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INVERSE AND FORWARD SURROGATE MODELS FOR EXPEDITED DESIGN OPTIMIZATION OF UNEQUAL-POWER-SPLIT PATCH COUPLERS

Slawomir Koziel[1, 2], Adrian Bekasiewicz[1]

1) *Reykjavik University, School of Science and Engineering, 101 Reykjavik, Iceland* (✉ *koziel@ru.is*, +354 599 6886)
2) *Gdańsk University of Technology, Faculty of Electronics, Telecommunications and Informatics, G. Narutowicza 11/12, 80-233 Gdańsk, Poland* (*adrian.bekasiewicz@pg.edu.pl*)

Abstract

In the paper, a procedure for precise and expedited design optimization of unequal power split patch couplers is proposed. Our methodology aims at identifying the coupler dimensions that correspond to the circuit operating at the requested frequency and featuring a required power split. At the same time, the design process is supposed to be computationally efficient. The proposed methodology involves two types of auxiliary models (surrogates): an inverse one, constructed from a set of reference designs optimized for particular power split values, and a forward one which represents the circuit S-parameter gradients as a function of the power split ratio. The inverse model directly yields the values of geometry parameters of the coupler for any required power split, whereas the forward model is used for a post-scaling correction of the circuit characteristics. For the sake of illustration, a 10-GHz circular sector patch coupler is considered. The power split ratio of the structure is re-designed within a wide range of −6 dB to 0 dB. As demonstrated, precise scaling (with the power split error smaller than 0.02 dB and the operating frequency error not exceeding 0.05 GHz) can be achieved at the cost of less than three full-wave EM simulations of the coupler. Numerical results are validated experimentally.

Keywords: inverse modelling, patch coupler, computer-aided design, forward modelling, unequal-split coupler.

1. Introduction

Microstrip hybrid quadrature couplers find applications in a variety of microwave systems, among others, power dividers, balanced mixers, Butler matrices, or baluns [1, 2]. One of the consequences of stringent performance specifications imposed on contemporary communication systems is that suitability of conventional *branch line couplers* (BLCs) is becoming limited for some of the aforementioned applications. This is mainly due to considerable size of *transmission-line* (TL)-based BLCs. In this context, *patch couplers* (PCs) seem to be a better alternative [3, 4]. The main advantages of PCs include their simple topologies (rectangular, circular or elliptical [5]) and strong mechanical structure. PCs are well suited for centimetre-frequency applications because their typical dimensions at this frequency range make them easy to fabricate [6]. Another advantage is broader (as compared to standard BLCs) operational bandwidth. Last but not least, PCs can conveniently perform unequal power split operation [5].

Similarly as for any other microwave structure, a bottleneck of practical coupler design is design closure, *i.e.*, finding the values of geometry parameters that ensure optimum operation of the structure. This is especially challenging for miniaturized circuits which normally feature complex topologies described by a large number of parameters. On the other hand, cross-coupling effects present in modern couplers (and often considerable in densely arranged layouts of compact circuits) make full-wave *electromagnetic* (EM) simulation mandatory for reliable evaluation

of electrical characteristics [7–9]. Unfortunately, EM analysis may be computationally expensive [10]. Another design challenge is a necessity of handling several performance figures (operating frequency, bandwidth, phase characteristics, power split, footprint area) [7]. Furthermore, finding the best possible design does require simultaneous adjustment of all geometry parameters of the circuit. This can only be realized by means of numerical optimization. For the reasons elaborated on above, using conventional optimization algorithms is often impractical: a large number of EM simulations involved in the process may be simply prohibitive in computational terms [11]. There have been several techniques developed to speed up the design process. These include gradient-based search with adjoint sensitivities [12] as well as more and more popular *surrogate-based optimization* (SBO) methods [13]. SBO procedures, founded on the idea of replacing the expensive EM model by its cheaper representation (a surrogate), come in many variations such as space mapping [14], response correction methods [15], or feature-based optimization [16].

