Miniaturization of Rectangular Microstrip Patch Antenna Using Topology Optimized Metamaterial

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Abstract: A topology optimization method is proposed in this study to miniaturize a Rectangular Microstrip Patch Antenna (RMPA) operates at a frequency of 2.4 GHz using Metamaterials (MTMs) composed of complementary resonator. The metamaterial is placed in an intermediate layer between the patch and the ground, binary pixelation approach is used to build the structure of the complementary resonator and it is optimized using the Genetic Algorithm (GA). The conventional patch antenna and the proposed patch antenna are designed and simulated using High Frequency Electromagnetic Field Simulation (HFSS) software. A comparison between results of the two antennas is done. The area of the proposed patch antenna is reduced about 73.6\% compared with the conventional patch antenna, and the return loss is improved from -18 dB to -35 dB.

Keywords: patch antenna, metamaterial, genetic algorithm, return loss

Classification: Microwave and millimeter wave devices, circuits, and systems

References

1 Introduction

Microstrip patch antennas are widely used in wireless communication due to their distinct features like small size, light weight, compatible with planar and non-planar surfaces, simple and inexpensive to manufacturing using printed circuit technology, robust especially when mounted on rigid surfaces. In recent years, the demand for small size antennas operating at low frequencies is increased [1]. To obtain the specifications of microstrip antenna at low frequency with small size, different techniques have been adopted. Shorting posts [2] is one of these techniques, but it has a limitation in miniaturization extent [3].

Another technique is used to miniaturize the size of the patch antenna by using high permittivity dielectric substrate [4]. Although this method well miniaturizes patch antenna, but the high permittivity substrates lead to high cost and suffer from surface waves which degrade the radiation characteristics of the antenna by increasing the amount of side lobes significantly [5].

Another technique to miniaturization is performed by increasing the path of the current on the patch antenna; this technique includes slotting the patch [6], and iris structures [7]. Although these methods yield size reduction up to 30–50%, but these methods have some limitations such as low performance and manufacturing
complexity [8]. Therefore, in order to avoid these limitations, the researchers in the present time tend to use metamaterials to miniaturize the patch antenna and improve the performance. In order to reduce the size of patch antennas complementary split ring resonators (CSRRs) are etched on the ground plane [9, 10] for typically providing an average reduction of about 30% in the area. This method suffers from decreasing the front to back ratio, this problem is avoided by using an intermediate layer of MTM placed between the ground and the patch [8]. In this paper, a proposed square patch antenna operating at 2.4 GHz has been miniaturized using intermediate MTM layer located between ground and patch, which is designed by optimizing the topology of pixelated structure to operate as a complementary resonator.

2 Antenna design

The proposed patch antenna consists of two separate substrates where the metamaterial structure is placed in between, while a patch is placed on the surface of the top plane, and the ground is placed on the surface of the bottom plane. Fig. 1 shows the proposed antenna construction. The substrate F4BME has been used in this design, it is a Teflon woven glass fabric type, have a permittivity ($\varepsilon_r = 2.65$) and thickness (h=1mm).

The dimensions of conventional patch antenna are calculated using patch antenna formulas mentioned in references [11, 12] as below:

$$W_p = \frac{c_0}{2f_r} \sqrt{\frac{2}{\varepsilon_r + 1}}$$  \hspace{1cm} (1)

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[1 + 12 \frac{h}{W_p} \right]^{-0.5}$$  \hspace{1cm} (2)

$$\frac{\Delta L}{h} = 0.412 \frac{(\varepsilon_{eff} + 0.3)(\frac{W_p}{h} + 0.364)}{(\varepsilon_{eff} - 0.258)(\frac{W_p}{h} + 0.8)}$$  \hspace{1cm} (3)

$$L_p = \frac{C_0}{2f_r \sqrt{\varepsilon_{eff}}} - 2\Delta L$$  \hspace{1cm} (4)

Where $W_p$ is the patch antenna width, $C_0$ is the free space velocity, $f_r$ is the operating frequency, $\varepsilon_r$ is the dielectric constant of substrate, $\varepsilon_{eff}$ is the effective dielectric constant of patch antenna, $h$ is the thickness of substrate and $L_p$ is the patch antenna length. The width of ground ($W_g$) and the length of ground ($L_g$) are chosen three times of $W_p$ and $L_p$ respectively.

