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Artificial intelligence using Nelder-Mead algorithm- based design and performance optimization of microstrip patch antenna

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ABSTRACT

Artificial intelligence systems are one of the important machines in performing operations that are difficult to perform traditionally. Optimization is one of the difficult and delicate processes that AI can be used to accomplish, especially if the optimizations are too small for antennas like microstrip patch antenna. A Microstrip patch antenna is considered one of the most widely used antennas that vary from lightweight wireless devices to airplanes and airspaces applications. One of the most attractive points about those antennas is their lightweight, small size, and ease of fabrication process. Although this antenna has many advantages, it suffers from some drawbacks like low gain and limited bandwidth. In this paper, we are presenting an optimization process by using the Nelder-Mead algorithm to achieve a new design of patch antenna that offers a broader bandwidth and higher gain. This design is achieved by optimizing the dimensions of the width and the frequency of the antenna. The results show that this device is responding perfectly at 1.471GHz and the ranges of substrate dimensions and relative permittivity affect the device performance and behavior.

Keywords: Nelder-Mead Algorithm, AI, Optimization, Patch antenna, Finite Element Analysis.

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1. Introduction

The Nelder–Mead approach is a widely applied computational method of finding the minimum or maximum optimization problem in a multidimensional space[1]. It is indeed an existing optimization approach (relying on a method comparative analysis) and is mostly used for nonlinear optimization algorithms by which derivative would not be recognized [2]. Optimization consists of locating the ranges of real functions that describe the current state of the device in this case to obtain the best potential approximation of antenna gain for such a given frequency[3]. One of the concepts of optimization is that it is a mathematical discipline wherein humans seek to locate a minimal or optimum of the function f(x) (also named objective function or aim function) in a specified plurality X [4]. The optimal solution is the n-dimensional real function of the real variables labeled with f (x1, ..., xn)[4, 3]. Plurality indicates the field wherein the strategies can be sought that is considered right, probably physically feasible [5]. In this scenario, that is also form optimization, which involves adjusting vector parameters-mostly geometric measurements in order to obtain the maximal status of the tracked parameters. One of the main advantages of optimization is to find the optimum geometry for various applications such as the application of antennas. Antenna systems have been utilized in a variety of applications such as remote sensing and surveillance. Therefore, remote sensing techniques using antenna became interesting to many researchers[6]. The antenna plays an important and sensitive place in UWB radar systems. That is one of the fundamental specifications of the transmitter and receiver chains. The antennas that send and receive waves. The recent component is designed to irradiate and receive a wave that carries the data to be processed[6].

Microstrip antennas are fabricated on a printed circuit board (PCB), (Figure 1). This kind of antennas is based on thin dielectric substrates that have a ground plane on one side and a small metallic patch on the other PCB side [7]. Figure 1 shows the standard configuration for a rectangular patch antenna that has a microstrip line to feed the media. The primary beam of the radiation pattern of the antenna is usually reasonable to the PCB circuit, and its polarization can be modified to be linear or circular. The dimensions of the PCB and the patch are mainly decided by the antenna operating wavelength while the shape of the patch decides the other antenna characteristics like the radiation pattern and polarization [7-10]. For a standard microstrip antenna with a rectangular patch, the dimensions are recommended to be between λ/3 - λ\2 [11, 12]. Microstrip antenna suffers from limited bandwidth and low efficiency, but this can be enhanced and improved by increasing the substrate domain thicknesses[13-15]. On the other hand, increasing the thickness gives rise to surface waves which can reduce the efficiency by consuming the power through surface waves. The optimization problem includes multiple variables optimization which is chosen in this paper to be the antenna directivity. The antenna is designed for security applications, and the limited bandwidth is considered a desirable feature for the antenna while keeping the radiation in only the desired direction is a crucial factor in limiting the number of receivers [16-18]. While it is technically possible to describe exceedingly complex optimization problems, it is often not able to discover a solution that will solve the problem fully. If we plan to use optimizing procedures that are applied in software packages, the option is much more constrained. In this study, we have used an optimization process, that includes the COMSOL optimization module.

