Efficient Design Optimization of Compact Dual-Band Microstrip Branch-Line Coupler Using Response Features

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Abstract — **In this paper, computationally efficient design optimization of a miniaturized dual-band microstrip branch-line coupler is presented. Our optimization approach relies on suitably extracted features of a highly nonlinear response of the coupler structure under design. By formulating the design objectives in terms of the feature point locations, we carry out iterative optimization of the linear model of the features, embedded in the trust-region framework. Due to only slightly nonlinear dependence of the features on the designable parameters of the circuit, the optimized design satisfying prescribed performance requirements is obtained at the low computational cost of only 24 high-fidelity EM simulations of the structure.**

Index Terms — **simulation-driven design, miniaturized microwave circuits, microstrip couplers, dual-band couplers.**

I. INTRODUCTION

Design of miniaturized microwave components is a challenging task that involves handling multiple geometry parameters and, often, multiple objectives (e.g., related to matching, power split, port isolation, in case of coupler structures). Representative examples of such circuits are compact microstrip branch-line couplers (BLCs). These are important microwave/RF components, utilized, among others, in construction of circular polarization antennas [1], Butler matrices [2], and crossovers [3].

Various miniaturization strategies have been developed for BLCs [4], [5], including substitution of BLC sections with their corresponding slow-wave structures [6], ground plane perforations [7], etc. Size reduction unavoidably results in degradation of the transmission characteristics so that the design process usually aims at finding reasonable trade-off between the miniaturization rate and electrical performance. These issues are even more pronounced for dual-band couplers that exhibit more complex and highly nonlinear responses, particularly in the vicinity of the operating frequencies. At the same time, reliable evaluation of electrical performance of compact circuits requires full-wave EM analysis because simplified models (e.g., equivalent circuits) cannot account for considerable EM cross-couplings within highly compressed layouts [8].

Consequently, automated design closure of miniaturized BLCs through numerical optimization may be prohibitive in computational terms due to high cost of EM simulation (per design) and a large number of objective function evaluations required by conventional algorithms.

Efficient EM-driven design can be realized using surrogate-based optimization (SBO) methods [9], particularly those exploiting physics-based surrogates such as space mapping (SM) [10]. Unfortunately, SM requires a fast underlying low-fidelity model, typically an equivalent circuit, and circuit models of highly miniaturized structure are of limited accuracy.

In this work, we demonstrate computationally efficient derivative-free optimization of a compact dual-band BLC using the concept of response features introduced in [11]. We exploit the fact that dependence of the features on geometry parameters of the coupler is much less nonlinear than the dependence of the original responses (S-parameters versus frequency). Owing to this, iterative optimization of the linear model of the feature points, embedded in the trust-region framework, is capable to produce an optimized design at a low computational cost of 24 high-fidelity EM simulations of the BLC.

II. COMPACT DUAL-BAND MICROSTRIP COUPLER STRUCTURE

Consider a novel structure of a compact dual-band branch-line coupler shown in Fig. 1. The circuit is implemented on Taconic RF-35 dielectric substrate (h = 0.762 mm; ε_r = 3.5; tanδ = 0.0018). Design parameters are: $\boldsymbol{x} = [w_1\ w_2\ w_3\ l_1\ l_2\ l_3\ l_{31}]^T$. Variables $l_{1m} = 0.2\cdot\mathrm{abs}(l_3 + 3w_3 + 3l_{3m} + 4w_1)$, $l_{2m} = 0.2\cdot(l_3 + w_3 + l_{3m} + 0.5w_1 - 4.5w_2)$ and $l_{32} = w_1 + l_1 - w_3$, whereas $l_{3m} = 0.2$ and $w_0 = 1.7$ (all dimensions in mm). EM model of a structure is evaluated in CST Microwave studio (~300,000 mesh cells, simulation time 20 min). Design objectives, i.e., equal power split ($|S_{21}| = |S_{31}|$) as well as minimization of $|S_{11}|$ and $|S_{41}|$, are considered for the f_1 = 0.92 GHz and f_2 = 1.9 GHz frequencies.

