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Microstrip Directional Coupler Design with High Performance Using Optimization based on Evolution Strategy

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Abstract - In this paper, the optimal design of a novel microstrip directional coupler with a grooved housing for high directivity characteristic is presented. It will be shown that the high directivity of the microstrip coupler can be achieved simply by attaching an optimized housing structure over the microstrip, which is much easier to fabricate than other conventional types. The dimensions of the proposed structure are maximized by using (1+1) evolution strategy (ES) combined with the deterministic algorithm. To improve the effectiveness of the results, efficient optimization procedures suitable for the model are proposed. From these results, it is determined that the proposed structure indicates an improved directivity. The optimized results are verified by full wave analysis at the center frequency of 850MHz.

Keywords: directional coupler, directivity, grooved housing

1. Introduction

Directional couplers with parallel microstrip coupled transmission line are widely employed for various RF and microwave applications because they can be easily incorporated into and implemented with other circuits. It is known that all parallel-line couplers, whether true TEM or not, have the odd- and even-mode property that always results in the even- and odd-mode characteristic impedances [1]. True TEM couplers yield equal phase velocities for each mode, whereas microstrip (quasi-TEM) and certain other structures yield the different phase velocities between odd- and even-mode. In particular, the microstrip directional couplers suffer from poor directivity due to the inhomogeneous dielectric characteristic. The directivity performance of the microstrip directional coupler worsens when the coupling is decreased or the dielectric permittivity is increased [2]. This is a reason for using the stripline configuration, which requires greater fabrication costs and efforts than a conventional microstrip.

To improve directivity characteristics, a re-entrant mode structure was used [3, 4]. Although the structure yields much higher directivity, additional efforts are needed to fabricate this type of directional coupler due to inserting a floating conductor plane into a typical microstrip structure. Another approach was to employ microstrip-ridge structures [5, 6]. Among several structures to be reported in ref. [5], even though being remarkably different from application frequency range, it is revealed that only those models having the additional conductive material on a typical microstrip structure were available to achieve the high directivity.

In this paper, we made several attempts to find a simple microstrip directional coupler structure with loose coupling factor by employing an optimization algorithm that can be applied to 2D finite element analysis. A simple microstrip structure with grooved housing is finally proposed for high directivity and loose coupling. It will be shown that a high directivity characteristic can be obtained easily by attaching an optimized housing structure above the microstrip structure. The dimensions of the proposed model are made most effective by using (1+1) evolution strategy (ES) combined with the deterministic algorithm [7 8]. The optimization problem is a multi-objective one of minimizing the difference of even- and odd-phase velocities with the restriction of maintaining 20dB coupling factor and 50[Ω] matching impedance. Because the problem is very complicated, an enhanced procedure for efficient optimization suitable for the problem is proposed. To extract the phase velocities and characteristic impedances for each mode, 2-D finite element analysis (FEA) is applied. From the optimization, the proposed coupler structure is determined to yield significantly improved directivity. The optimized result is verified by full wave analysis at the frequency of 850MHz and is compared to that of a conventional directional coupler with a rectangular housing. At this time, a simple microstrip directional coupler for measurement is being fabricated.

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2. Analysis Model and Problem Definition

Fig. 1 shows the cross sectional view of various types of microstrip directional coupler structures. From various simulation and optimization processes, it was revealed that there is limitation to achieving a high directivity characteristic just by modifying dielectric substrate, as also shown in [5]. Among the considered structures in Fig. 1, the ridge-type structure II in Fig. 1(c) reveals a superior directivity characteristic (about 10dB) than the others (maximally 5~8dB). Therefore, the ridge-type II is selected as a basic structure. In this paper, to improve the directivity characteristic, a groove-shaped housing structure, which is attached over the ridge-type II coupler, is proposed.

Fig. 2 indicates the cross sectional view of the proposed structure for realizing the directional coupler with high directivity characteristics. In Fig. 2, the dashed line (AA') signifies a magnetic wall or electric wall when even- or odd-mode excitations are applied to the coupled line of the structure. The half cross section of the structure in Fig. 2 is analyzed by using FEA and the line (AA') is treated as a Dirichlet or Neumann boundary condition with respect to the odd- and even-mode, respectively.

