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DESIGN OF DUAL-BAND SLOTTED PATCH HYBRID COUPLERS BASED ON PSO ALGORITHM

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Abstract—A planar 3 dB patch hybrid coupler using cross and circular-shape slots is presented for a dual-band application. By inductively loading a pair of cross slots and four circular holes on a square patch, the matching and isolation performance of the miniaturized patch hybrid coupler is improved. In addition, the open-circuited shunt stubs are further installed at four ports to realize two operating bands. Since the slotted patch resonator cannot be characterized by the closed-form transmission line theory, the particle swarm optimization (PSO) algorithm is constructed and integrated with a full-wave solver to determine the variable parameters of the proposed structure. Finally, a prototype dual-band coupler operating at 915 MHz and 1575 MHz is designed and fabricated. Measured results show a good agreement with those obtained from simulation.

1. INTRODUCTION

As one of the most critical passive circuits, quadrature hybrid couplers are widely used in microwave mixers, amplifier circuits and antenna feeding networks. They provide 3 dB power assignments at two output ports with a 90° phase difference. In the modern communication systems, various characteristics such as broadband, compact size and multiband operation are in high demand for passive circuit design. For the traditional 3-dB branch-line coupler, it has poor performance at high operating frequencies due to the parasitic effects at the T- or cross-junctions and unwanted coupling among the adjacent low-impedance lines. To address this issue, patch hybrid coupler was

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proposed [1]. Recently, the different types of miniaturized patch hybrid couplers were proposed for the single- and dual-band applications [1–3]. By asymmetric loading cross slots on the patch [1] or using different etched shapes in the ground plane [2], the size of the single-band patch couplers can be effectively reduced without compromising the bandwidth. After optimizing the convex bounding around the periphery of the patch, a dual-band rectangular patch hybrid coupler was designed in [3]. Unfortunately, this kind of patch hybrid couplers cannot be characterized by the closed-form transmission line theory because of the complicated current distribution along the patch. Therefore, a number of variables have to be determined by the optimization algorithm.

In this paper, a planar 3-dB patch hybrid coupler is designed and optimized based on the concept of particle swarm optimization (PSO), which is a robust global search algorithm and derived from artificial life and evolutionary computation theory. PSO was initially proposed in 1995 [4] and has been widely used to solve general N-dimension, linear and nonlinear optimization problems. Compared with the Genetic algorithm (GA) used in [3, 5, 6], PSO is easier to carry out and has higher efficiency [7], because just velocity and position update formulas were used in a single-object optimal model, while selection, crossover and mutation operations were needed in GA, which make it more complicated. As shown in Fig. 1, the four circular holes are symmetrically etched on the cross-slotted patch resonator [1], in order to further improve the matching and isolation performance of the patch hybrid coupler. With the help of the four open-circuited

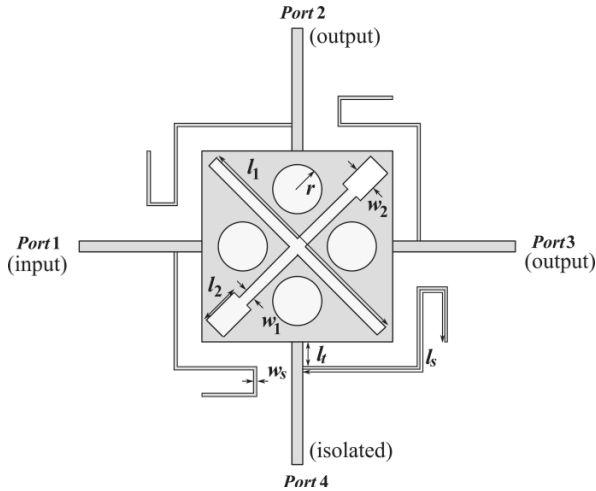


Figure 1. Configuration of the proposed dual-band coupler.

shunt stubs [8, 9], a dual-band hybrid patch coupler is then carried out, aiming to achieve two operating bands at UHF RFID band (915 MHz) and GPS band (1575 MHz) simultaneously. By following the design guidelines of the cross-slotted patch hybrid couplers [1] and dual-band branch-line couplers [9], the initial dimensions of the proposed physical topology are determined and then optimized by the PSO algorithm. The final results are verified by the experimental results of the fabricated prototype circuit.