III. COUPLER OPTIMIZATION USING RESPONSE FEATURES

The major challenges in automated design optimization of the compact structures include: high individual cost of EM simulation of the circuit, highly nonlinear responses, multiple objectives, and (in some cases) large number of design variables.

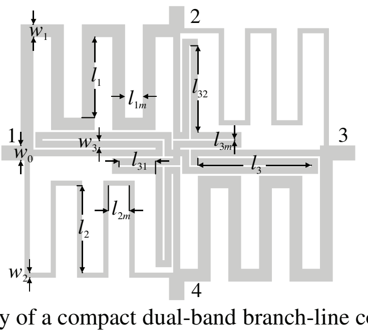

Fig. 1. Geometry of a compact dual-band branch-line coupler.

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At the same time, conventional SBO techniques such as space mapping are difficult to apply because of unreliability of equivalent circuit models (that could be used as the underlying low-fidelity model in the SM process). Here, we adopt the feature-based optimization approach of [11] and extend it for BLC design by handling some of the design specifications through suitably defined constraints.

A. Response Features of Compact Dual-Band BLC

Figure 2 shows typical responses of a compact dual-band coupler. Because we are interested in ensuring equal power split as well as good matching and isolation at both operating frequencies f_1 and f_2, the features of interest are local maxima of $|S_{21}|$ and $|S_{31}|$ and minima of $|S_{11}|$ and $|S_{41}|$ around f_1 and f_2. Some of these points are marked in Fig. 2. Each feature point is characterized by two coordinates: frequency (F) and level (L). Figure 3 shows a family of coupler responses corresponding to designs along certain line segment in the design space. Note that despite of highly nonlinear dependence of S-parameters on the coupler geometry, behavior of the feature points (cf. Fig. 4) is close to linear. Consequently, expressing the design goals in terms of the feature points and using feature-based surrogates is expected to speed up the optimization process considerably.

B. Objective Function and Constraints

The coupler design problem is formulated as:

$$\boldsymbol{x}^* = \arg\min_{\boldsymbol{x}} U(\boldsymbol{F}(\boldsymbol{x}), \boldsymbol{L}(\boldsymbol{x})) \tag{1}$$

where U is the objective function formulated in terms of the feature vectors $\boldsymbol{F}(\boldsymbol{x})$ and $\boldsymbol{L}(\boldsymbol{x})$ (i.e., frequency and level coordinates of the respective feature points), where $\boldsymbol{x}$ is a vector of geometry parameters to be adjusted. The objective function is defined as the maximum of the feature point levels corresponding to the minima of $|S_{11}|$ and $|S_{41}|$ at both operating frequencies with added penalty terms that are proportional to the deviations between the frequency coordinates of all feature points and the respective operating frequencies. Thus, the primary objective is to improve matching and isolation at the operating frequencies f_1 and f_2 and move the points of equal power split to f_1 and f_2.

We also consider the following equality constraints:

$$c_k(\boldsymbol{L}(\boldsymbol{x})) = 0, \quad k = 1, 2 \tag{2}$$

which are formulated in terms of the feature point level coordinates, i.e., $c_k = l_{21.k} - l_{31.k}$, where $l_{21.k}$ and $l_{31.k}$ are the feature point levels corresponding to the maxima of $|S_{21}|$ and $|S_{31}|$ around the operating frequency f_k. The constraints (2) allow for enforcing equal power split at both frequencies.

