Optimization of Aperture Coupled Microstrip Patch Antennas

M. Dogan[1, 2], **G. K. Sendur**[2], **and F. Ustuner**[1]

[1]TUBITAK-UEKAE, Kocaeli, Turkey
[2]Sabanci University, Istanbul, Turkey

Abstract— Aperture coupled microstrip patch antennas (ACMPA) are special class of microstrip antennas with high gain and wide impedance bandwidth. These antennas differ from other microstrip antennas with their feeding structure of the radiating patch element. Input signal couples to the radiating patch through the aperture that exists on the ground plane of the microstrip feedline. These special antennas are multilayer stacked type of antennas with so many design variables that will affect the antenna performance. This paper presents the design and optimization procedure of ACMPA while taking care of all possible design variables and parameters to get the highest possible antenna gain and minimum VSWR.

1. INTRODUCTION

Microstrip antennas (MSA) are one of the most popular antenna types which were first produced by Deschamps [1]. Because of their low profile and conformal structure, they have been widely used in wireless, aerospace, vehicular and other areas where large antennas are not practical to use. Among several advantages in application, MSAs suffers from major drawbacks such as low gain and narrow impedance bandwidth. In 80s, Pozar [2, 3] invented the multilayer configuration which was named Aperture Coupled Microstrip Patch Antenna. This new microstrip antenna demonstrates improvement on the impedance bandwidth from 5% to 50% and 4–5 dBi gain enhancement. Due to their structural complexity, it is challenging job to get the expected gain and bandwidth improvements. Therefore a well planned optimization process needs to be performed to get the highest possible antenna gain while having minimum VSWR at the antenna input terminal.

A powerful optimizer is implemented with MATLAB optimization toolbox which runs HFSS and collects data via HFSS Script. In this paper, the optimization process is presented step by step from the initial settings of design parameters; variables, bounds on variables, constraint and objectives, to the final optimized results.

2. ANTENNA OPTIMIZATION SETUP

The optimization is performed for designing the ACMPA with highest possible gain and minimum VSWR, while keeping the gain above some lower limit (8 dBi), VSWR below the upper limit (1.5) without exceeding the maximum allowed antenna dimensions (10 cm $\times$ 10 cm $\times$ 2.5 cm).

Next step in optimization is separating the design parameters which are always constant during the optimization from the design variables that are going to be changed. There are several design parameters and variables of double layer ACMPA as shown in Figure 1. There are several factors that affect the performance of ACMPA such as length of tuning stub, patch dimensions, aperture length and width, relative location of the aperture w.r.t to the patch, shape of coupling aperture, antenna substrate properties, height of each stacked layers from the ground plane, reflector height, thickness of the metal layers on the dielectric materials. The more the number of variables, the slower the optimization process. Thus, we need to decrease the number of variables and set some variables constant and accept them as parameters.

In our ACMPA example, ROGERS 4003C is used as a dielectric material, so the relative dielectric permittivity ε_r (3.38), substrate height (0.81 mm), metal layer thickness (17 µm), tangential loss (0.0027) are all constant. Preliminary simulation demonstrates that reflector height should be around 8 mm, and the radiating patch needs to be placed 13.2 mm above the aperture plane. Impedance of the microstrip feedline should be 50-Ω, so the feedline width (1.78 mm) is constant. Effect of aperture width is negligible and it is fixed at 2 mm.

There are four geometric variables which are highly effective on antenna performance after setting up the optimization parameters. The stub length (L_s) is used to tune the excess reactance of the aperture coupled antenna. Antenna performance is very sensitive to the variations of stub length. The radiating patch length (L_p) determines the resonant frequency of the antenna and the width (W_p) affects the resonant resistance of the antenna. The wider patch results the lower resonant resistance. The aperture length (L_a) mainly determines the coupling level of the input signal to the radiating patch, so it has direct effect on the resonant resistance. As L_a increases, coupling of the input signal increases and as a result the resonant frequency increases. Upper bounds for all those variables come from the size of the surrounding metal cavity.