The effective microstrip permittivities for even- and odd modes are calculated as follows:

$$\varepsilon_{effe} = \frac{C_e}{C_{e1}} \tag{1}$$

$$\varepsilon_{effo} = \frac{C_o}{C_{o1}} \tag{2}$$

where C_e , C_o are even- and odd-mode capacitance respectively and the second subscript 1 refers to a free-space ('air').

In order to calculate the capacitance of the even- and odd-mode directional couplers, we firstly have to calculate the stored energy within the coupler using FE calculations [9], [10]. Regardless of the dielectric media involved, the stored energy is given by

$$W = \frac{1}{2}\int \varepsilon_0 \varepsilon_r \nabla u \cdot \nabla u \; dS \tag{3}$$

where ε_0 is the permittivity of free space, ε_r is relative permittivity, and u the electric scalar potential. By using the energy W, the capacitance can be calculated as

$$C = \frac{2W}{(\Delta u)^2} \tag{4}$$

where Δu means the potential difference between the two conductors.

The even- and odd-mode characteristic impedances Z_{0e}, Z_{0o} are then calculated by

$$Z_{0e} = (v_0\sqrt{C_e C_{e1}})^{-1} = \frac{\sqrt{\varepsilon_{effe}}}{v_0 C_e} \tag{5}$$

$$Z_{0o} = (v_0\sqrt{C_o C_{o1}})^{-1} = \frac{\sqrt{\varepsilon_{effo}}}{v_0 C_o} \tag{6}$$

where v_0 is the velocity in free space. From (5) and (6), coupling factor k can be calculated by (7) and characteristic impedance can be found by (8).

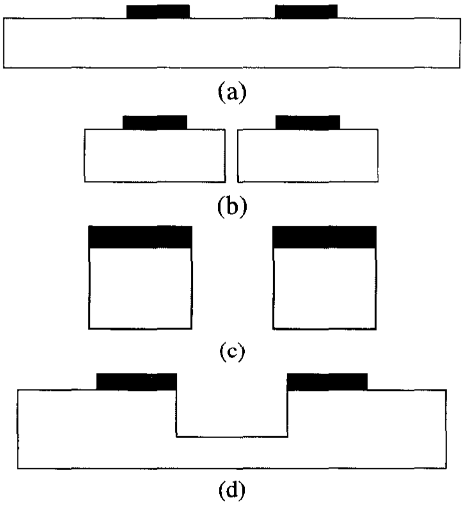

Fig. 1 Various types of directional coupler structures (a) general type (b) ridge-type I (c) ridge-type II (d) groove-type

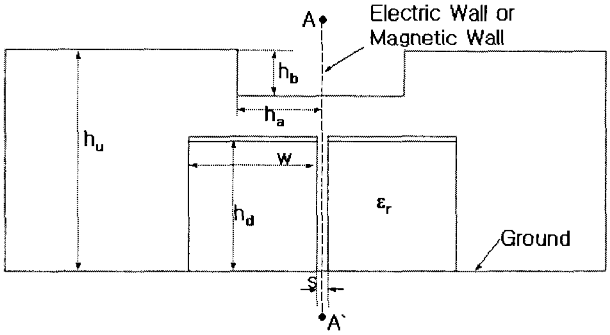

Fig. 2 Cross-sectional view of microstrip directional coupler with grooved housing.

$$k = \frac{Z_{oe} - Z_{oo}}{Z_{oe} + Z_{oo}} \tag{7}$$

$$Z_{oe}Z_{oo} = Z_o^2 \tag{8}$$

The main objective of this study is to obtain high directivity while maintaining the values of characteristic impedance Z_0 and coupling value K. Therefore, the optimal solution should satisfy the following three conditions.

$$\varepsilon_{eff_e} = \varepsilon_{eff_o} \tag{9}$$

$$K = -20 \log k = Const. \tag{10}$$

$$Z_0 = \sqrt{Z_{0e}Z_{0o}} = 50\,\Omega \tag{11}$$

3. Optimization Method

3.1 (1+1) Evolution Strategy (ES)

The (1+1) evolution strategy is employed as a focal optimization technique for directional coupler optimization.