C. Optimization Algorithm

The problem (1) is solved iteratively as

$$\boldsymbol{x}^{(i+1)} = \arg\min_{\|\boldsymbol{x}-\boldsymbol{x}^{(i)}\| \le r^{(i)}} U(\boldsymbol{F}_S^{(i)}(\boldsymbol{x}), \boldsymbol{L}_S^{(i)}(\boldsymbol{x})) \tag{3}$$

with the constraint

$$c_k^{(i)}(\boldsymbol{L}_S^{(i)}(\boldsymbol{x})) = 0, \quad k = 1, 2 \tag{4}$$

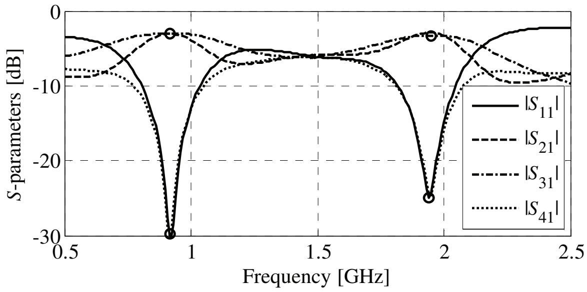

Fig. 2. Typical responses of a dual-band coupler. Selected feature points are marked with the circles (here, corresponding to the maximum of $|S_{21}|$ around the lower operating frequency f_1, maximum of $|S_{31}|$ around the higher operating frequency f_2, as well as the two minima: of $|S_{41}|$ around f_1, and of $|S_{11}|$ around f_2).

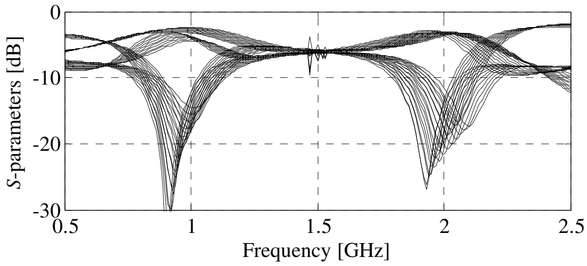

Fig. 3. Family of coupler responses corresponding to its geometries along certain line segment in the design space showing highly nonlinear behavior of S-parameters on geometry variables of the circuit.

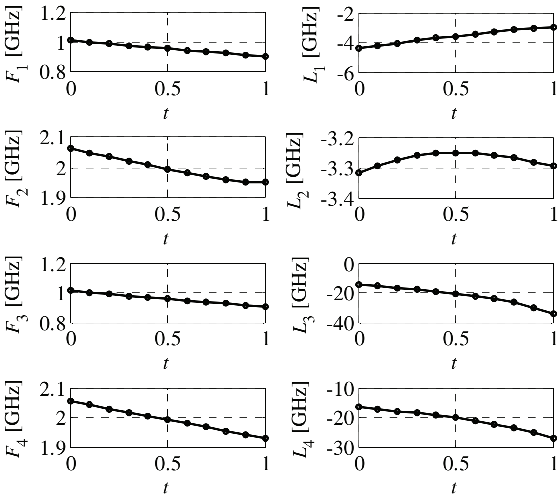

Fig. 4. Selected feature points (as marked in Fig. 2) corresponding to coupler geometries along the same line segment parameterized by t as in Fig. 3. Note that dependence of feature coordinates on coupler geometry is close to linear.

where $\boldsymbol{x}^{(i)}$, i = 0, 1, …, is a sequence approximating $\boldsymbol{x}^*$, whereas $\boldsymbol{F}_S^{(i)}$ and $\boldsymbol{L}_S^{(i)}$ are linear approximation models of the feature point vectors $\boldsymbol{F}(\boldsymbol{x})$ and $\boldsymbol{L}(\boldsymbol{x})$ established at the current design $\boldsymbol{x}^{(i)}$ using n perturbed designs around $\boldsymbol{x}^{(i)}$ and the corresponding feature points. The algorithm (2) is embedded in trust-region framework [12] with the search radius $r^{(i)}$ updated using standard rules [12].