Constraints of the optimization and the main objective should be clearly defined before starting the optimization. According to the formal definition of the optimization problem, we need to maximize gain and minimize VSWR while the gain is above 8 dBi (1) and VSWR is below 1.5 (2). Multi-objective design is little bit tricky. The antenna gain is simply related with the patch area however VSWR depends on all four parameters, therefore we keep minimum VSWR as the only objective of the optimization (3). In (1), (2) and (3); $\vec{x}$ is the vector includes variables, $\vec{p}$ is parameter vector, f_i simulation frequencies and λ_i is the weighting coefficient.

$$-\text{Gain}\,(\vec{x},\,\vec{p},\,f_i) + 8.0 \le 0 \ \forall f_i \ \text{ such that } 2.2\,\text{GHz} \le f_i \le 2.4\,\text{GHz} \tag{1}$$

$$\text{VSWR}\,(\vec{x},\,\vec{p},\,f_i) - 1.5 \le 0 \ \forall f_i \ \text{ such that } 2.2\,\text{GHz} \le f_i \le 2.4\,\text{GHz} \tag{2}$$

$$\min\left\{J\,(\vec{x},\,\vec{p})\right\} = \min\left\{\sum\nolimits_{i=1}^{i=9} \lambda_i \left(\text{VSWR}\,(\vec{x},\,\vec{p},\,f_i) - 1\right)^2\right\} \ \text{ where } \sum\nolimits_i \lambda_i = 1 \tag{3}$$

Here, antenna optimization is done with MATLAB optimization toolbox instead of using other commercial EM Design tools. MATLAB runs the HFSS via scripts, takes the output data (VSWR, Gain) from the HFSS, processes them according to the formulas which are based on gradient based optimization, checks whether any constraint violation and finishes the optimization after couple of iterations and function evaluations. The advantage of this method is that during optimization,

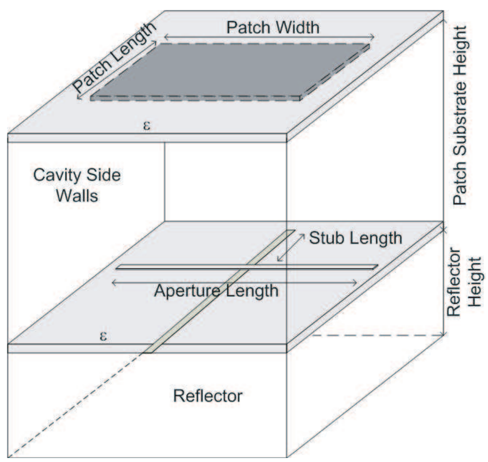

Figure 1: Double layer aperture coupled microstrip patch antenna embedded in a metal cavity.

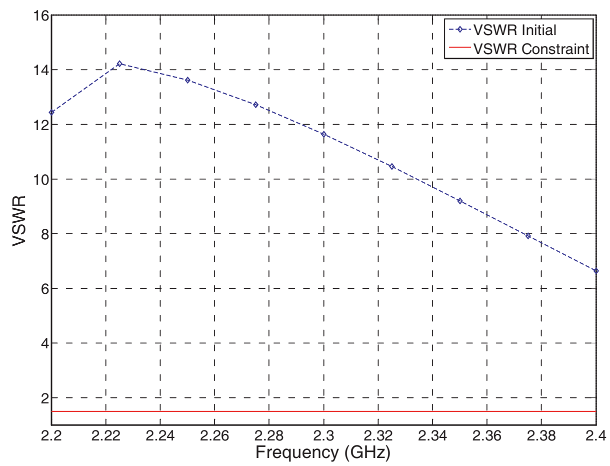

Figure 2: VSWR before optimization (1st trial).