In several stochastic methods, evolution strategy (ES) uses the principles of organic evolution as rules for the optimum seeking process. They rely on imitating the collective learning paradigm of natural populations based upon Darwin's observations and the modern synthetic theory of evolution. The evolution strategy is widely used because it can generate a global optimal solution, the algorithm is simple, and convergence speed is fast. The algorithm roughly consists of four parts – *reproduction*, *mutation*, *competition*, and *selection* [7, 8].

The (1+1) evolution strategy is a simple mutation-selection scheme referred to as two membered ES. The "population" consists of one parent only, determined by a certain parameter configuration, creating one descendant by means of adding a normally distributed random vector (mutation) to the parameter values. The "fitter" of both individuals, obtained by evaluating the objective function, serves as the ancestor of the following iteration (selection). The step width is adjusted periodically (e.g., after $10*n_p$ function calls, where n_p is the number of optimization parameters) in such a way that the ratio of successful mutations over all mutations becomes *p(pos)*. This strategy parameter is usually set to *p(pos)* = 0.2. In this paper, an annealing factor is set to be 0.85 and the shaking process is also considered to prevent a solution from converging to a local minimum.

3.2 Optimization Strategies

Because the optimization problem is a multi-objective one, we firstly defined an objective function, which is to be minimized, as

$$F_1 = \alpha_1 \left|\varepsilon_{eff_o} - \varepsilon_{eff_e}\right| + \alpha_2 \left|Z_0 - 50\right| + \alpha_3 \left|K - K_0\right|$$

where, α_1, α_2 ,α_3 are three suitable weighting factors and K_0 *is* a predetermined coupling value that should be satisfied. As a rule, the multi-objective problem makes it difficult to effectively find an optimum because the objective function is greatly wrinkled. When solving such kinds of problems, proper determination of the weighting factors is crucial. After some careful simulations, it was found that the last term of (12) was very sensitive with respect to design variables compared to the others and it proved very difficult to maintain the value as a constant. Therefore, in this paper, the last term is removed from the objective function and it is used as a constraint. Then, the problem is reduced to

$$F_2 = \alpha_1 \left|\varepsilon_{eff_o} - \varepsilon_{eff_e}\right| + \alpha_2 \left|Z_0 - 50\right| \quad \text{with } K_{0m} < K < K_{0M}$$

where K_{0m} and K_{0M} are minimum and maximum limits of the coupling value, respectively. The objective function that does not satisfy the constraint is set to be zero. It is proved, from the simulation, that the convergence characteristic is significantly improved after removing the coupling factor from the objective function.

By careful considerations given to the importance and value order of the two remained functions, two weighting factors α_1 and α_2 are determined. The values are set as 100 and 1, respectively.

In the process, however, there exists the setback that the optimal values are apt to converge near the C_{0M}. This is because the difference between odd- and even-mode effective permittivity is decreased when the value of K is increased. Therefore, following the ES optimization, a deterministic algorithm [11] is used to locate an optimal solution that minimizes value F_1 in Eq. (12) to achieve a given coupling value K_0.

4. Optimization Results

Five design variables are used for the optimization. Those are width of dielectric substrate (w), height of dielectric substrate (h_d), coupling gap distance (s), and dimensions of grooved housing structure (h_a, h_b), which are indicated in Fig. 1. The height of housing (h_u) is fixed as $1.7 \times h_d$ and the relative permittivity (ε_r) is given as 2.2.

Table 1 indicates the ranges of the design variables when the aimed coupling value K_0 is 20(dB). The ranges are determined by considering some results obtained from a random search of the entire available search space.

Table 2 presents the optimization results. From the table, it is discovered that all the generated results are sufficiently satisfactory.

Table 1 Range of design variables

Variable	w (mm)	h_d (mm)	s (mm)	h_a (mm)	h_b (mm)
Min.	0.5	0.8	0.1	0.5	0.1
Max.	2	1.2	0.4	1.2	0.5

Table 2 Optimization results

Parameters	Values
w (mm)	1.05
H_d (mm)	0.915
s (mm)	0.242
h_a (mm)	1.07
h_b (mm)	0.312
ε_{effo}	1.238587
ε_{effe}	1.238580
$\varepsilon_{effe} - \varepsilon_{effo}$	-7e-6
Z_0 (Ω)	49.974
K (dB)	19.5

Fig. 3 shows the effect of groove depth h_b on the variation of even- and odd mode effective permittivities around the optimal solution. From the figure, it can be known that the even-mode permittivity is more influenced by the groove depth of the housing. The difference of the decreasing rate causes the permittivities to be matched with each other. In addition, we can see from the figure that well-manufactured housing is important, because the directivity is highly sensitive to the dimension of the groove depth.