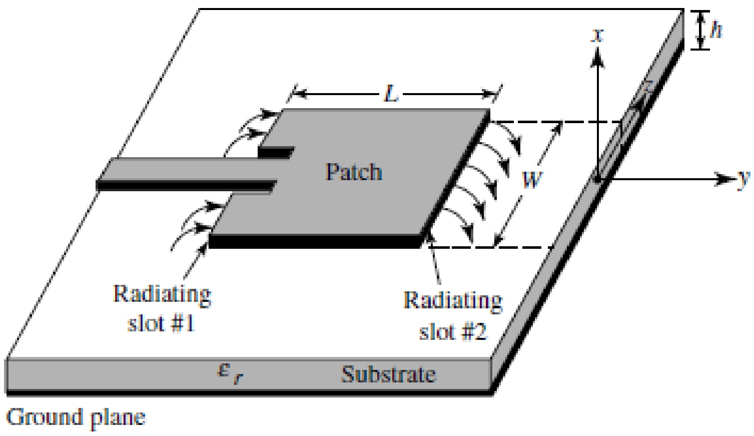

Figure 1. Regular microstrip patch antenna

2. Nelder mead algorithm

A the Nelder Mead algorithm is a metaheuristic optimizations tool that would correlate to the nonstationary point on matters that could overcome by alternatives techniques [19]. The approach utilizes the definition for simplexes, specific polytopes of n+1 vertexes in n-dimensions [20]. Instances of simplicity included the row section on the line, a plane triangular, a three-dimensional space tetrahedron, and so on. The approach estimates the optimal solution dilemma with n variables is when the optimization model differs easily and is modeled. Standard implementations decrease variables, and we optimize f(x)by reducing −f(x). We opt to minimize the function f(x), where x ∈ Rn. Our test points are as (x1,…, xn+1).

Many steps are required to solve the Nelder-Mead algorithm as follow:

1. Order depending on the values of the vertices:
$f(x_1) \leq f(x_2) \leq \cdots . \leq f(x_{n+1})$
2. The second step is calculating x_o, the center for the point except for x $_{n+1}$
3. Reflections
By computing the reflected points $x_r = x_o + \alpha\,(x_o - x_{n+1})$ note that $\alpha > 0$. When the reflected points are best as the second point worse, hence, worst as the best, $f(x_1) \leq f(x_r) < f(x_1)$, later on, find a newer simplex by changing the not better points (x_{n+1}) by the mirror points (x_r) then return step1.
4. Expansions
When the reflected points are away far the best point, $f(x_r) < f(x_1)$, after that we should be computing the expanded points $(x_e = x_o + \gamma\,(x_r - x_o))$, $\gamma > 0$. Also, if the expand points are way good as the returned point, $f(x_e) < f(x_r)$, then find a newer simplex by changing the not better points x_{n+1} by the expand points

(x_e) then return step1. If not, find the new simplex by switching the not best point $x_{n+1}$by the back points x_r and return step 1.

5. Contractions
Sure that the relation, $f(x_r) \geq f(x_n)$. Note that the value x_n is second to the highest. Computing contract points $(x_c = x_o + \rho\ (x_{n+1} - x_o))$ by $(0 < \rho \leq 0.5)$ .. when the contracted points are better as the not better point. $f(x_c) < f(x_{n+1})$, that find a newer simplex by switching not better points (x_{n+1}) by a contract point x_c then return step1;

6. Shrinking.
Change all the points but the most better (x_1) by $(x_i = x_1 + \sigma\ (x_i - x_1))$ then return to step1. Worth noting: γ, α, σ, and ρ denoted the expansion, reflection, shrink coefficients, and contraction, respectively. The standard values of them are as follow: γ = 2, α = 1, σ = 0.5, ρ = 0.5. Since the simplex x_{n+1}represents the vertex with a high associated value between vertex, an exception can be done for finding the lowest value at x_{n+1} in the other side which formed by each vertex $x_i$except x_{n+1} [13].