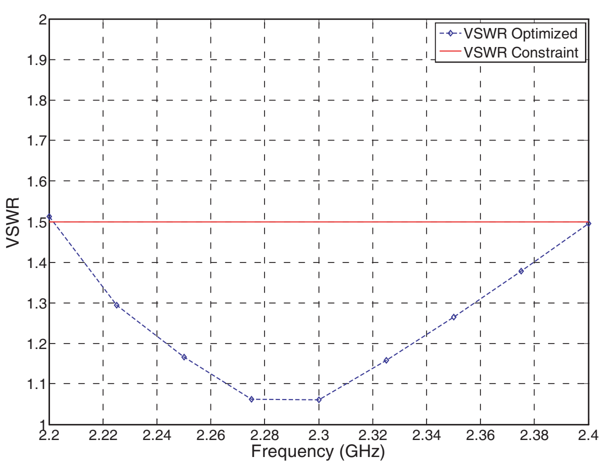

Figure 3: VSWR after optimization (1st trial).

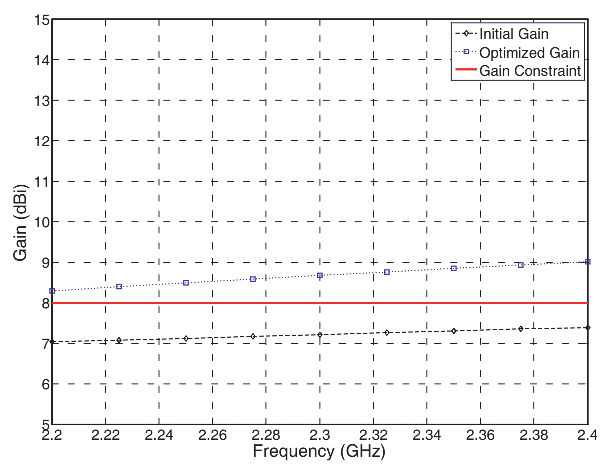

Figure 4: Antenna gain before and after the optimization (1st trial).

designer will able to see and control the optimization process. Additionally, MATLAB did not stop until user defined criteria are met which is not the case in other EM Design Tools.

3. OPTIMIZATION RESULT

Performance of the optimization is directly affected by the weighting coefficients. Initially, weighting coefficient at 2.3 GHz was maximum and gradually decreases as going to 2.2 and 2.4 GHz. This configuration worked pretty well in the neighborhood of the center frequency but VSWR exceeds 1.5 around the corner frequencies. Then all coefficients are equally weighted and the results get better.

In the first optimization trial, the lower and upper bounds of the design variables are relatively close. For instance, the lower bound of design variables is $\vec{x}_{lb}$: $[L_s\ L_a\ L_p\ W_p] = [1\ 2\ 2\ 2]$ and upper bound is $\vec{x}_{ub} = [45\ 90\ 90\ 90]$. The initial design vector is $\vec{x}_0 = [30\ 80\ 70\ 70]$. The initial value of the objective function $J(x, p)$ is 105.67 and the maximum constraint violation is 12.70. After 27 iteration and 218 function evaluations $J(x_{opt}, p) = 0.096$ and the maximum constraint violation is 0.0132 only at one frequency where the optimum design vector is $\vec{x}_{opt} = [19.6322\ 73.4904\ 40.4162\ 78.4580]$.

4. SENSITIVITY ANALYSIS

The next step in optimization is finding dependency of the design problem on the design variables at the optimum point. Ideally, the optimum design should not be so sensitive to the small variation on the optimal values. For this purpose, the sensitivity of the VSWR and the antenna gain to the all design variables at 2.3 GHz in the ±10% range of the optimal values are performed and depicted from Figure 5 to Figure 12. The rate of change of VSWR and the gain is close to zero in the close

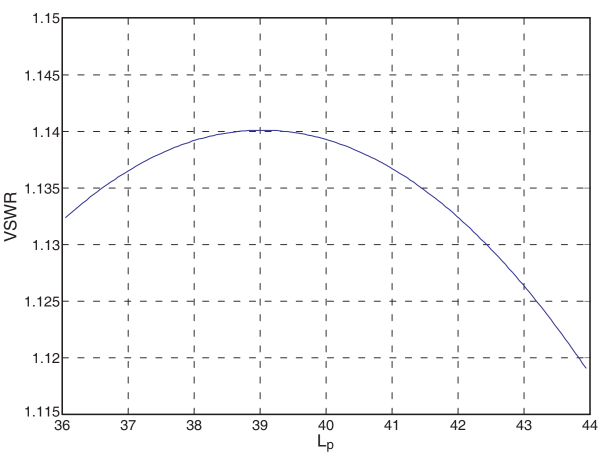

Figure 5: Sensitivity of VSWR to the patch length at 2.3 GHz.

