on a Rogers RO4003C substrate (ε_r = 3.55, h = 0.813 mm, tanδ = 0.0021). The proposed BLC is based on a circuit of [2]. However, the design includes asymmetrical cross-section lines to introduce additional degrees of freedom and enable bandwidth enhanced operation (cf. Fig. 2). Compact size of the coupler is ensured using meandered transmission line sections (cf. Fig. 1b). The structure is represented using a 16-variable vector $\boldsymbol{x} = [w_{11}\ w_{21}\ l_{11}\ s_{11}\ w_{12}\ w_{22}\ l_{12}\ s_{12}\ w_{13}\ w_{23}\ l_{13}\ l_{23}\ l_{33}\ l_{43}\ s_{13}\ g]^T$. Fixed dimensions are w_0 = 1.7 and c = 0.2, whereas relative parameters are $l_1 = l_{11} + w_{11} - w_{21}$, $l_2 = |2s_{13} + 3.5w_{13} + 0.5(\max(w_{22}, w_{21}) - w_{22}) - \max(w_{12}, w_{22}) - s_{12} + g|$, and $l_3 = 0.5(w_0 + 5s_{11} - w_{23} - c) + 2w_{11} + w_{21} - w_{13} + g$ (cf. Fig. 1). The unit for all dimensions is mm.

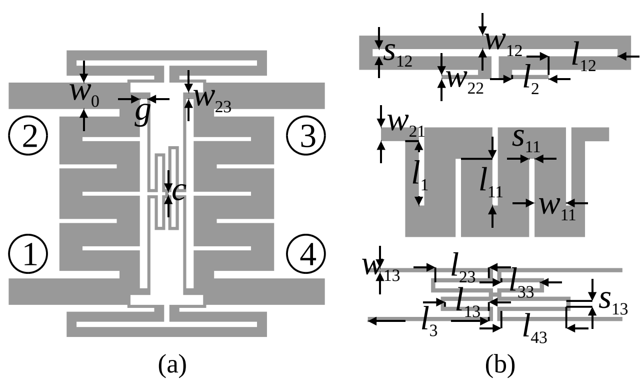

Fig. 1. Geometry and parameterisation of the proposed bandwidth-enhanced BLC: (a) the assembled coupler and (b) individual sections of the structure.

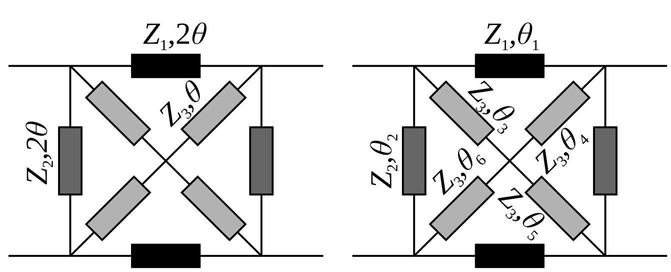

Fig. 2 Conventional (left) and modified (right) DB BLC circuits.

The design specifications are as follows: equal power-split for the lower and upper centre frequencies of $f_{0.1}$ = 2.5 GHz and $f_{0.2}$ = 5.4 GHz, respectively, and bandwidth (calculated for $|S_{11}|$ and $|S_{41}|$ both below –20 dB) of 200 MHz for $f_{0.1}$ and 400 MHz for $f_{0.2}$.

Low cost of the structure design is ensured using a surrogate-based optimization (SBO) approach of [6]. The low- (equivalent circuit) and high-fidelity (electromagnetic; EM) models of the proposed BLC are prepared at the level of its individual sections, as well as the entire circuit. The models are evaluated using Keysight ADS circuit simulator and Keysight Momentum solver (setup: mesh density of 40 cells/wavelength with edge mesh, coupler simulation time: 4.5 min), respectively.