One of frequently executed tasks in microwave engineering is design of the same structure for various operating conditions such as operating frequency or power split ratio, as well as different material parameters (*e.g.*, substrate permittivity or thickness). The standard approach requires re-optimization of the structure dimensions to ensure meeting the new performance requirements. Clearly, this is just as expensive as obtaining the original (or any other) design. Acceleration of this process is possible by reusing already available designs. The most straightforward technique based on this idea involves design curves [17], often obtained using analytical or equivalent network representations. More sophisticated approaches employ inverse surrogate modelling methods [18]. The surrogate is often a regression model [18] constructed using reference designs pre-optimized for a predefined set of operating conditions. The fundamental advantage of inverse models (as opposed to forward ones) is that they directly return close-to-optimal geometry parameter values corresponding to required operating conditions (and/or material parameters of the substrate, depending on the model setup). A methodology based on this concept, proposed in [18], enables dimension scaling operating frequency of miniaturized rat-race couplers. In [19], a technique for coupler scaling with respect to the power split ratio has been reported, also based on inverse surrogates.

One of disadvantages of the methods outlined in the previous paragraph is that correction of (usually unavoidable) scaling errors with respect to performance figures different from those for which the inverse models have been constructed is virtually impossible. This is because the inverse model does not depend (neither explicitly nor implicitly) on those figures. For example, scaling w.r.t. the operating frequency may result in power split errors or degradation of bandwidth which cannot be corrected other than through explicit optimization.

The purpose of this paper is introduction of an improved dimension scaling technique which enables post-scaling correction of secondary coupler characteristics. In our approach, similarly as in [18], the circuit re-design with respect to the primary operating conditions is performed by means of an inverse surrogate model. At the same time, a forward model of the coupler

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S-parameter gradients is constructed and used to perform post-scaling correction of all relevant characteristics. The forward model is a data-driven regression surrogate which makes the correction computationally efficient (a typical cost is up to three EM simulations of the structure at hand). The proposed methodology is demonstrated using a circular hybrid patch coupler operating at 10 GHz. The circuit re-design is carried out with respect to the power split ratio in a wide range of −6 dB to 0 dB. The results indicate that the scaling process is very precise with the power split ratio error lower than 0.02 dB (as compared to a required value), and the operating frequency error lower than 0.05 GHz. The numerical data are validated through measurements of fabricated coupler prototypes.

2. Coupler re-design with surrogate-assisted correction

In this section, we first recall the basics of dimension scaling using inverse surrogate models, then formulate the proposed design correction techniques involving forward surrogates. Demonstration examples are provided in Section 3 along with experimental verification.

2.1. Dimension scaling problem. Reference designs

We denote by $\boldsymbol{S}_f(\boldsymbol{x}) = [S_{11}(\boldsymbol{x})\ S_{21}(\boldsymbol{x})\ S_{31}(\boldsymbol{x})\ S_{41}(\boldsymbol{x})]$ a response of the full-wave EM simulation model of the coupler structure of interest. The vector $\boldsymbol{x} \in R^n$ represents relevant (adjustable) geometry parameters.

In this work, without loss of generality, coupler re-design with respect to the power split ratio $P = |S_{21}(\boldsymbol{x})| - |S_{31}(\boldsymbol{x})|$ is considered. We denote by $\boldsymbol{x}(P_S)$ the design optimized for the power split ratio P_S at the operating frequency f_0. The optimization process is carried out to satisfy several performance requirements as listed below:

- Obtaining the required power split, *i.e.*, $P_S = |S_{21}| - |S_{31}|$;
- Minimizing the reflection response $|S_{11}|$ at f_0;
- Minimizing the isolation response $|S_{41}|$ at f_0;
- Allocating the minimum of $|S_{11}|$ and $|S_{41}|$ at f_0.

The reference designs are obtained using conventional means (here, trust-region gradient search with numerical derivatives [20]). At this point, it should be mentioned that the reference designs can also be selected from already existing designs, previously found for a given structure. Clearly, reusing the designs is a simple way of reducing the computational cost of inverse model construction.

The dimension scaling problem can be formulated as follows. Given a set of reference designs $\boldsymbol{x}(P_{S.k})$ optimized for various power split ratios $P_{S.k}$, $k = 1, \ldots, N$, find the geometry parameters' values $\boldsymbol{x}(P_S)$ corresponding to the optimized design (in the sense given above) for any power split ratio P_S within the range of interest $P_{S.\min} \le P_S \le P_{S.\max}$.