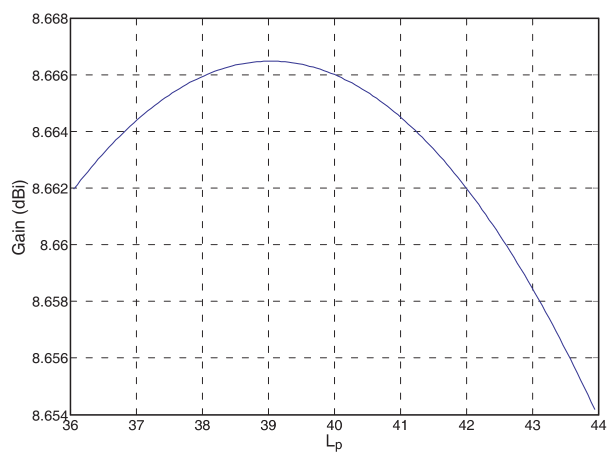

Figure 6: Sensitivity of gain to the patch length at 2.3 GHz.

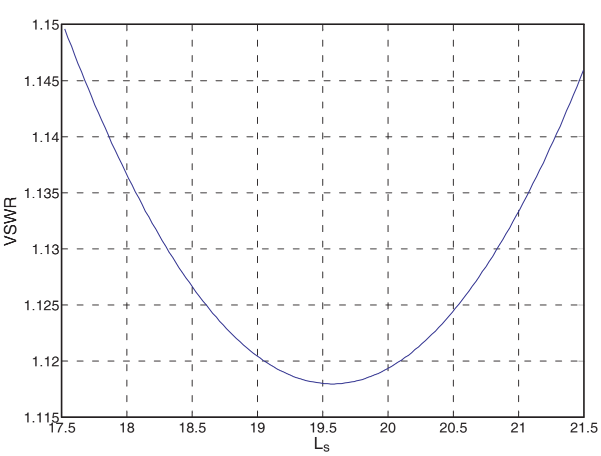

Figure 7: Sensitivity of VSWR to the stub length at 2.3 GHz.

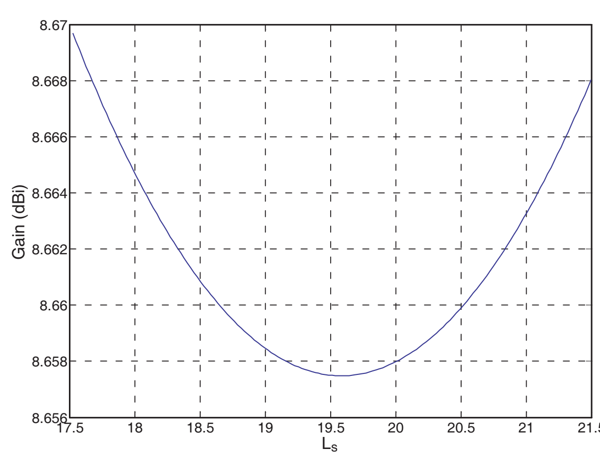

Figure 8: Sensitivity of gain to the stub length at 2.3 GHz.

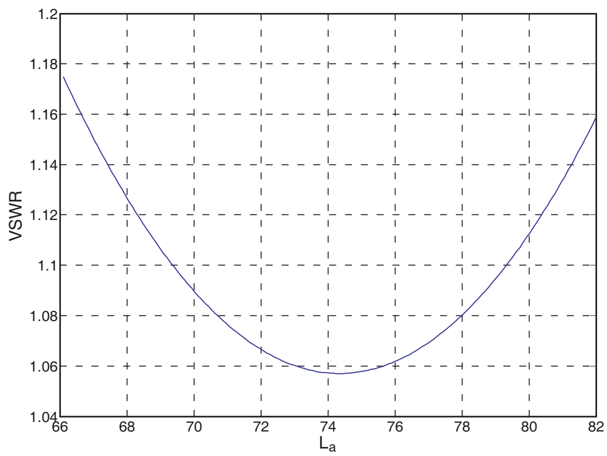

Figure 9: Sensitivity of VSWR to the aperture length at 2.3 GHz.