3. Surrogate-Assisted Coupler Design

The coupler design procedure involves the following steps: (i) modification of the DB circuit of [2] and its bandwidth-enhancement-oriented optimization, (ii) structure decomposition and utilization of individual sections as references for design of compact cells at the low-fidelity level, (iii) SBO-based refinement of the cells to the high-fidelity model level, (iv) SBO-based refinement of the circuit assembled from the optimized cells, and (vi) fine-tuning of the coupler.

In the first step of the design process, the reference BLC (cf. Fig. 2) is synthesized based on the transmission line theory [2]. Subsequently, its topology is modified as shown in Fig. 2 and the structure is optimized w.r.t. the imposed design specifications. Characteristics of the individual sections extracted from the obtained circuit are used as the reference for determination of compact cells layouts shown in Fig. 1a. The miniaturized cells are then sequentially optimized to match the performance of the reference lines. The design problem is formulated as the following minimization task

$$\boldsymbol{x}^* = \arg\min_{\boldsymbol{x}} U\left(\boldsymbol{R}(\boldsymbol{x})\right) \qquad (1)$$

where $\boldsymbol{R} = \boldsymbol{R}_{c.k}$ (k = 1, 2, 3) is the equivalent-circuit model response of the kth compact cell at hand. The objective function $U = U_1$ is given by

$$U_1 = N^{-1}\sum_{i=1}^{N}\left(\left|\boldsymbol{R}_0(f_i) - \boldsymbol{R}(\boldsymbol{x}, f_i)\right|\right)^2 \qquad (2)$$

where $\boldsymbol{R}_0 = \boldsymbol{R}_{0.k}$ represent responses of kth reference section, whereas f is the frequency sweep. After optimization, compact cells are refined to the high-fidelity model level using SBO. The algorithm generates a sequence of approximations to (1) by solving [6]

$$\boldsymbol{x}^{(i+1)} = \arg\min_{\boldsymbol{x}} U\left(\boldsymbol{R}_s^{(i)}(\boldsymbol{x})\right) \qquad (3)$$

The surrogate $\boldsymbol{R}_s^{(i)} = \boldsymbol{R}_{s.k}^{(i)}$ of kth cell is constructed as the equivalent-circuit model corrected using a combination of implicit space mapping and frequency scaling [6]. The goal of the process is to minimize the objective function (2). As a result, the dimensions of optimized cells represent a decent starting point for optimization of the entire BLC.

In the next step, the BLC of Fig. 1b is assembled from the compact cells and the structure is further optimized in an SBO setup. Here, the surrogate model is constructed from the low-fidelity model corrected using implicit and output space mapping, as well as frequency scaling [6]. The objective function for coupler optimization $U = U_2$ is given by:

$$U_2 = \max\left(|S_{11}|, |S_{41}|\right)_{\substack{\text{2.4 GHz to 2.6GHz} \\ \text{5.2 GHz to 5.6 GHz}}} + \beta\sum_{i=1}^{2}\max(d_i, 0) \qquad (4)$$

The penalty components of (4) are given by $d_k = \{(||S_{21}| - |S_{31}|| - d)/d\}_{f0.k}^2$, ($k$ = 1, 2, d = 0.5 dB), whereas the penalty factor is set to $\beta = 5$. Note that penalty components are active only when the requirement *d*, concerning maximum acceptable power-split imbalance at the centre frequencies, is violated.

In the last step, the structure is fine-tuned starting from the design obtained from (3). To ensure high quality of the results, the process is performed using only the high-fidelity model responses. The tuning is realized using a gradient algorithm embedded in trust-region (TR) framework with TR radius updated using standard rules [7].