2.2. Constructing inverse surrogate. Scaling procedure

The scaling algorithm is based on the procedure of [18], and the inverse surrogate model obtained as described in Section 2, using the reference designs $\boldsymbol{x}(P_{S.k})$. The model is denoted as $\boldsymbol{x}_s(P_S, \boldsymbol{P})$ to emphasize the fact that it is a function of the power split ratio and its parameter vector $\boldsymbol{P}$. We have:

$$\boldsymbol{x}_s(P_S, \boldsymbol{P}) = [x_{s.1}(P_S, \boldsymbol{p}_1)\ \ \ldots\ \ x_{s.n}(P_S, \boldsymbol{p}_n)]^T. \tag{1}$$

In (1), $x_{s.k}(P_S,\boldsymbol{p}_k)$ represents a model of the k-th geometry parameter; $\boldsymbol{p}_k$ are the model coefficients. We also have $\boldsymbol{P} = [\boldsymbol{p}_1 \ \ldots \ \boldsymbol{p}_n]$. As mentioned before, $\boldsymbol{P}$ represents the aggregated parameter vector for the entire model.

The analytical form of the inverse model has been selected following the guidelines of [18]:

$$x_{s.k}(P_S) = p_1 + p_2 \cdot \exp(p_3 P_S), \tag{2}$$

where $\boldsymbol{p} = [p_1\ p_2\ p_3]$. Exponential curves have been shown to be sufficiently flexible yet described by a small number of parameters, which enables to limit the number of the reference designs necessary to set up the model.

The surrogate is identified by solving the following nonlinear regression problem:

$$\boldsymbol{p}_k = \arg\min_{\boldsymbol{p}} \sum_{j=1}^{N} \left(x_{s.k}(P_{S.j},\boldsymbol{p}) - x_{j.k}\right)^2 \tag{3}$$

for $k = 1,\ldots,n$. The symbol $x_{j.k}$ denotes the k-th component of the reference design vector $\boldsymbol{x}(P_{S.j})$.

The coupler re-design for a required power split ratio P_S is carried out simply by evaluating the inverse surrogate at P_S, *i.e.*, we have $\boldsymbol{x}(P) \approx \boldsymbol{x}_s(P)$.

2.3. Design correction using forward model of coupler response gradients

Due to the limited prediction accuracy of the inverse surrogate model and, more importantly, the fact that it only accounts for the power split ratio but not for other performance figures (*e.g.*, the operating frequency), the scaled designs may disagree to some extent with the specification. This paper proposes a novel scheme to perform a post-scaling correction of all relevant performance figures. The correction procedure works as described below. In the first step, a simple (second-order polynomial) forward model of the coupler response Jacobians $J_S(\boldsymbol{x})$ is constructed using the following procedure:

– For all reference designs $\boldsymbol{x}(P_{S.k})$, $k = 1,\ldots,N$, obtain Jacobian $J_S(\boldsymbol{x}(P_{S.k}))$;
– Fill in the system matrix:

$$\boldsymbol{A} = \begin{bmatrix} 1 & P_{S.1} & P_{S.1}^2 \\ 1 & P_{S.2} & P_{S.2}^2 \\ \vdots & \vdots & \vdots \\ 1 & P_{S.N} & P_{S.N}^2 \end{bmatrix} \tag{4}$$

and calculate $\boldsymbol{B} = (\boldsymbol{A}^T\boldsymbol{A})^{-1}\boldsymbol{A}^T$;
– Calculate components $J_{S.j.r}(P_S)$ of the forward model for a power split ratio of interest P_S as:

$$J_{S.j.r}(P_S) = \lambda_{j.r.1} + \lambda_{j.r.2}P_S + \lambda_{j.r.3}P_S^2, \tag{5}$$

where:

$$\begin{bmatrix} \lambda_{j.r.1} \\ \lambda_{j.r.2} \\ \lambda_{j.r.3} \end{bmatrix} = \boldsymbol{B} \begin{bmatrix} J_{S.j.r}(\boldsymbol{x}(P_{S.1})) \\ \vdots \\ J_{S.j.r}(\boldsymbol{x}(P_{S.1})) \end{bmatrix} \tag{6}$$

and $J_{S.j.r}(\boldsymbol{x}(P_{S.k}))$ is the $(j,\ r)$ component of the k-th reference design Jacobian.