3. Method

We will continue as follows to refine the measurements of the patch antenna. In order to allow the best possible transmission of waves from cable to antenna, we have changed the scale of the power port using the S11 parameters. Due to the heavy requirements on processing power, one frequency 5.6GHz-identified as f x-first performs its optimization. After receiving a general description of the optimization feature, we measured the frequency spectrum from f min to f max. Basic dimensional optimization variance is dependent on[5]. The initial simplex is very significant. A very relatively small simplex can contribute to an objective function, so the NM could get stuck more easily. Thus, the simplex must rely heavily on the scope of the issue. The main study, however, proposed a simplex in which an initial point is granted as x 1 and all the others produced by a specified phase on each aspect in turn. The approach is also susceptible to the scale of variables that influence x. Criteria are required to interrupt the loop of iteration. Nelder-Mead has used a standard deviation sample of the existing simplex function values. If these drops below any threshold, the loop is interrupted and the deepest point throughout the simplex is returned to the suggested optimum. Notice that a very flat function will get an almost identical cost function throughout a wide domain, such that the solution is adaptive to tolerance. As an antenna, it is affected by changing the properties of its materials as well as the dimensions have a significant impact on the response of the antenna as well as the antenna's performance. So, we decided to change the relative permittivity of the device as well as the height of the substrate. The decision of the value of these two variables is taken through an arbitrary range, which is consistent with the literature.

Table 1. Test model specifications

	Model
Substrate thickness	0.001524 m
Patch width	0.053 m
Patch length	0.052 m
Tuning stub width	0.007 m
Substrate width	0.016 m
Substrate length	0.1 m
Dielectric constant	0.1 m
50-ohm line width	0.0032
Relative permittivity	0.5

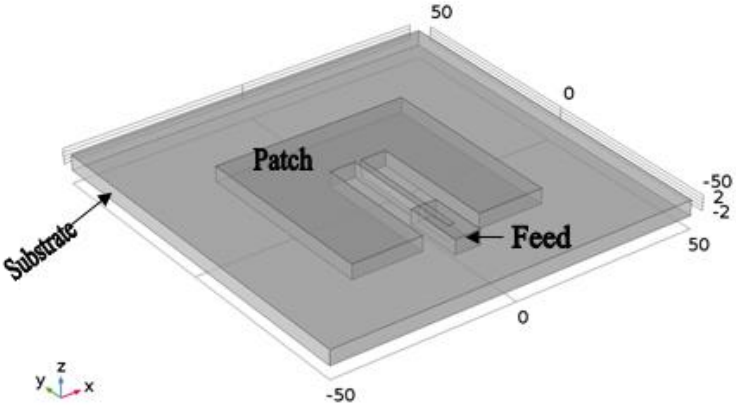

Figure 2. The proposed microstrip patch antenna

4. Modeling and system design

4.1. Modeling

The numerical analysis of any device, whatever its type, requires full knowledge of all the mathematical equations that the analytical tool we are working on, or at least requires accurate knowledge of mathematical equations for the application to be analyzed. Since the device for which a numerical analysis is to be performed does not include a specific application, at least in this paper, noting that the device has many and wide applications, not one of them mentioned in this study; We have worked extensively to select appropriate general and specific governing equations that serve most applications in the communication fields. The choice is electromagnetic physics through COMSOL finite element software. As a finite element model, we have a general electromagnetic wave equation to obtain all specifications for the proposed device.

$$\nabla \times \mu_r(\nabla \times \mathbf{E}) - k_0^2\left(\epsilon_r - \frac{j\sigma}{\omega\epsilon_0}\right)\boldsymbol{E} = 0$$

Where:
E: the electric field, σ: the electric conductivity, k_0: the wavenumber, and ϵ_r is the relative permittivity of the electric displacement section and could be taken from the material.
B: the constitutive relation and is related to the magnetic field, B can be expressed as $\boldsymbol{B} = \mu_o\mu_r\boldsymbol{H}$**,** and μ_r is the relative permeability.

4.2. System design

The reported antenna (Microstrip patch) model is simulated with the aid of COMSOL Multiphysics 5.1 finite element software packages. Table 1 represents the table of the specifications of the proposed patch antenna. Square-like geometry with 100 x 100 mm2 while its thickness is varied to simulate the antenna substrate. The total length of the patch is 52mm, and the width is 53 mm while the height of the patch is varied in a specific range. Some other dimensions related to the model can be shown in figure 3. The comfortable design and fabrications make the Microstrip patch antenna been used in a wide range of applications. This work is the development and characterization of a microstrip patch antenna to find out some of the specifications of its work, which includes broadcast, sending/ receiving the signal, power consumptions, polarization, and the frequency that the antenna is functioning with. In this paper, we used COMSOL Multiphysics finite element software for the fabrication as well as the rendering. The microstrip design has been done using the CAD facilities of the COMSOL. The mesh and the post-processing have been done with the same software, which is the COMSOL software. Results were taken after examining the device frequency working to ensure that the fabricated device is operating in the safe zone and the results are correct. This device considers a simple profile and low-cost for network applications so that the characterization of such software would be beneficial.