4. Results and Discussion

The proposed BLC was designed using the methodology described above. The synthesized parameters of the structure of [2] Z_1 = 47.7 Ω, Z_2 = 74.5 Ω, Z_3 = 60.6 Ω, θ = 56.3° were used as the starting point for optimization of the modified circuit topology. The optimized parameters are Z_1 = 46.6 Ω, Z_2 = 77.2 Ω, Z_3 = 120 Ω, θ_1 = 120.8°, θ_2 = 61.4°, θ_3 = 26.1°, θ_4 = 17.3°, and θ_5 = 72.8° (cf. Fig. 2). The initial parameter set of the BLC assembled from compact cells optimized in the SBO setup is $\boldsymbol{x}_0$=[1.08 1.16 3.15 0.27 0.51 0.2 4.59 0.22 0.2 0.24 2.77 3.12 3.06 3.06 0.3 0.5]^T. The design $\boldsymbol{x}_1$ = [1.44 1.37 2.37 0.26 0.54 0.26 3.76 0.29 0.79 0.2 0.37 2.35 1.1 2.5 2.19 0.3 0.45]^T was found after 11 iterations of the SBO algorithm. The final BLC parameters $\boldsymbol{x}^*$ = [1.44 1.36 2.36 0.26 0.62 0.21 3.5 0.33 0.2 0.44 2.21 1.78 1.77 2.21 0.3 0.5]^T were obtained after 3 iterations of the fine tuning process. A comparison of the BLC responses at $\boldsymbol{x}_0$, $\boldsymbol{x}_1$ and $\boldsymbol{x}^*$ designs is shown in Fig. 3. The computational cost of structure design (excluding cells development/optimization) corresponds to only 35.3 EM model simulations (~2.6 hours).

The optimized BLC fulfills the imposed performance specifications. Its fractional bandwidths (expressed as $|S_{11}|$ and $|S_{41}|$ both below –20 dB) range from 2.39 GHz to 2.6 GHz (8.4% w.r.t. $f_{0.1}$) and from 5.2 GHz to 5.6 GHz (7.4% w.r.t. $f_{0.2}$), respectively. Moreover, the structure maintains phase difference of ±90° ±2° from 2.3 GHz to 2.7 GHz (16%) and from 5.2

GHz to 5.69 GHz (9.1%). The coupler offers power split imbalance of 3 ±0.5 dB from 2.21 GHz to 2.76 GHz and from 5.33 GHz to 5.59 GHz, respectively. The BLC was fabricated and measured. A photograph of the manufactured prototype is shown in Fig. 4, whereas comparisons of simulations and measurements in terms of scattering parameters and phase difference are provided in Fig. 5. The results are in acceptable agreement. Visible discrepancies are due to fabrication tolerances, as well as utilization of simplified EM structure model (i.e., without SMA connectors) for optimization.

The proposed BLC was compared with other dual-band couplers from the literature [1]-[5] in terms of bandwidths and size. For fair comparison, footprints of the structures were expressed in guided wavelength (calculated for the lower operating frequency and given substrate parameters). The size reduction factor (SRF) was calculated w.r.t. conventional single-band BLC operating at the lower frequency of the respective structure included to comparison. Couplers bandwidths were calculated for $|S_{11}|$ and $|S_{41}|$ below –15 dB. The results from Table 1 indicate that the circuit of [1] features broadest bandwidth of all considered structures, but—due to implementation as a two-section structure—it is almost 14-fold larger than the reference single-band coupler. At the same time, the BLC of [5] is the smallest one, yet its lower band is over 2-fold narrower compared to the proposed circuit. Among the compared BLCs, the proposed structure is the only one which offers small size along with enhanced bandwidths for both center frequencies.

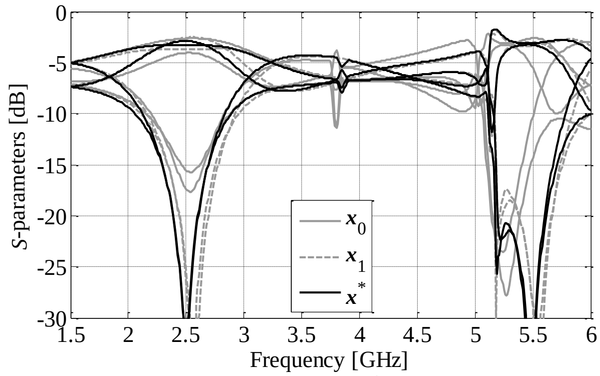

Fig. 3. Comparison of coupler responses at designs $\boldsymbol{x}_{0}$, $\boldsymbol{x}_1$ and $\boldsymbol{x}^*$.