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It is important to note that the Jacobians $J_S(\boldsymbol{x}(P_{S.k}))$ are already available because they were estimated (using finite differentiation) in the stage of optimizing the reference designs. Consequently, construction of the forward model does not incur any extra computational cost. It should also be mentioned that, in practice, separate Jacobians for all four responses of interest (S_{11} through S_{41}) are considered, which was omitted here for simplicity of notation. The Jacobian estimated using the forward model will be referred to as $J_s(P_S)$.

The post-scaling design correction is performed using a standard trust-region optimization procedure involving $J_s(P_S)$:

$$\boldsymbol{x}(P_S) \leftarrow \arg\min_{\boldsymbol{x}} U\left(\boldsymbol{S}_f(\boldsymbol{x}(P_S)) + J_s(P_S)\cdot(\boldsymbol{x}-\boldsymbol{x}(P_S))\right). \tag{7}$$

The objective function $U(.)$ encodes the design specifications for the coupler (see Section 2.1 for details) and it is also used to obtain the reference designs. The argument of U is a linear expansion model of the coupler responses obtained using the EM-simulated response $\boldsymbol{S}_f(\boldsymbol{x}(P_S))$ at the current design $\boldsymbol{x}(P_S)$ and its estimated Jacobian. A solution of (7) is constrained to the small vicinity of $\boldsymbol{x}(P_S)$, which is further adjusted according to the trust region rules [20]. It is important to note that because the expected change of the design in the correction stage is small, using the fixed Jacobian estimation $J_s(P_S)$ (not updated through iterations of (7)) is well justified. Typically, two or three iterations of (7) are sufficient to achieve convergence.

3. Case study

In order to illustrate the operation and performance of the design procedure of Section 2, an example of circular sector microstrip patch coupler [5] is considered. The circuit geometry has been shown in Fig. 1. The coupler is implemented on Arlon AD 250 substrate ($\varepsilon_r = 2.5$, $h = 0.762$ mm). The design variables are $\boldsymbol{x} = [r_1\ r_2\ a\ b]^T$ (the unit for the first two parameters is mm; the unit for the last two parameters is degree). The circuit is supposed to operate at 10 GHz. The computational model $\boldsymbol{S}_f$ is implemented in CST Microwave Studio [21] ($\sim 290{,}000$ mesh cells; simulation time around 2 min).

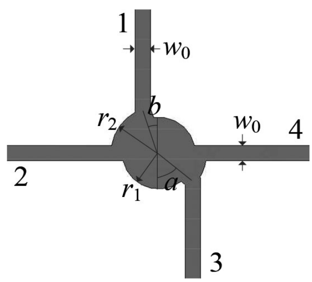

Fig. 1. Geometry of the considered patch coupler [5].

The coupler is to be re-designed for various power split ratios in the range from −6 dB to 0 dB (equal split). The reference designs have been allocated uniformly within the range of interest, specifically, for $P_S = -6$ dB, −3 dB, and 0 dB. Fig. 2 shows the EM-simulated S-parameters of the coupler at the reference designs. The inverse surrogate model has been extracted as in (2). The dimensions of the coupler for all reference designs and the plots of the inverse surrogate model are shown in Fig. 3. Note that the model is interpolative because the number of reference designs is equal to the number of model coefficients.