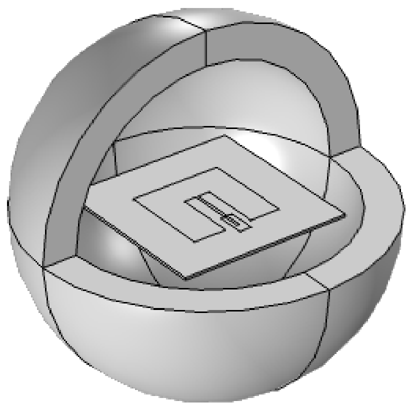

Figure 3. Assembly of the proposed patch antenna

4.3. Study

By using COMSOL Multiphysics, two studies were used in this research to finalize the results. The first study was step 1 which was an adaptive frequency sweep. In this step, we were trying to find the optimum frequency where it should have the maximum return losses. We used arbitrary dimensions to the proposed model. The second study was step 2 which was a frequency-domain study that has the calculated frequency from step 1 and we should add the optimization module study to find the best result of S11. The optimized variables were the substrate thickness and the dielectric constant of the width of the power line.

$$f = abs\,(comp1.emw.S11dB)$$

5. Simulation results

5.1 First study results

COMSOL 5.1 Multiphysics finite element software was used to simulate the Microstrip patch antenna, and it was utilized for calculating and plotting the results. After the proposed design has been completed, the first step was run with a range of frequency ranging (1.45[GHz],100[kHz],1.5[GHz]) to find the return loos and the corresponding frequency. Figure 4 represents the frequency and the corresponding return loss in which the device operates stably. The simulation indicates that the device responds perfectly without too much loss at 1.472 GHz with a return loss = -33.6 dB, where the negative value indicates that this antenna device had not many losses while transmitting the signal.

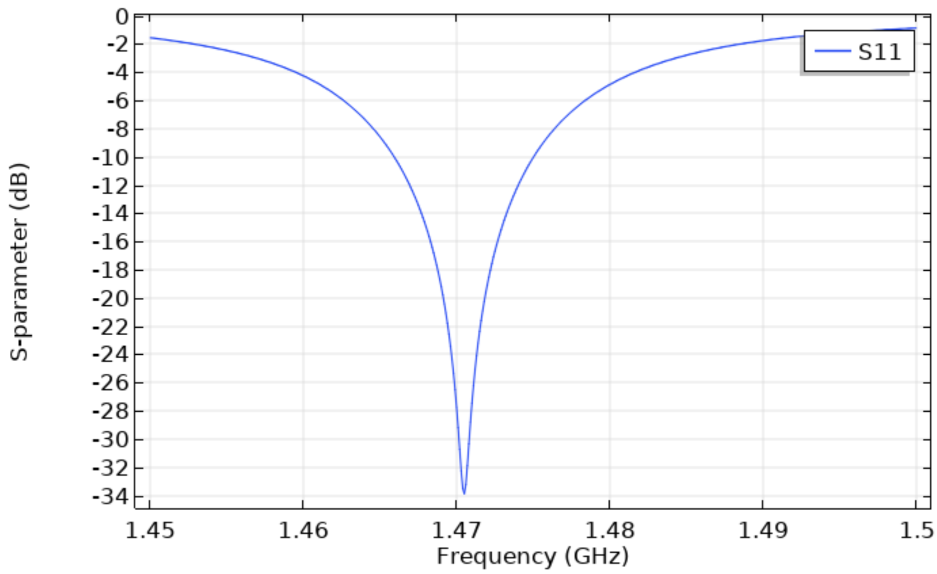

Figure 4. The course of the S11 depending on the frequency range for optimizing the power line

