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***Abstract*—The paper proposes a dual-port patch antenna for MIMO applications, optimized using surrogate-based optimization techniques. The antenna uses two resonant modes (TM_{100} and TM_{200}) to generate two independent radiation patterns. To enhance the bandwidth of TM_{200} mode, the patch ground plane was realized as a meshed surface. The proposed approach provides 97 MHz of bandwidth, while preserving a low profile of 1.5 mm between the patch and the groundplane (ε_r = 3.5). The numerical optimization involved 12 adjustable geometry parameters.**

I. Introduction

MIMO antenna systems are becoming more and more popular, increasing communication capacity of radio communication systems. Although initially, such systems relied on a number of individual antennas, the requirement for greater integration brought attention to more compact solutions [1-3]: a single antenna with multiple ports, where each port is able to create a different radiation pattern, hence supporting uncorrelated signals. Among those, multi-mode patch antennas were investigated in [3]. These structures involve multiple patches of various sizes, each operating in a different resonance mode (here TM_{100} and TM_{200}). Such antennas are simple and low profile, however higher resonance modes would produce narrower bandwidth, limiting antenna operability.

In this paper we propose a dual-mode patch antenna, which has been designed to increase the bandwidth of the TM_{200} mode. This was achieved by replacing a solid ground plane with a grid. To maximize the antenna performance, numerical optimization of the high-fidelity electromagnetic (EM) simulation model of the antenna structure implemented in CST Microwave Studio was conducted. Because of a large number of geometry parameters to be simultaneously adjusted and a high computational cost of the EM analysis, surrogate-based optimization techniques have been utilized involving, among others, a faster version of the EM model with reduced accuracy. The final design obtained at a reasonable CPU cost provides 97 MHz of bandwidth.

II. Antenna Description

The antenna operates at 5.6 GHz and consists of two patches (see Fig. 1), realized using three layers of Taconic™ RF-35 substrate (each layer being 1.5 mm high) and four metallization layers.

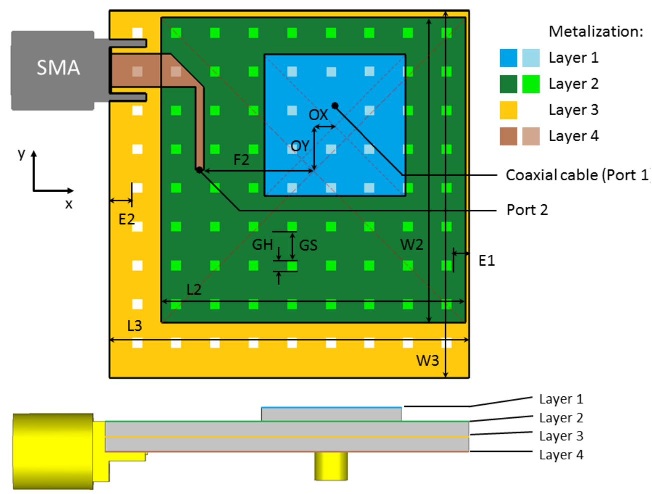


Fig. 1. The structure of the proposed antenna. All marked parameters have been utilized in the optimization process.

The top-most Layer 1 is a TM_{100} resonator, which is fed via a coaxial cable. Its dimensions are $W_1 = L_1 = 14.5$ mm, and the feed is located 2 mm from its center. Those dimensions are kept fixed throughout the optimization process.

The larger patch, operating at TM_{200} resonance mode, is located on Layer 2. It serves as a ground plane for the TM_{100} patch and is therefore kept as a solid conductor to ensure good isolation between the two modes. Its dimensions are W_2 and L_2. To simplify optimization, the larger patch is fed directly from a discrete port located at a distance F_2 from the center, between Layers 2 and 3. The port impedance is one of the optimization parameters Z_{in}. Parameters OX and OY describe the horizontal and vertical offset between the centers of the two patches, respectively.

The ground plane of the TM_{200} patch is realized on Layer 3 as a mesh, with square slots of the width GH, separated by a distance GS. This is to increase the bandwidth of the TM_{200} resonance and was subjected to the optimization process. The areas at distances E_1 and E_2 from the edges is solid, i.e. without slots.

The lowest Layer 4 accommodates the impedance transformer and the SMA connector. These components were not excited, as the larger patch was fed from the discrete port 2, located between Layers 2 and 3. However, they were utilized at a later stage of antenna's development and were included in the optimization, as their presence is expected to influence the radiation performance.