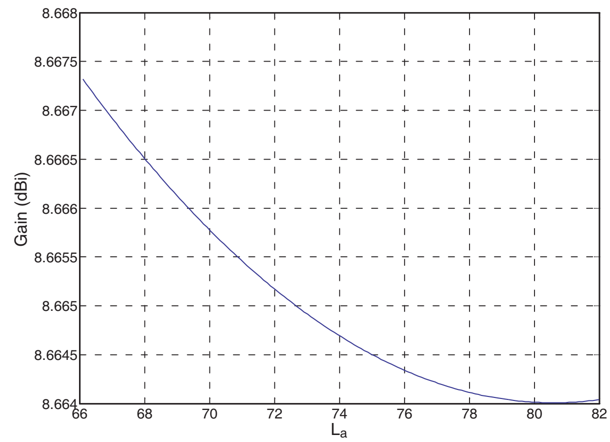

Figure 10: Sensitivity of gain to the aperture length at 2.3 GHz.

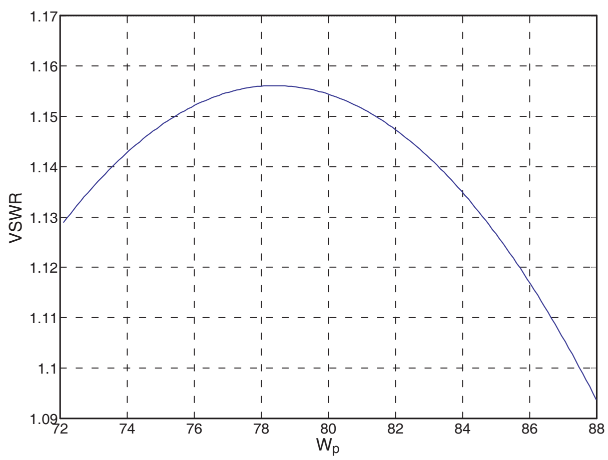

Figure 11: Sensitivity of VSWR to the patch width at 2.3 GHz.

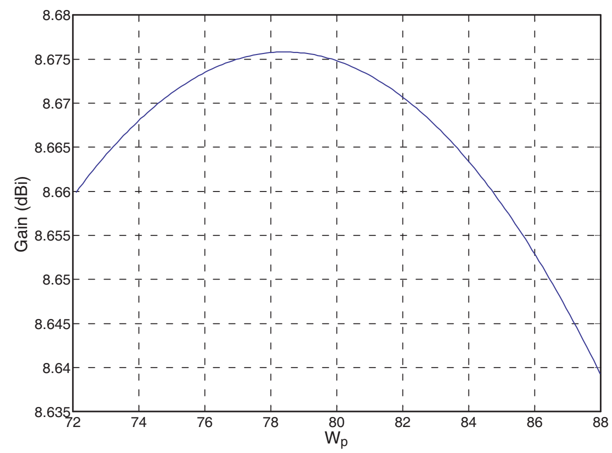

Figure 12: Sensitivity of gain to the patch width at 2.3 GHz.

proximity of the optimum values, so the optimal design is not sensitive to the variation on the final design vector which should be the case.

5. CONCLUSION

The optimization of the ACMPA is explained step by step with the details and then sensitivity analysis performed on the optimal design vector. The optimization process is developed and finalized after several trial and errors. During these trial and errors, the importance of the weighting coefficients, upper and lower bounds on the design variables are observed. The constraints and the objective should be well defined and powerful. Sensitivity analyses are performed to see the dependency of the optimal antenna performance around the neighborhood of the optimal design variables. Results depict that final design is stable at the optimal values.

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