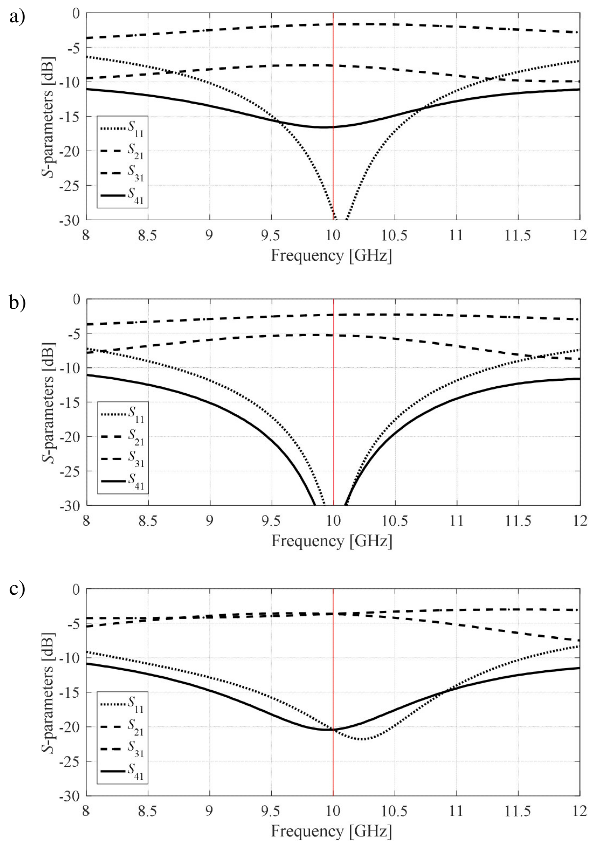

Fig. 2. EM-simulated coupler responses at the reference designs corresponding to: a) $P_S = -6$ dB; b) $P_S = -3$ dB and c) $P_S = 0$ dB.

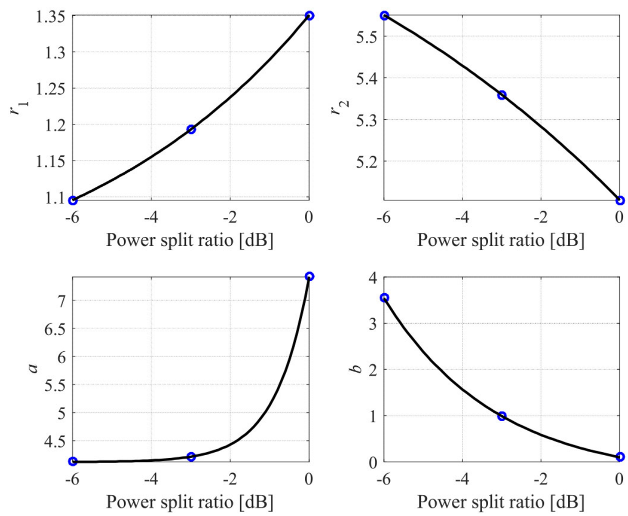

Fig. 3. Dimensions of the three reference designs (∘) and the extracted inverse surrogate model (—).

The scaling procedure has been comprehensively validated by re-designing the coupler for the following six power split ratios: –1.2 dB, –1.5 dB, –2.5 dB, –4.0 dB, –4.5 dB, and –5.3 dB. Table 1 lists geometry parameter values for all verification designs, whereas Fig. 4 shows the EM-

Table 1. Parameter values of the Scaled Patch Coupler.

Geometry parameters	**Target power split P_S [dB]**					
	–1.2	–1.5	–2.5	–4.0	–4.5	–5.3
r_1	6.63	6.59	6.49	6.26	6.22	6.15
r_2	5.22	5.25	5.33	5.44	5.47	5.53
a	3.12	3.38	5.72	3.32	3.92	3.72
b	0.10	0.10	0.10	0.76	1.73	2.28