III. Optimization

The high-fidelity EM simulation antenna model $\boldsymbol{R}_f$ is implemented in CST MWS (time domain solver) with ~3,000,000 mesh cells. Its simulation time is about 90 minutes on an 8-core 2.1 GHz Intel Xeon CPU with 64GB RAM. The goal is to solve the following maximization problem

$$\boldsymbol{x} = \arg\max_{\boldsymbol{x}} BW(\boldsymbol{R}_f(\boldsymbol{x})) \qquad (1)$$

where $BW(\boldsymbol{R}_f(\boldsymbol{x}))$ is the antenna bandwidth, whereas $\boldsymbol{x}$ is a vector of geometry parameters as described in Section II. Because $\boldsymbol{R}_f$ is very expensive, the optimization process is conducted using its faster version, the low-fidelity model $\boldsymbol{R}_c$, which is the same as $\boldsymbol{R}_f$ but with relaxed convergence criteria (–15 dB accuracy instead of –35 dB for $\boldsymbol{R}_f$; simulation time 25 minutes). The low-fidelity model overestimates the bandwidth but it is well correlated with $\boldsymbol{R}_f$.

The optimization process has three stages:

1. Direct optimization of $\boldsymbol{R}_c$ to find its approximate optimum;
2. Surrogate-based optimization of $\boldsymbol{R}_f$ using local response surface approximation (RSA) models constructed from sampled $\boldsymbol{R}_c$ data and space mapping correction [4].
3. Design tuning through sequential approximate optimization of $\boldsymbol{R}_f$, also based on its local RSA models.

Stage 1 of the process gives a good initial design (pattern search [5] is utilized due to numerical noise contained in $\boldsymbol{R}_c$ and resulting from limited simulation accuracy). The RSA models utilized in Stages 2 and 3 are second-order polynomials (without mixed terms) established using star-distribution training set ($2n$ + 1 points with n being the number of design variables) [5]. Stage 1 required 200 evaluations of $\boldsymbol{R}_c$; Stage 2 required 5 iterations of setting up the RSA model and its optimization (cost: $25 \times \boldsymbol{R}_c$ and $1 \times \boldsymbol{R}_f$ per iteration); Stage 3 required 2 iterations (cost $25 \times \boldsymbol{R}_f$ per iteration). Thus, the total optimization cost was corresponding to about 140 evaluations of the high-fidelity EM model (~200 hours of CPU time).

IV. Results

The optimized antenna parameters are as follows: $L_2 = 31.2$ mm; $W_2 = 31.2$ mm; $L_3 = 36.9$ mm; $W_3 = 37.6$ mm; $E_1 = 1.7$ mm; $E_2 = 0.2$ mm; $GH = 1.2$ mm; $GS = 2.8$ mm; $OX = 2.2$ mm; $OY = 4.6$ mm; $F_1 = 11.7$ and $Z_{in} = 228\ \Omega$.

Figure 2 shows the reflection and transmission characteristics of the optimized antenna. It can be observed, that the TM_{200} mode has significantly higher quality factor than the TM_{100} one. Despite of this, the achieved bandwidths for both modes are comparable: 143 MHz for S_{11} and 100 MHz for S_{22}. Isolation is better than 19 dB within the entire band of interest.

Figure 3 shows radiation patterns for the both modes. Excitation at port 1 produces a unidirectional beam with realized gain of 7.2 dBi. Excitation at port 2 produces radiation directed sideway with maximum realized gain of 4.6 dBi.

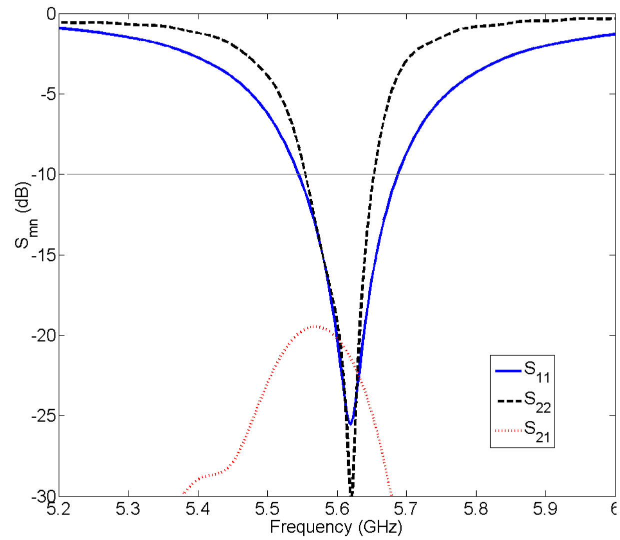
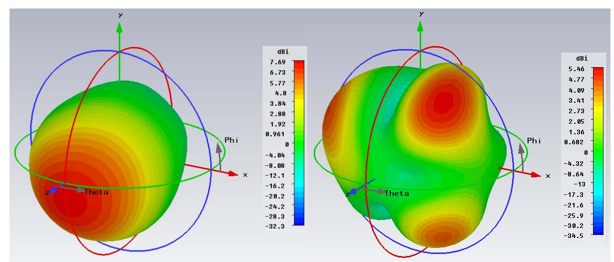


Fig. 2. Simulated reflection and transmission characteristics of the proposed antenna.



(a) (b)

Fig. 3. Simulated radiation patterns of the optimized antenna at 5.6 GHz: (a) port 1; (b) port 2.

Acknowledgement

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