IV. NUMERICAL RESULTS

The coupler structure of Fig. 1 has been optimized using the algorithm of Section III. The initial design $\boldsymbol{x}^{(0)}$ = [1.39 0.58 0.99 8.66 9.19 5.02 12.73]^T mm has been obtained by optimizing the equivalent circuit model of the coupler structure. Figure 5 shows the responses at $\boldsymbol{x}^{(0)}$ indicating non-equal power split at both operating frequencies as well as frequency shift for matching and isolation characteristics for f_2.

Owing to close-to-linear dependence of the feature points on $\boldsymbol{x}$, only three iterations of the algorithm (3), (4), i.e., 24 EM simulations of the coupler, were necessary to yield the final design $\boldsymbol{x}^*$ = [1.61 0.66 0.91 8.66 9.55 5.47 12.24]^T mm. It can be noted (cf. Fig. 6) that the responses are now centered around the operating frequencies, and equal power split has been achieved ($|S_{21}| - |S_{31}| < 0.02$ dB for f_1, and $|S_{21}| - |S_{31}| <$ 0.05 dB for f_2).

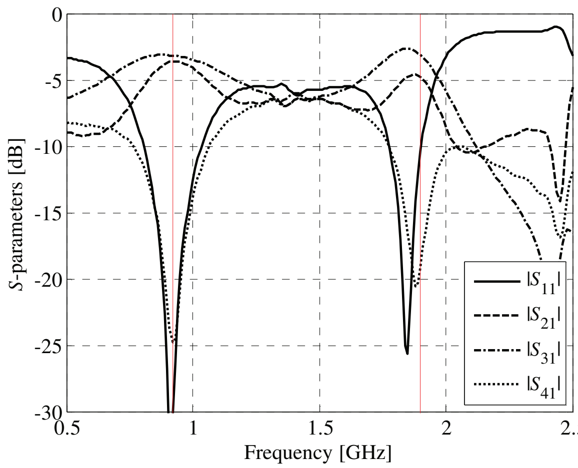

Fig. 5. Responses of the compact dual-band coupler at the initial design. Operating frequencies f_1 = 0.92 GHz and f_2 = 1.90 GHz are marked using vertical lines.

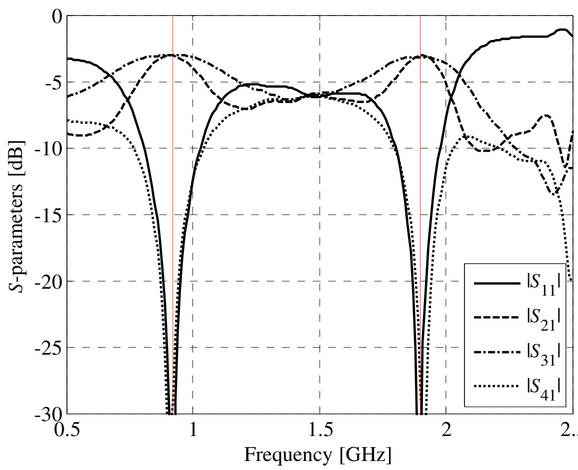

Fig. 6. Responses of the compact dual-band coupler at the design obtained by feature-based optimization. Operating frequencies f_1 = 0.92 GHz and f_2 = 1.90 GHz are marked using vertical lines.

V. CONCLUSION

Rapid design closure of a compact dual-band microstrip coupler using feature-based optimization has been presented. Our approach utilized surrogate-based optimization with the surrogate model constructed (of both objective function and constraints) from critical points—both frequency- and level-wise—of the highly nonlinear responses of the structure (i.e., *S*-parameters versus frequency). Because of almost linear dependence of the feature point coordinates on the geometry variables of the structure at hand, the optimization process is characterized by a very low cost, despite of being conducted exclusively at the high-fidelity EM simulation level and without using sensitivity data. The future work will focus on extending the presented design methodology to variable-fidelity EM-simulation framework.

ACKNOWLEDGEMENT

The authors thank Computer Simulation Technology AG, Darmstadt, Germany, for making CST Microwave Studio available. This work was supported in part by the Icelandic Centre for Research (RANNIS) Grant 130450051.

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