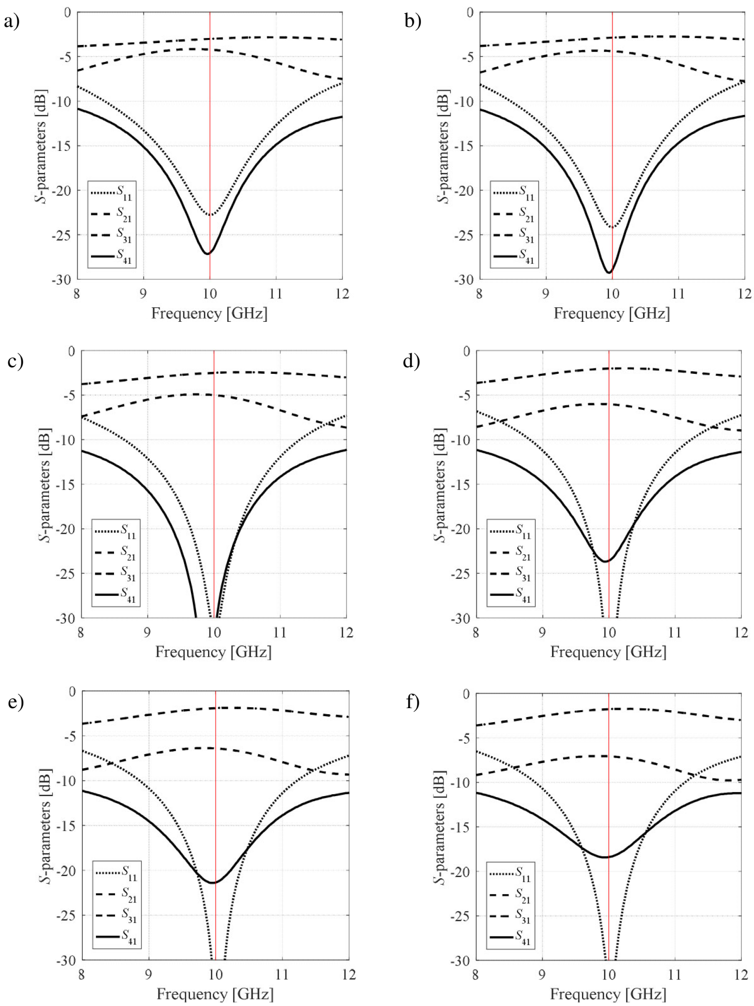

Fig. 4. Responses of the patch coupler scaled using the proposed methodology, for the power split ratios: a) –1.2 dB; b) –1.5 dB; c) –2.5 dB; d) –4.0 dB; e) –4.5 dB and f) –5.3 dB.

simulated coupler responses. It can be observed in Table 2 that the power split ratio is somehow deviated from the required values before executing post-scaling correction of Subsection 2.3. Upon correction, the power split ratio error does not exceed 0.02 dB for all designs. This is also illustrated in Fig. 5 for selected designs. The verification designs have been fabricated and measured. Fig. 6 shows photographs of the coupler prototypes. The simulated and measured values of S-parameters are shown in Fig. 7.

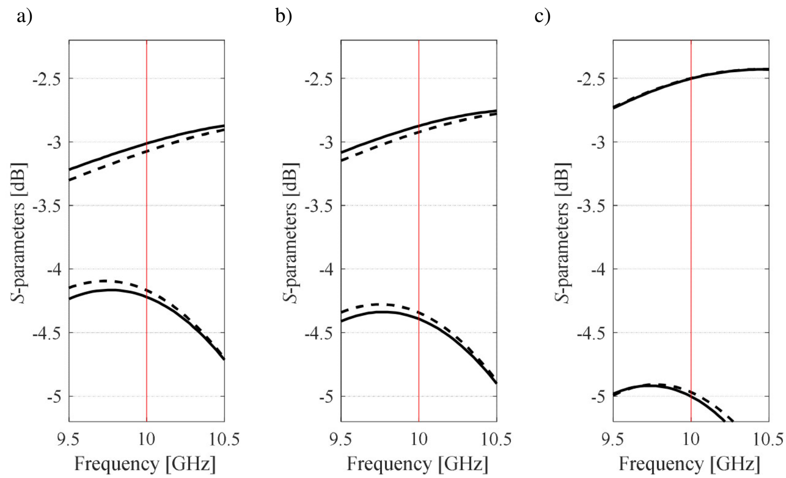

Fig. 5. EM-simulated power split of the scaled patch coupler before (- - -) and after (—) the correction stage of Section 2.3. Plots for selected verification cases: a) −1.2 dB; b) −1.5 dB and c) −2.5 dB.

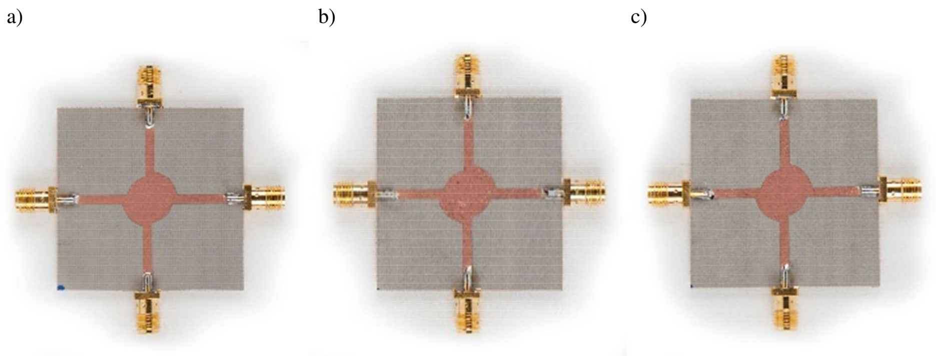

Fig. 6. Fabricated prototypes of patch couplers for selected verification cases: a) −1.2 dB; b) −1.5 dB and c) −2.5 dB.

