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Novel Structure and Design of Enhanced-Bandwidth Hybrid Quadrature Patch Coupler

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Abstract: A novel structure and design optimization procedure of an enhanced-bandwidth hybrid quadrature patch coupler is proposed. Improved performance of the circuit has been obtained by parameterizing the coupler sections using splines, which introduces additional degrees of freedom. Due to computational complexity of the parameter adjustment problem, a sequential design procedure is applied. In each iteration, a selected number of spline control points is used and their radial coordinates are optimized. The design found this way is then used as a starting point for the next iteration with an increased number of spline control points. The final design parameterized by 20 control points exhibits over 50-percent bandwidth at the operational frequency of 10 GHz, and acceptable footprint of 13.8 mm × 15.7 mm.

Keywords: Patch couplers, EM-driven design, computer-aided design, topology evolution, design optimization.

1. Introduction

Microstrip hybrid patch couplers (PCs) are important components of microwave systems, including power dividers, Butler matrices, and others [1], [2]. Standard PC realizations based on circular or rectangular geometries [1]-[5] exhibit limited bandwidth (BW)—defined in terms of power-split imbalance—which make them unsuitable for contemporary multi- or broad-band systems. Bandwidth enhancement can be obtained by means of appropriate topological modifications, including stubs [2], slots [2], impedance transformers [6], stepped-impedance feeds (25-percent BW obtained in [4]), circular sections of different radii (22-percent BW achieved in [3]), or combinations thereof (e.g., 35.9-percent BW obtained by using stepped-impedance feeds and ground plane slots [6]). A disadvantage of the aforementioned designs is manually pre-selected (thus, fixed) topology of the coupler which, on one hand, makes the design problem easier, but also limits opportunities for performance improvements.

A workaround is introduction of more flexible parameterization of topologies (e.g., [7], [8]). A practical design challenge that arises here is a large number of variables that need to be simultaneously adjusted, which required rigorous numerical optimization [9], [10]. When executed at the EM-simulation modeling level (a necessity of majority of microwave structures), it is associated with high computational costs, especially when global optimization methods are utilized [11]. Designs speedup can be obtained using surrogate-assisted techniques [12] or adjoints sensitivities [13], if available.

In this letter, a novel structure of a spline-parameterized hybrid quadrature patch coupler is proposed along with its design procedure. In order to alleviate the difficulties related to highly-dimensional parameter space, a sequential topology evolution is developed and utilized. In each design iteration, the coupler geometry is parameterized using an increasing number of control points and optimized. The starting design for the subsequent iteration is obtained by re-interpolating the solution found in the previous iteration. As a result, both the structure complexity and its performance are increasing, the former in a computationally manageable manner. The final design of the circuit operating at 10 GHz exhibits a wide bandwidth of over 50 percent, and acceptable footprint of 13.8 mm × 15.7 mm. Experimental validation is also provided.

Benchmarking using state-of-the-art patch couplers from the literature indicates superiority (performance-wise) of the proposed circuit solution.

2. Coupler Structure

Geometry of the proposed patch coupler has been shown in Fig. 1. The structure is based on a spline-shaped geometry. It is implemented in microstrip technology on a 0.762-mm-thick Arlon AD250 dielectric substrate (ε_r = 2.5, tanδ = 0.0014). The centre frequency is set to f_0 = 10 GHz. The coupler consists of a spline-parameterized patch fed through four 50 ohm transmission lines. The shape of each half of the patch is controlled using the same vector of control points (also referred to as knots) $\boldsymbol{x}_k = [r_1\ r_2\ \ldots\ r_k]^T$, k = 8, 9, …, 20, implemented in a cylindrical coordinate system. Parameter w_0 = 2.1 is fixed to ensure 50 ohm input impedance. The unit for all dimensions is mm. The angular distance between the knots is fixed to π/k. It should be noted that a relatively large number of knots (up to twenty) ensures reasonable flexibility of the spline in terms of possible coupler shapes. In particular various standard shapes (e.g., rectangular [2] or cylindrical [5]) can be approximated with reasonable accuracy. The structure is implemented in CST Microwave Studio and simulated using its time domain solver [14]. The model consists of ~300,000 hexahedral mesh cells and its average evaluation time on a dual Intel Xeon E5540 machine with 64 GB RAM is 5 min.