In this paper the conventional antenna has been designed at 2.4 GHz and the
feeding point is optimized using MATLAB and HFSS to obtain minimum return loss, while the miniaturized antenna is designed to have the half dimensions of the conventional antenna, the approach that has been used in this design is calculating the dimensions of miniaturized antenna for a frequency is a double of operating frequency using the same equations above. Therefore the miniaturized antenna is designed at 4.8 GHz and the operating frequency is shifted to the required frequency 2.4 GHz using the resonance effect of MTMs. This approach does not include the antenna feeding microstrip line, which is calculated for the required frequency. Fig. 2 shows the two types of antennas, while Table I. shows the dimensions of each antenna.

![Fig. 1. Proposed miniaturized patch antenna construction where the proposed MTM layer is placed between the square patch and ground.](image1)

![Fig. 2. Miniaturized and conventional patch antennas, (a) miniaturized, and (b) conventional.](image2)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Conventional PA1</th>
<th>Miniaturized PA2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground Length (LG)</td>
<td>109.7 mm</td>
<td>55.8 mm</td>
</tr>
<tr>
<td>Ground Width (WG)</td>
<td>133.7 mm</td>
<td>69.3 mm</td>
</tr>
<tr>
<td>Patch Length (LP)</td>
<td>36.6 mm</td>
<td>16.8 mm</td>
</tr>
<tr>
<td>Patch Width (WP)</td>
<td>44.5 mm</td>
<td>21 mm</td>
</tr>
<tr>
<td>Feeding Strip width (W)</td>
<td>2.75 mm</td>
<td>5.3 mm</td>
</tr>
<tr>
<td>Substrate thickness (T)</td>
<td>1 mm</td>
<td>2 mm</td>
</tr>
<tr>
<td>Total Area</td>
<td>14667 mm²</td>
<td>3867 mm²</td>
</tr>
</tbody>
</table>
3 Circuit Model

The equivalent circuit model of a patch antenna loaded with complementary resonator has been discussed in [13]. Equivalent circuit model of conventional patch antenna and patch antenna loaded with complementary resonator are presented in Fig.3, where $Z_L$, $Z_{L1}$, and $Z_{L2}$ represent the impedance of the transmission line, the parallel combination of $L_p$ and $C_p$ represent the conventional patch antenna resonator, and the parallel combination of $L_r$ and $C_r$ represent the proposed complementary resonator.

From the equivalent circuit models, there are two resonance frequencies of the patch resonator and the complementary resonator can be identified respectively as follows:

$$f_p = \frac{1}{2\pi\sqrt{L_p C_p}} \quad (5)$$

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \quad (6)$$

The resonance frequency of patch antenna $f_p$ depending on the dimensions of the patch which are calculated using equations (1-4), when the dimensions are miniaturized the resonance frequency $f_p$ will be higher than the required frequency, but when the miniaturized patch antenna is loaded with complimentary resonator, it can resonate at the resonance frequency of complementary resonator $f_r$ also. Using topology optimization for the structure of proposed complementary resonator; the resonance frequency $f_r$ can make it equal to the required frequency. Simply it is the way to miniaturized patch antenna using a metamaterial composed of complementary resonator.

![Fig. 3. Equivalent circuits of (a) conventional patch antenna, (b) patch antenna loaded with complementary resonator [13].](image-url)
4 Metamaterial design
The proposed metamaterial layer consists of a thin copper layer (0.08 mm) with dimensions of (2LP * 2WP) and four square cells located within the central area with dimensions of (LP * WP), where each cell consists of (4 x 4) square pixels and it is represented in optimization algorithm using two dimensional binary array (4 x 4), each of these pixels is either to have one or zero value according to optimization process. One of the four cells is generated by the optimizer and the other three cells have been generated by flipping the first cell horizontally and vertically around the X and Y axes. The layout of four cells is etched through the intermediate copper layer to create the MTM. Fig. 4 shows the MTM layer construction.

4 Methodology of simulation and optimization
MATLAB and HFSS software have been used to implement the simulation and optimization system. A genetic algorithm is used for optimization, the population is selected to 30 and the stop condition is either to get the minimum reflection coefficient scattering parameter $S_{11}$(dB) or complete the numbers of iterations of generation, where it is selected to 20 iterations. The topology of MTM layer is optimized and the goal of optimization is to get the minimum of $S_{11}$(dB) at the frequency of 2.4 GHz to ensure obtaining the resonance in the complementary resonator at the required frequency. By this way, the design of MTM and patch antenna has been completed. Fig. 5 shows the block diagram of simulation and optimization methodology, and it can be seen the array of MTM before and after optimization. Fig. 4b shows the optimized MTM. The solution which is obtained at the end of optimization is one of many other solutions can be obtained. It can obtain a different solution for each new optimization algorithm execution.