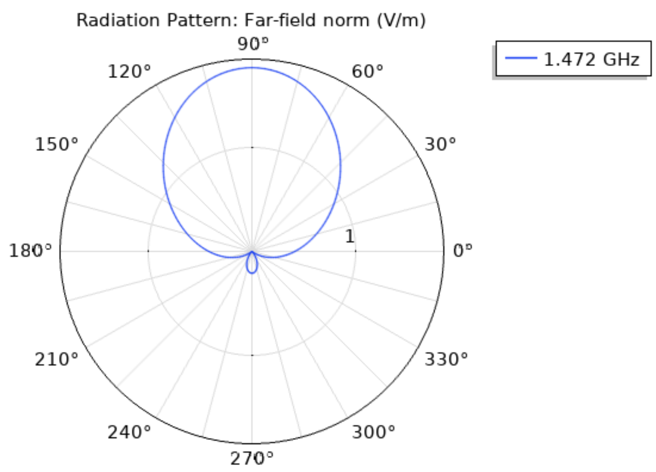

Figure 5. The radiation pattern: Far-field norm

Figure 5 shows the 2D radiation pattern of the far-field norm when the frequency was in the maximum return losses. From the figure, the distribution is uniform, and the propagation of the power from the antenna is distributed around 90°. Figure 6, is a 3D representation of the distribution of the power from the antenna when we have four different frequencies. The Far-field norm seems low when the frequency is 1.45 GHz and getting bigger with the frequency until it getting the maximum when the frequency is 1.472 GHz then returns to be smaller until frequency 1.5 GHz the Far-field become 0.73 (V/m).