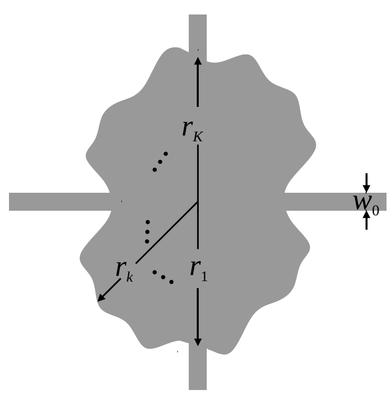


Fig. 1. Topology of the proposed spline-parameterized hybrid patch coupler.

3. Design Optimization

The design objective is to maximize bandwidth (BW) of the coupler—defined as power split imbalance (symmetrical w.r.t. f_0) below 0.5 dB—while maintaining low reflection and isolation at the centre frequency. Practical difficulties concerning design closure of the proposed coupler structure concern high complexity of the optimization problem and a large number of geometry parameters. Here, a sequential design optimization strategy is adopted to address both challenges. At the first stage, a simplified spline parameterization with eight control points is used. The starting point is determined based on the empirical formula for the centre frequency radial patch coupler [3]. Upon optimization (using trust-region gradient search [15]), the number of control points is increased, the design obtained in the previous iteration is re-interpolated and utilized a starting point for the next iteration. The process continues until reaching the assumed parameterization complexity (20 control points). Numerical experiments indicate that straightforward optimization at the maximum complexity leads to the design which is inferior compared to the one found with the aforementioned iterative approach.

4. Results and Comparisons

The initial design of the coupler (for 8 control points) is $\boldsymbol{x}_8$ = [5.17 5.17 5.17 5.17 6.8 6.8 6.8 6.8]^T. The final design is $\boldsymbol{x}_{20}^*$ = [5.91 6.3 5.75 5.04 4.41 4.26 4.57 5.2 6.78 6.69 7.72 7.72 7.09 6.38 6.3 6.3 6.7 6.54 6.54 7.64]^T. Frequency characteristics of the structure for selected numbers of control points are shown in Fig. 2. Performance figures obtained for the optimized structure including power split d_s at f_0, as well as power-split-error-based bandwidth (BW_1), and bandwidth defined for $|S_{11}|$ and $|S_{41}|$ below –10 dB (BW_2), both symmetrical w.r.t. f_0, are gathered in Table 1.

The coupler has been fabricated and measured. The photograph of the manufactured circuit is shown in Fig. 3, whereas comparison of its simulated and measured responses is given in Fig.

4. Discrepancies between the characteristics are due to utilization of a simplified coupler model, without the SMA connector, for the optimization. This contributes to increased losses, as well as the presence of a second resonance in the measured circuit. Notwithstanding, the agreement between the results is acceptable.

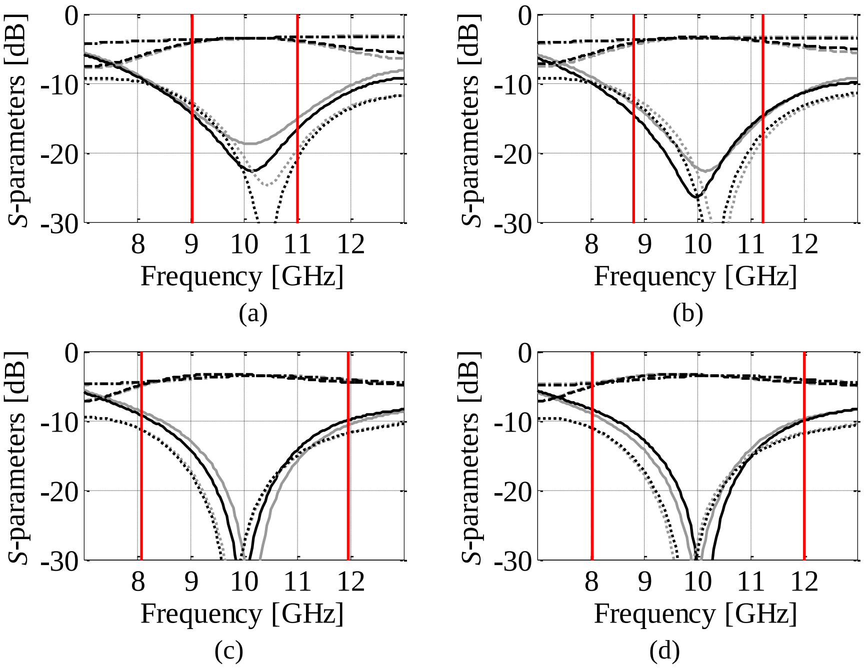


Fig. 2. Frequency characteristics $|S_{11}|$ (—), $|S_{21}|$ (– –), $|S_{31}|$ (····), and $|S_{41}|$ (–·–) of the bandwidth-enhanced patch coupler at the initial (gray) and optimized (black) designs. Plots shown are for parameterization with: (a) 8-control-point splines, (b) 12-control-point splines, (c) 16-control-point splines, (d) 20-control-point splines,