2. PARTICLE SWARM OPTIMIZATION

Recently, PSO algorithm is proposed as a heuristic algorithm inspired by the choreography of a bird flock [4]. It has been widely used to solve general N-dimensional, linear and nonlinear optimization problems. PSO has the advantage of its algorithmic simplicity and robustness. PSO and Modified PSO have been used in electromagnetic community for different applications such as antenna array synthesis, antenna design and microwave passive components design [7, 10–20].

The fitness function (or target function) of PSO is defined as:

$$\min : F_{\text{fitness}} = \sum_n^{i=1} w_i \times F_i(\mathbf{x}_k) \quad (1)$$

where, n defines the number of objective functions, F_i and w_i indicate the i th objective function and its weight, respectively. For each fitness function, \mathbf{v}_k and \mathbf{x}_k denote the velocity and position vectors in the k th iteration, respectively.

The key point of this optimization algorithm is to update velocity and position iteratively as follows:

$$\mathbf{v}_{k+1} = c_0 \times \mathbf{v}_k + c_1 \times \text{rand} \times (p\text{best}_k - \mathbf{x}_k) + c_2 \times \text{rand} \times (g\text{best}_k - \mathbf{x}_k) \quad (2)$$

$$\mathbf{x}_{k+1} = \mathbf{x}_k + \mathbf{v}_{k+1} \quad (3)$$

where $p\text{best}_k$ is the best personal value, $g\text{best}_k$ is the global best value, c_0 is the inertia weight, c_1 , c_2 are the acceleration constants [10, 11].

The main steps of PSO are shown below:

Step 1. Initialize the particle positions (\mathbf{x}_k);

Step 2. Calculate the fitness functions (F) for each particle;

Step 3. Update the personal best value ($p\text{best}_k$) and global best value ($g\text{best}_k$);

Step 4. Update the velocity (\mathbf{v}_k) and position (\mathbf{x}_k) for each particle;

Step 5. Repeat step 2 to step 4 until the specified minimized fitness value is achieved.

In order to optimize the physical dimensions of the proposed coupler in this work, the initial four-port S -parameters of the coupler are at first obtained from a full wave simulator (HFSSTM) and then transferred to the aforementioned PSO iteration as the fitness function. The flow chart of this iterative procedure is shown in Fig. 2. After obtaining the pre-specified coupler performance, the final design parameters can be determined.

3. DUAL-BAND COUPLER DESIGN

The physical layout of the proposed dual-band coupler is shown in Fig. 1. To minimize the size of the square patch resonator, a pair of cross slots is asymmetrically loaded on the patch. The current flow path along the patch surface, which is shown in Fig. 3, is extended and bent by the slots, and the patch resonance is thus shifted to a lower frequency for the purpose of the size reduction [1]. However, the optimized dimension in [1] is obtained manually and it is very

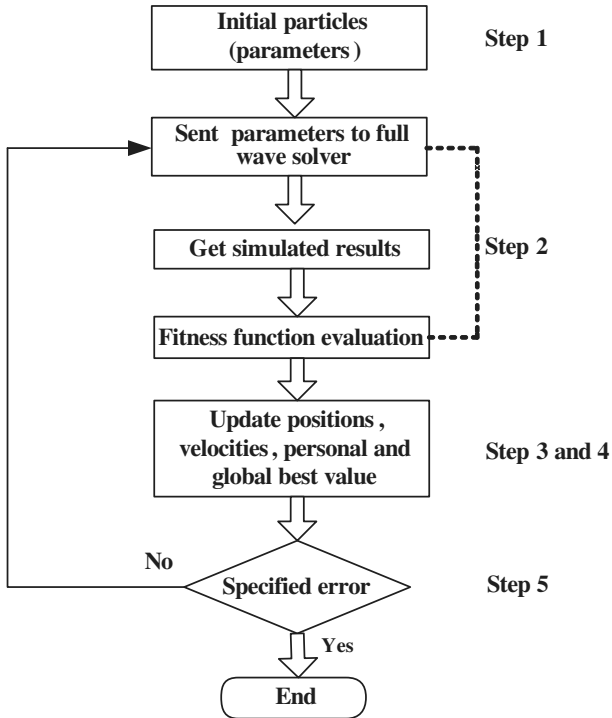


Figure 2. Flow chart of PSO integrated with full wave solver.