Table 2. Power split before and after correction step.

$\|\|S_{21}\| - \|S_{31}\|\|$ [dB]	**Target power split P_S [dB]**					
	−1.2	−1.5	−2.5	−4.0	−4.5	−5.3
P_S before correction	−1.07	−1.41	−2.45	−4.05	−4.53	−5.25
P_S after correction	−1.21	−1.52	−2.50	−4.01	−4.50	−5.29

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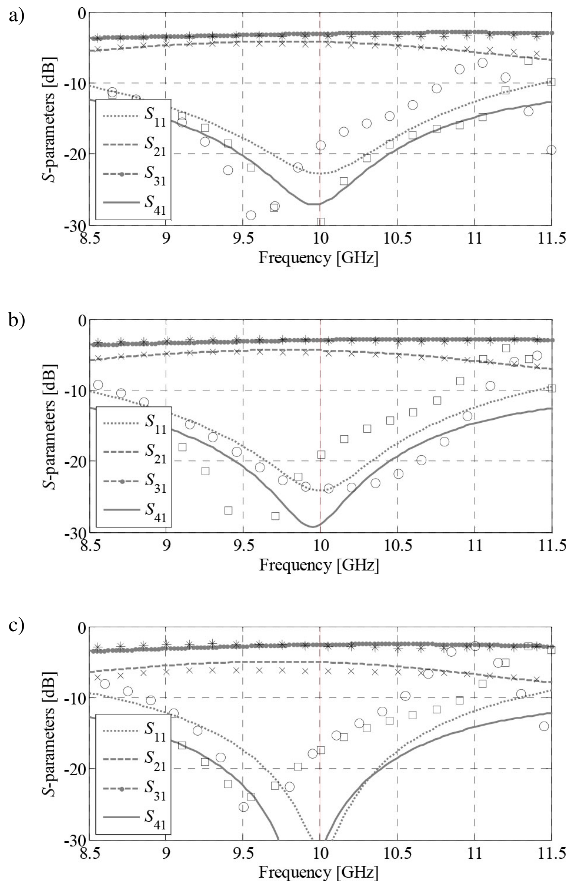

Fig. 7. Simulated (o, ×, ∗, and □, for $|S_{11}|$, $|S_{21}|$, $|S_{31}|$, and $|S_{41}|$, respectively) and measured S-parameters for selected verification cases: a) −1.2 dB; b) −1.5 dB and c) −2.5 dB.

It can be observed that the agreement between the simulation and measurement data is acceptable. A slight frequency shift is mostly the result of the SMA connectors present in the measurement setup but not in the computational model. For the same reason, certain level degradation of the $|S_{21}|$ and $|S_{31}|$ characteristics can be observed as well.

4. Conclusion

The paper proposed a novel methodology for rapid re-design (dimension scaling) of unequal power split patch couplers. Our technique is based on two types of surrogate models: an inverse surrogate for performing the initial scaling, and a forward surrogate of the coupler response Jacobians for an iterative (post-scaling) design correction. It is a combination of this two approaches that enables precise structure re-design (with the power split error smaller than 0.02 dB) at a low computational cost of up to three EM simulations of the structure at hand. For the sake of demonstration, a circular section hybrid microstrip patch coupler operating at 10 GHz has been considered and re-designed within a wide range of power split ratios of −6 dB to 0 dB. Experimental validation confirms reliability and correctness of the proposed method. The future work will be focused on extending the technique to other classes of microwave and antenna structures.

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References

[1] Zheng, S.Y., Yeung, S.H., Chan, W.S., Man, K.F., Leung, S.H., Xue, Q. (2008). Dual-band rectangular patch hybrid coupler. *IEEE Trans. Microwave Theory Tech.*, 56(7), 1721–1728.

[2] Zheng, S., Chan, W.S., Leung, S.H., Xue, Q. (2007). Broadband Butler matrix with flat coupling. *Electronics Lett.*, 43(10), 576–577.

[3] Zheng, S.Y., Yeung, S.H., Chan, W.S., Man, K.F., Leung, S.H. (2009). Size-reduced rectangular patch hybrid coupler using patterned ground plane. *IEEE Trans. Microwave Theory Tech.*, 57(1), 180–188.