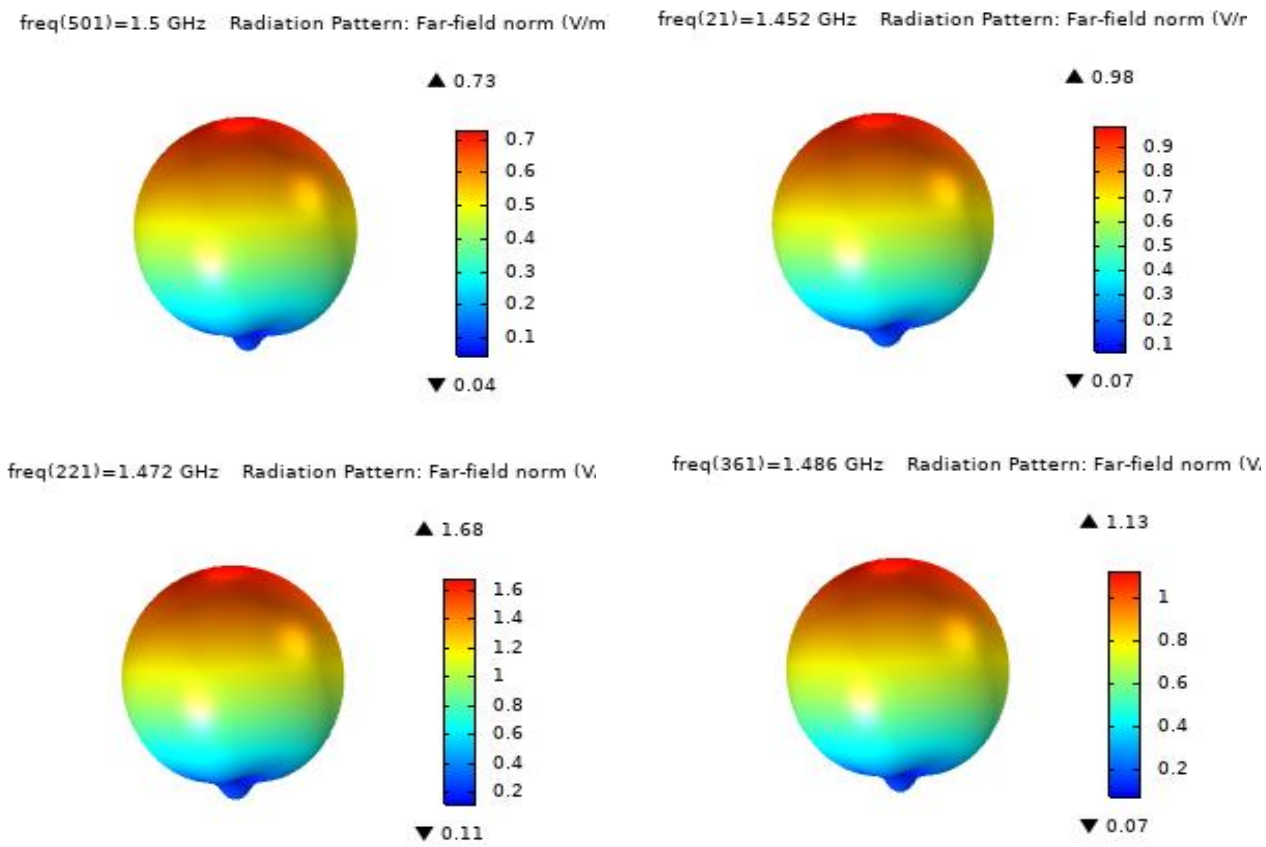

Figure 6. The radiation pattern: Far-field norm

On the other hand, we wanted to test the proposed antenna with the arbitrary dimensions and the frequency range to explore the electric field by selecting four frequency values the corresponding maximum return loss of one of them. Figure 7 represents the demonstration of the dimension effect on the electric field of the proposed antenna.