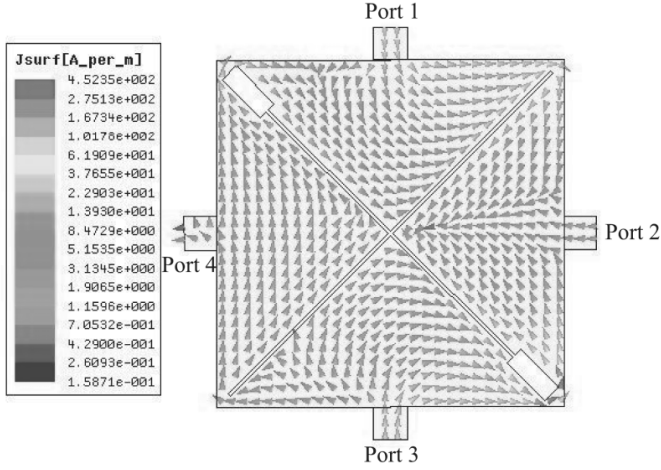


Figure 3. Current distribution for the patch coupler loading with cross slot.

time-consuming. By employing PSO, we can design the proposed coupler more efficiently. At the same time, the matching and isolation performance are also limited by the complicated current distribution along the patch. To circumvent this issue, four circular holes are further loaded on the patch symmetrically, which provide an additional degree of freedom for the performance adjustment. Since the most of the currents concentrate along the cross slots, as shown in Fig. 4, the center operating frequency of the coupler is only slightly affected by the additional circular holes. However, as mentioned in Section 1, there is no closed-form transmission line theory to characterize these loaded cross and circular holes. Hence, the PSO algorithm is employed here to reduce the rounds of the full wave simulation and find the optimized dimensions efficiently.

For the single-band coupler, the fitness function is defined as:

$$F = w_1 \times F_1 + w_2 \times F_2 \quad (4)$$

and

$$F_1 = |S_{21}(f_d)| - |S_{31}(f_d)| \quad (5)$$

$$F_2 = |S_{11}(f_d)| \quad (6)$$

where w_1 and w_2 were chosen as 0.6 and 0.4 respectively in our optimization; here f_d defines the desired frequency. According to the theory of hybrid coupler design, the ideal 3-dB hybrid has the following

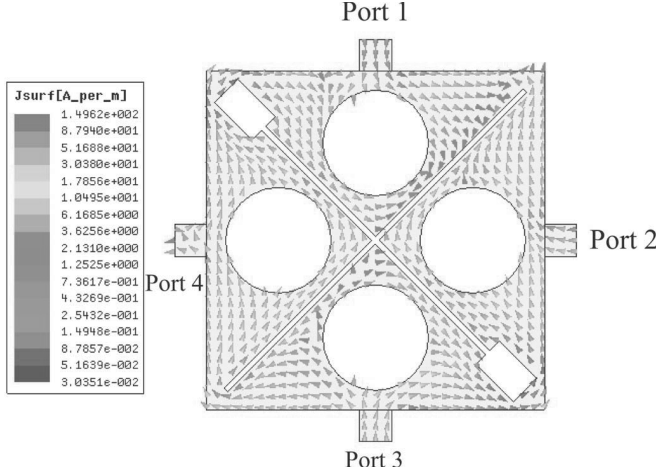


Figure 4. Current distribution for the patch coupler loading with cross slot and circular holes.

specifications:

$$|S_{21}| = |S_{31}| = 0.707 \quad (7)$$

$$|S_{11}| = |S_{41}| = 0. \quad (8)$$

For the single coupler design, the amplitude imbalance (F_1) defined in (5) plays a more important role than matching condition (F_2) defined in (6). Thus, w_1 is set to 0.6, which is slightly larger than w_2 with 0.4. On the other hand, we just need to optimize S_{11} rather than S_{11} and S_{41} at the same time, because S_{41} will also reach the minimum when S_{11} is minimized. In this design, $l_1 = 37$ mm and $w_1 = 1$ mm are chosen first based on the design guideline presented in [1]. By optimizing the positions and radius of the circular holes, the fitness function F is targeted to be smaller than 0.1. Fig. 5(a) shows the optimized S -parameters of the single-band coupler with four circular holes. As expected, both matching and isolation responses are improved by loading four circular holes, as shown in Fig. 5(b).