[4] Sun, S., Zhu, L. (2010). Miniaturised patch hybrid couplers using asymmetrically loaded cross slots. *IET Microwaves, Ant. Prop.*, 4(9), 1427–1433.

[5] Zheng, S.Y., Deng, J.H., Pan, Y.M., Chan, W.S. (2013). Circular sector patch hybrid coupler with an arbitrary coupling coefficient and phase difference. *IEEE Trans. Microwave Theory Tech.*, 61(5), 1781–1792.

[6] Zheng, S.Y., Chan, W.S., Wong, Y.S. (2013). Reconfigurable RF quadrature patch hybrid coupler. *IEEE Trans. Industrial Electr.*, 60(8), 3349–3359.

[7] Koziel, S., Bekasiewicz, A. (2017). Computationally efficient two-objective optimization of compact microwave couplers through corrected domain patching. *Metrol.Meas. Syst.*, 25.

[8] Tseng, C.-H., Chang, C.-L. (2012). A rigorous design methodology for compact planar branch-line and Rat-Race couplers with asymmetrical T-structures. *IEEE Trans. Microw. Theory Techn.*, 60(7), 2085–2092.

[9] Kurgan, P., Kitlinski, M. (2011). Doubly miniaturized rat-race hybrid coupler. *Microwave Opt. Tech. Lett.*, 53(6), 1242–1244.

[10] Bekasiewicz, A., Koziel, S., Zieniutycz, W. (2016). A structure and design optimization of novel compact microscrip dual-band rat-race coupler with enhanced bandwidth. *Microwave and Optical Technology Letters*, 58(10), 2287–2291.

[11] Nocedal, J., Wright, S. (2006). *Numerical Optimization*. 2nd edition, New York: Springer.

[12] Bakr, M.H., Nikolova, N.K. (2004). An adjoint variable method for time-domain transmission-line modeling with fixed structured grids. *IEEE Trans. Microwave Theory Tech.*, 52(2), 554–559.

[13] Koziel, S., Yang, X.S., Zhang, Q.J. (eds.), (2013). *Simulation-driven design optimization and modeling for microwave engineering*. Imperial College Press.

[14] Bandler, J.W., Cheng, Q.S., Dakroury, S.A., Mohamed, A.S., Bakr, M.H., Madsen, K., Søndergaard, J. (2004). Space mapping: the state of the art. *IEEE Trans. Microwave Theory Tech.*, 52(1), 337–361.

[15] Koziel, S., Bekasiewicz, A. (2016).Rapid microwave design optimization using adaptive response scaling. *IEEE Trans. Microwave Theory Tech.*, 64(9), 2749–2757.

Metrol. Meas. Syst., Vol. 26 (2019), No. 3, pp. 463–473
DOI: 10.24425/mms.2019.129578

[16] Koziel, S., Bandler, J.W. (2015). Rapid yield estimation and optimization of microwave structures exploiting feature-based statistical analysis. *IEEE Trans. Microwave Theory Tech.*, 63(1), 107–114.

[17] Caenepeel, M., Ferranti, F., Rolain, Y. (2016). Efficient and automated generation of multidimensional design curves for coupled-resonator filters using system identification and metamodels. *Int. Conf. Synthesis, Modeling, Analysis and Simulation Methods and Applications to Circuit Design (CMACD)*.

[18] Koziel, S., Bekasiewicz, A. (2015). Expedited geometry scaling of compact microwave passives by means of inverse surrogate modeling. *IEEE Trans. Microwave Theory Tech.*, 63(12), 4019–4026.

[19] Koziel, S., Bekasiewicz, A. (2016). Surrogate modeling for expedited two-objective geometry scaling of miniaturized microwave passives. *Int. J. RF & Microwave CAE*, 26(6), 531–537.

[20] Koziel, S., Bandler, J.W., Cheng, Q.S. (2010). Robust trust-region space-mapping algorithms for microwave design optimization. *IEEE Trans. Microwave Theory and Tech.*, 58(8), 2166–2174.

[21] CST Microwave Studio, ver. 2013, Dassault Systems, 10 rue Marcel Dassault, CS 40501, Vélizy-Villacoublay Cedex, France.