![Fig. 4. Proposed MTM construction (a) before optimization, (b) after optimization.](image)
5 Results and Discussion

Fig 6, Fig. 7, and Fig. 8 show the HFSS simulation results of the conventional and proposed miniaturized antennas, while Table II. shows the comparison between their results. The proposed antenna has saved about 73.6% of total area of the conventional antenna and improved return loss about 18dB at a frequency of 2.4GHz but the gain and 10dB bandwidth have reduced about 1.2dB and 39% respectively. A typical impedance match antenna specification is VSWR ≤ 2, corresponding to reflection coefficient $|\Gamma| \leq 0.333$ and return loss $RL \geq 9.5dB$ [12], it is the reason to calculate the bandwidth of antenna at 10dB return loss. The results are acceptable compared with the obtained area saving, and it is better than the results given in [3, 8].

The miniaturized patch antenna has been implemented using two layers of (F4BME) substrate with 1 mm thickness and dielectric constant of 2.65, and the fabrication process has been done using PCB milling CNC machine, Fig. (9) shows the fabricated antenna. $S_{11}(dB)$ of the implemented antenna has been measured using Keysight N9916A vector network analyzer; where the obtained experimental results are almost similar to the simulated results. Fig. (10) shows the measured $S_{11}(dB)$ of implemented antenna, and Table III. shows a comparison between the results of the simulated antenna and implemented antenna which shows the fabrication error effect.

**Fig. 5.** Block diagram of the design methodology.
Fig. 6. $S_{11}$(dB) (return loss) of the conventional and miniaturized antennas

Fig. 7. Radiation pattern of conventional and miniaturized antennas

Fig. 8. 3D polar plot gain of the conventional and miniaturized antennas
6 Conclusion

An effective method to miniaturize square patch antenna is presented in this paper. In this method a square patch antenna operates at 2.4 GHz has been miniaturized using a horizontal MTM layer placed between the ground layer and patch layer which is designed using topology optimization. The results indicate that the proposed method can miniaturize the area of square patch antenna to a quarter of the conventional patch antenna area with a little and acceptable deterioration in the antenna performances comparing to the big amount of miniaturization.

![Implemented patch antenna](image)

**Fig. 9.** Implemented patch antenna, (a) Patch layer, (b) MTM layer, (c) Ground layer, (d) and (e) Front and back view of completed antenna respectively.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Conventional PA1</th>
<th>Miniaturized PA2</th>
<th>Amount of Change</th>
<th>Amount of Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Area</td>
<td>14667 mm²</td>
<td>3867 mm²</td>
<td>-73.6%</td>
<td>73.6%</td>
</tr>
<tr>
<td>Return Loss (maximum)</td>
<td>-18 dB</td>
<td>-35 dB</td>
<td>-17 dB</td>
<td>17 dB</td>
</tr>
<tr>
<td>Bandwidth 10dB (VSWR = 2:1)</td>
<td>33 MHz</td>
<td>20 MHz</td>
<td>-13 MHz</td>
<td>-39%</td>
</tr>
<tr>
<td>Antenna Gain</td>
<td>5.2 dBi</td>
<td>4 dBi</td>
<td>-1.2 dB</td>
<td>-1.2 dB</td>
</tr>
</tbody>
</table>
Fig. 10. Measured $S_{11}$ (dB) (return loss) of implemented antenna (inverted image of the Keysight VNA screen shot).

Table III. Comparison between the results of simulated and implemented antennas.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Simulated PA</th>
<th>Implemented PA</th>
<th>Fabrication Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center Frequency</td>
<td>2.4GHz</td>
<td>2.408GHz</td>
<td>8MHz</td>
</tr>
<tr>
<td>Return loss (maximum)</td>
<td>-35dB</td>
<td>-35dB</td>
<td>0dB</td>
</tr>
<tr>
<td>Bandwidth 10dB (VSWR= 2:1)</td>
<td>20MHz</td>
<td>20MHz</td>
<td>0MHz</td>
</tr>
</tbody>
</table>