In order to validate the compatibility of PSO algorithm for the structure with more design parameters, the dual-band coupler with four shunt open stubs are further considered here. Different from the single-band case, a number of parameters have to be optimized in the two operating frequencies at the same time. In this case, the initial value $l_s = 33.6$ mm is chosen about quarter-wavelength based on the design equation reported in [9]. In this design, six dimensions (l_2 , w_2 , r , l_t , w_s and l_s) have to be optimized at two operating frequencies

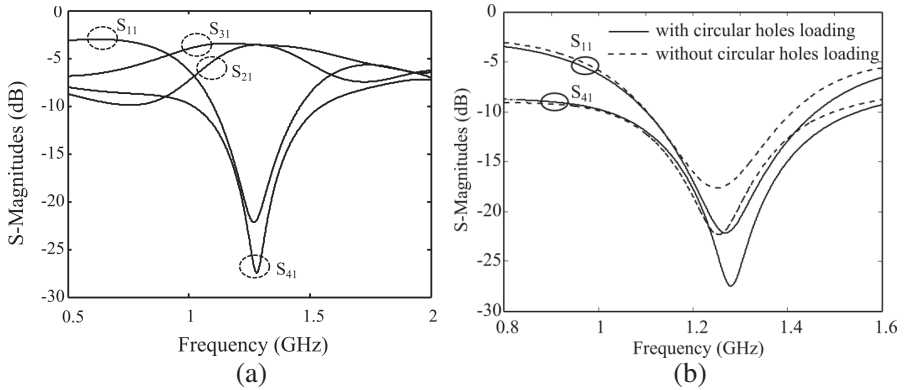


Figure 5. S -magnitudes of the optimized single-band coupler. (a) S -magnitudes. (b) Matching and isolation responses with and without circular holes.

915 MHz and 1.575 GHz simultaneously. The fitness function used is similar to the previous case and is defined as:

$$F = w_1 \times F_1 + w_2 \times F_2 \quad (9)$$

and

$$F_1 = (|S_{21}(f_{d1})| - |S_{31}(f_{d1})|) + (|S_{21}(f_{d2})| - |S_{31}(f_{d2})|) \quad (10)$$

$$F_2 = |S_{11}(f_{d1})| + |S_{11}(f_{d2})| \quad (11)$$

where $w_1 = 0.6$ and $w_2 = 0.4$; here f_{d1} defines the first desired frequency (915 MHz) and f_{d2} defines the second desired frequency (1.575 GHz).

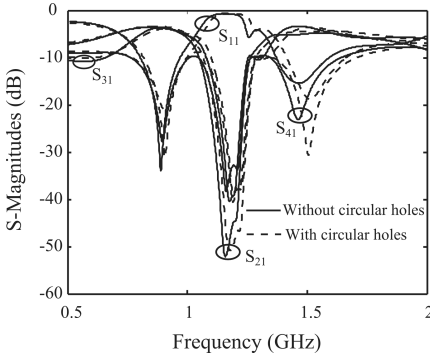
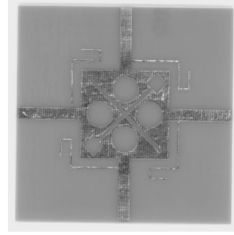
After optimization, the values of initial and optimized parameters are tabulated in Table 1. The optimized amplitude response at 915 MHz are $S_{11} = -24.78$ dB, $S_{21} = -3.91$ dB, $S_{31} = -3.56$ dB, $S_{41} = -20.13$ dB, while at 1.575 GHz, they are $S_{11} = -15.02$ dB, $S_{21} = -3.89$ dB, $S_{31} = -4.37$ dB, $S_{41} = -16.56$ dB. The phase difference at two output ports is 90.13° at 915 MHz, while it is 90.24° at 1.575 GHz.