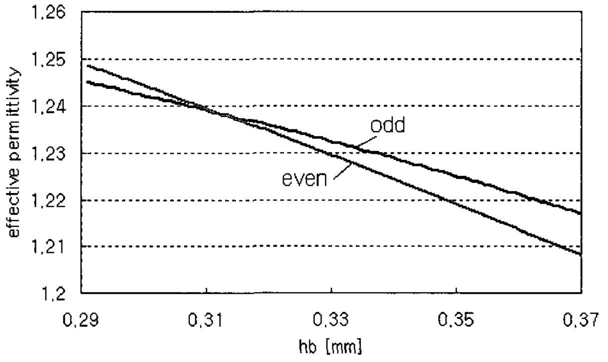

Fig. 3 Effect of groove depth h_b on the variation of even- and odd mode effective permittivities.

Fig. 4 shows the full-wave simulation result done by Ansoft-HFSS at the center frequency of 850MHz. The calculated directivity is above 30[dB]. In Table 3, the directivity of the optimized model is compared to that of a coupler optimized without housing. From the outcome, it can be concluded that the proposed structure yields enhanced directivity performance. However, because we place emphasis on the directivity, the coupling value of the model with housing obtained a 2dB higher value than the designed coupling one.

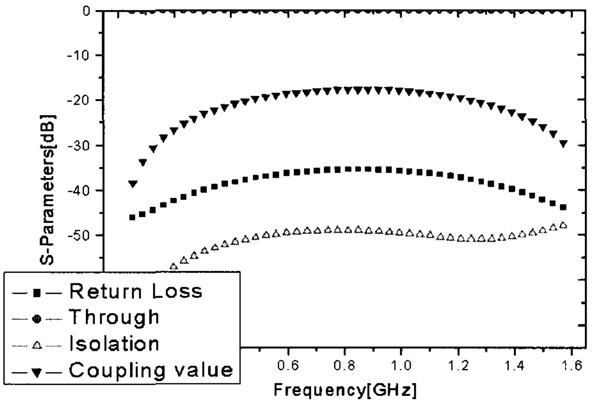

Fig. 4 Full-wave simulation result for the optimized 20dB coupler using Ansoft-HFSS.

Table 3 Comparison of directivity characteristic between models with and without housing

Housing	Groove	Typical
Coupling (dB)	18	22
Directivity (dB)	31	9
Return loss (dB)	35	35

5. Conclusion

In this paper, an optimal design of a novel microstrip directional coupler with grooved housing for high directivity characteristic was presented. By the optimization processes including some modification appropriate to the proposed model, optimal parameters were found to achieve the high directivity characteristic. Of course, we believe that the fabrication of the proposed structure requires a little more carefulness than conventional structures. The optimized results were verified by full wave analysis using Ansoft-HFSS and showed greatly improved directivity characteristic. It is expected that the optimization design procedures can be applied to microwave passive components of arbitrary shape with a quasi-TEM type of line in MMIC, RFIC, and MEMS process.

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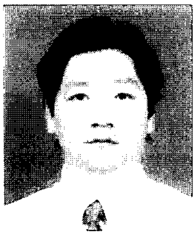

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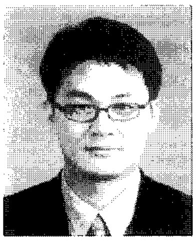

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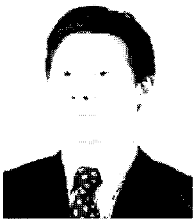

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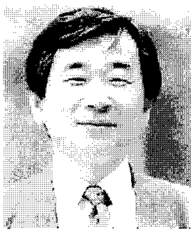

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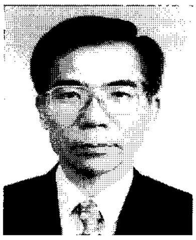

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