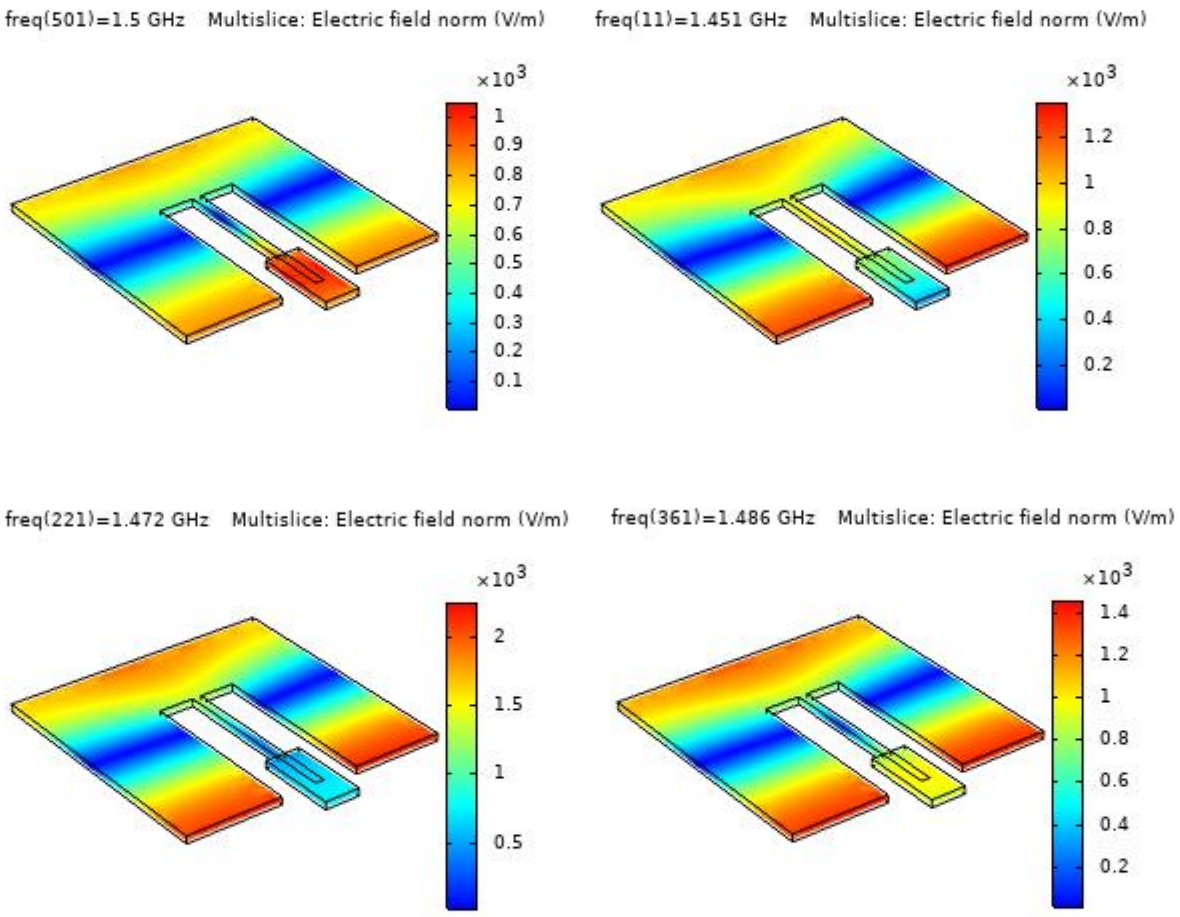

Figure 7. Electrical field distribution

5.2 Second study results

5.2.1 Optimization using S11

In this case, it is possible to improve the power line by using one of the antenna dimensions. In this optimization process, we used the line width to be our goal to be optimized. In COMSOL Multiphysics software we used **f = abs (comp1.emw.S11dB)** formula to evaluate the optimum width concerning the maximum value of S11. After several iterations through COMSOL, we obtained the optimum value of the parameter. The figures below describe the optimization process results. Figure 8 represents the far-field after obtaining the optimum value of the width parameter which can be seen that the far-field radiation is greater than what we had in figure 6 which means that in this step we reached the optimum parameter. Figure 10 shows the electric field of the antenna with the new width of the antenna. If we compare the electric field values in figure 7 and the electric field value in figure 10 we can notice the big difference even if we compare the performance of the device when it is lower return loss. That means, if we further run optimization by using other parameters we will achieve a great antenna performances.

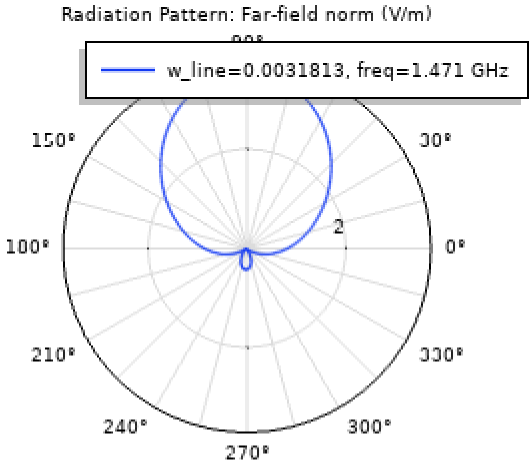

Figure 8. S11 after optimization

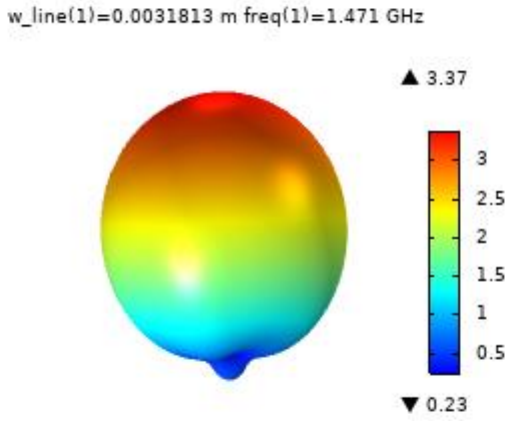

Figure 9. Far-field radiation after optimization

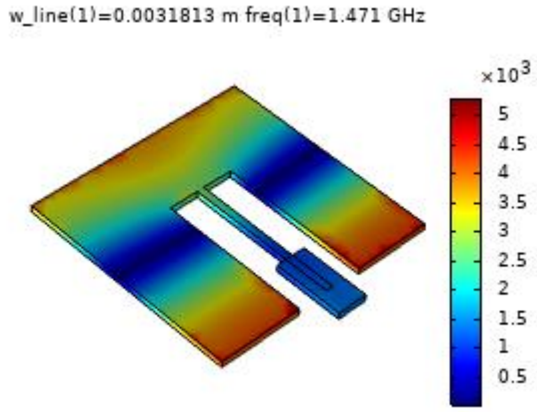

Figure 10. Far-field radiation after optimization

6. Conclusion

The optimization method should be incremental and multicriterial. Independent optimization methods tend to remain in simulations at nearby extents, which is why it is very essential to have the right fundamental understanding of the performance of the mathematical and physical prototype. Sequentially steps throughout the measurement have verified the predicted behavior of the simulation and mistakes in the hand calculations due to the simplified calculation. A Microstrip patch antenna has been modeled and designed via one of the finite element analysis software. All the steps of designing and modeling as well as the rendering and getting the results have been done using COMSOL 5.2 finite element software. Two variables were used to do the modeling optimization, which are the relative permittivity and the substrate height. The results showed that in each selection the performance and the behavior of the antenna vary. The one variable is independent to decide the proposed antenna performance.

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