Actually, the improved matching and isolation performance of the single-band coupler can effectively enhance the performance of the dual-band coupler. Fig. 6 shows the S -magnitudes of the dual-band coupler with and without four circular holes. In the first operating band, their responses are almost the same. However, in the second operating band with higher frequency, the matching and isolation performance can be effectively improved by installing four circular holes.

Table 1. Initial and optimized parameters for proposed coupler.

Variables in PSO	$\mathbf{x}(1)$	$\mathbf{x}(2)$	$\mathbf{x}(2)$
Parameters in couplers	l_2	w_2	r
Initial values	2 ~ 8 mm	2 ~ 8 mm	3 ~ 6 mm
Optimized value	5 mm	5.2 mm	4.6 mm
Variables in PSO	$\mathbf{x}(4)$	$\mathbf{x}(5)$	$\mathbf{x}(6)$
Parameters in couplers	l_t	l_s	w_s
Initial values	1 ~ 5 mm	33.6 mm	0.5 ~ 1.5 mm
Optimized value	3 mm	37.6 mm	0.7 mm

Substrate: FR4 with thickness of 1.6 mm, and permittivity of 4.2.

**Figure 6.** S -magnitudes of the proposed dual-band coupler with and without four circular holes.**Figure 7.** Photograph of the fabricated dual-band coupler.

4. FABRICATION AND MEASURED RESULTS

To verify the performance of our proposed dual-band coupler, an optimized prototype is finally fabricated and measured. The photograph of the fabricated coupler is shown in Fig. 7. Simulated and measured amplitude responses of the proposed coupler are shown in Fig. 8. A good agreement has been achieved between the simulated and measured results. In particular, the measured 1 dB amplitude imbalance achieves 17% bandwidth in the first band and 16.4% in the second band, while the measured phase differences are also within $\pm 5^\circ$ in these two bands, as shown in Figs. 9(a) and 9(b).

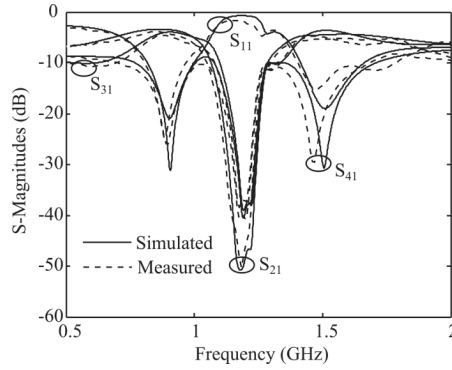


Figure 8. Simulated and measured S -magnitudes of the dual-band coupler.

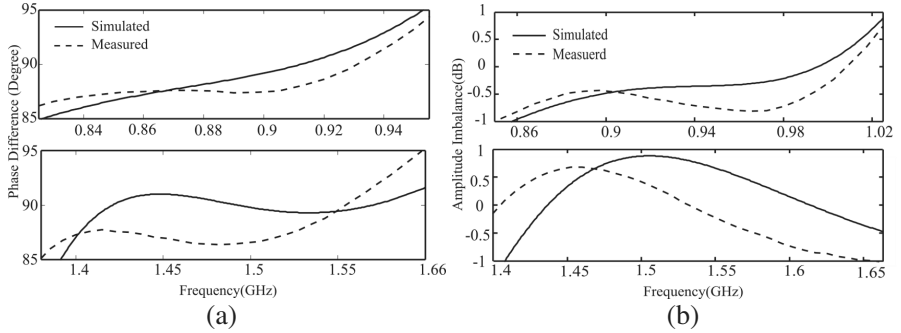


Figure 9. Simulated/measured phase difference and amplitude imbalance. (a) Phase difference. (b) Amplitude imbalance.

5. CONCLUSION

In this work, a dual-band patch coupler with cross and circular holes has been successfully designed and optimized at UHF RFID band and GPS band. After optimizing the fitness functions in the PSO algorithm, the variable parameters of the proposed coupler have been determined. Finally, the optimized coupler has been fabricated and verified experimentally.

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