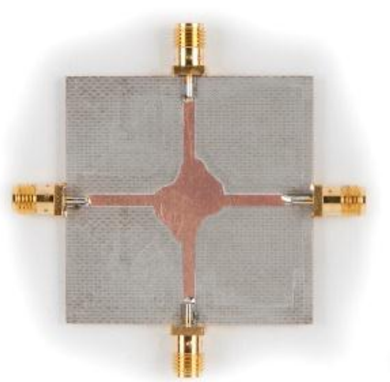
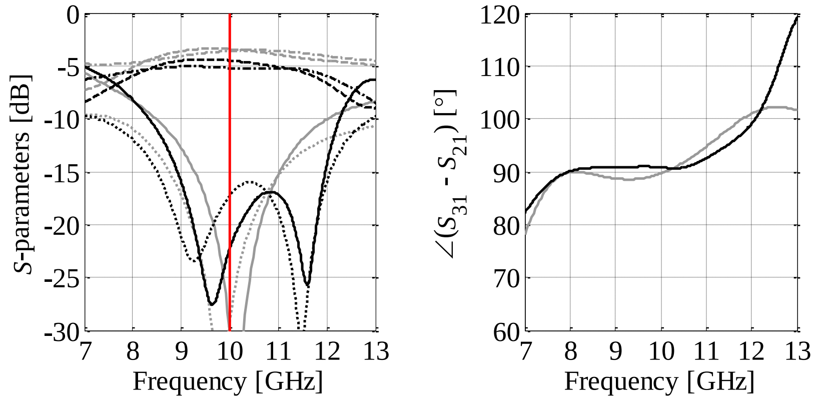


Fig. 3 Photograph of the fabricated coupler prototype.



a b

Fig. 4 Comparison of simulated (gray) and measured (black) frequency characteristics of the patch coupler prototype: (a) $|S_{11}|$ (—),$|S_{21}|$ (– –), $|S_{31}|$ (–·–), and $|S_{41}|$ (····), and (b) phase difference.

Table 1: Performance Figures of the Proposed Patch Coupler

Obtained w.r.t. f_0							
$\|S_{11}\|$ [dB]	$\|S_{21}\|$ [dB]	$\|S_{31}\|$ [dB]	$\|S_{41}\|$ [dB]	d_S [dB]	BW_1 [GHz]	BW_2 [GHz]	$\angle(S_{21} - S_{31})$ [°]
–30	–3.4	–3.6	–29	0.2	4.1	3.04	89.7

Table 2: Comparison with State-of-the-Art RRCs

Coupler	f_0 [GHz]	BW_N [%]	BW [GHz]	Size [mm × mm]	Size [λ_g^2]
[16]	30	11.2	3.36	8.1 × 9.6	1.46
[2]	4.0	36.7	1.47	36.0 × 44.1	0.61
[5]	3.5	38.2	1.34	18.0 × 24.4	0.12
[3]	10	35.5	3.55	12.0 × 12.0	0.31
This work	10	50.4	4.08	13.8 × 15.7	0.50

The proposed design has been compared to state-of-the-art patch couplers reported in the literature [2], [3], [5], [16]. Table 2 shows relevant figures for the benchmark structures in terms of their electrical performance and size. It should be noted that BW of PCs from the literature is normally defined without enforcing the symmetry condition around the centre frequency. Therefore, for the sake of fair comparison, the non-symmetrical bandwidth (BW_N) obtained for the design has been utilized. The results indicate that the proposed coupler (BW_N of 5.04 GHz) significantly outperforms the circuits for which the enhanced bandwidth has been achieved through manual (or semi-manual) modifications of geometry. At the same time, the structure has a competitive size and simple topology.

5. Conclusion

In this letter, a novel structure of a spline-parameterized hybrid patch coupler (PC) has been proposed. Introducing a large number of degrees of freedom allows for significant enhancement of the operational bandwidth (defined in terms of the frequency range for which the imbalance between the transmission and coupling is below 0.5 dB). Iterative optimization involving variable number of spline control points permits finding the optimum design featuring over 50% bandwidth competitive footprint. As demonstrated through comprehensive comparisons, the proposed coupler outperforms state-of-the-art PCs reported in the literature in terms of performance.

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