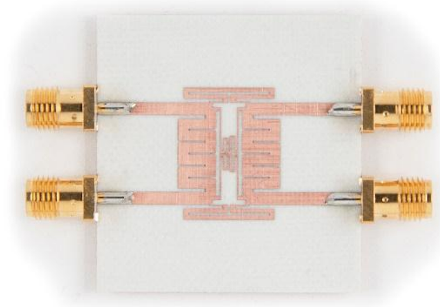

Fig. 4. A photograph of the fabricated prototype of dual-band BLC with enhanced bandwidth.

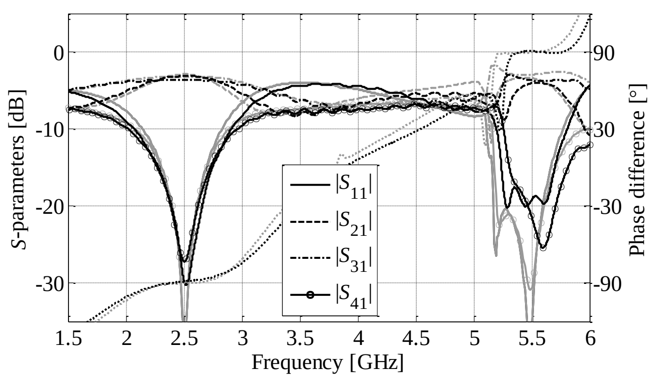

Fig. 5. Comparison of simulated (black) and measured (grey) scattering parameters and phase difference.

Table 1: Comparison with state of the art dual-band BLCs

Coupler	$f_{0.1}/f_{0.2}$ [GHz]	BW_1/BW_2 [%]*	$\Delta P_1/\Delta P_2$ [%]#	Dimensions [mm × mm]	Size [mm^2]	Size [λ_g^2]	SRF [%]$
[1]	2.2/5.5	28.2/11.3	20.6/6.0	100 × 65.8	6575	0.944	1388
[2]	1.0/2.0	12.4/6.2	12.0/6.3	64.3 × 64.3	4134	0.126	185
[3]	1.0/2.0	13.5/6.5	10.7/5.8	99.2 × 48.0	4762	0.095	140
[4]	1.0/2.0	12.0/4.0	16.0/2.0	32.3 × 32.3	1041	0.032	47
[5]	0.9/1.8	7.0/9.0	9.1/4.8	31.0 × 31.0	961	0.015	22
This work	2.5/5.4	16.0/9.0	16.0/9.1	18.2 × 14.0	255	0.049	72

* Calculated for $|S_{11}|$ and $|S_{41}|$ both below –15 dB (w.r.t. $f_{0.1}$ and $f_{0.2}$)

Calculated for $\angle S_{21} - \angle S_{21}$ of ±90° ± 2° (w.r.t. $f_{0.1}$ and $f_{0.2}$)

$ Calculated w.r.t. the size of conventional single-band BLC designed for $f_{0.1}$

5. Conclusion

A compact DB BLC with enhanced bandwidth is proposed. Bandwidth-enhanced operation is achieved by breaking the symmetry between cross-coupled sections of the structure whereas compact dimensions are obtained through meandering of coupler sections. The circuit is characterized by fractional bandwidths of 200 MHz and 400 MHz for the 2.5 GHz and 5.4 GHz centre frequencies and footprint of only 255 mm^2. The proposed structure represents the first attempt to design DB BLC with both small size and enhanced bandwidth.

Acknowledgment

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