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DESIGN AND OPTIMIZATION OF COMPACT BALANCED ANTIPODAL VIVALDI ANTENNA

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Abstract—In this paper, the conformal finite-difference time-domain (CFDTD) method using PSO optimization is applied to design a compact directive balanced antipodal Vivaldi antenna for ultra-wideband (UWB) applications. This paper demonstrates miniaturized antipodal Vivaldi antenna ($32 \times 35 \times 1.6\,\text{mm}^3$), having low-cross polarization levels and reasonable gain from 3.1 to 10.6 GHz. The antenna peak gain is 5.25 dBi in the specified band. The simulated and experimental results of return loss, far field patterns and gain are presented.

1. INTRODUCTION

In recent years, ultra-wideband (UWB) antennas have been developed in medical and military applications. Due to the FCC, a spectrum from 3.1 GHz to 10.6 GHz frequency band is used for UWB communications. The transmitter and receiver antennas for such systems must be

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compact and lightweight for portability. Besides the requirement on their compact size, gain stability, low distortion and low delays over the frequency band must be considered.

Vivaldi antennas have suitable features for high directivity, low cross polarization and broad bandwidth [1–6]. The dual exponentially tapered slot antenna (DETSA) has a broader bandwidth and better pattern characteristic [3, 4], which leads to achieving precision imaging without ghost targets due to supporting the sub nanosecond pulse transmission with less distortion. Although antipodal Vivaldi antennas satisfy UWB requirements, their dimensions are normally greater than 10 cm. Therefore, size reduction of those UWB antennas is very challenging. Reference [5] demonstrates a compact balanced antipodal Vivaldi antenna with dimensions of $52 \times 57\,\mathrm{mm}^2$. Also a small antipodal Vivaldi antenna is introduced in [6] with a dimension of $40.16 \times 42.56\,\mathrm{mm}^2$ with FR4 substrate.

In this paper, the design and optimization of a compact directive balanced antipodal Vivaldi antenna using the conformal finite difference time domain (CFDTD) technique [7, 8] with Particle Swarm Optimization (PSO) algorithm [9–11] is presented. To verify the correctness of the results of BAVA with CFDTD code the results were simulated and comprised with those of Ansoft high-frequency structure simulator (HFSS) and were then proved with measured results.

2. DESIGN OF BALANCED ANTIPODAL VIVALDI ANTENNA

The proposed balanced antipodal Vivaldi antenna is shown in Fig. 1. The antenna is designed on a FR4 substrate with $\varepsilon_r = 4.4$ and $h = 1.6\,\mathrm{mm}$. The tapered radiation structure of the antenna is designed from the intersection of the quarter of two ellipses. The major radii are (L-L_1) and (r-L_1) in which L is the same as the length of the substrate and the secondary radii are w_1 and w_2, with respect to [5] they are:

$$W_1 = \frac{W}{2} - \frac{W_m}{2} \tag{1}$$

$$W_2 = \frac{W}{2} + \frac{W_m}{2} \tag{2}$$

For designing the width of the antenna we used (3).

$$w = \frac{c}{2f_{lo}}\sqrt{\frac{2}{(\varepsilon_{\mathrm{r}}+1)}} \tag{3}$$

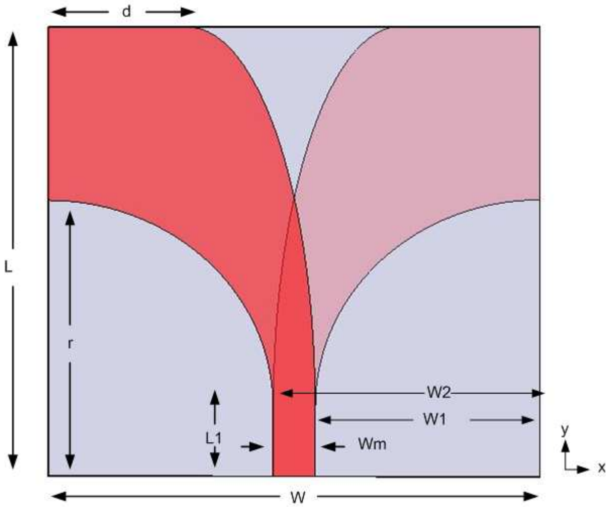


Figure 1. Geometry of BAVA.

L_1 has a fixed value with regards to [5]. W_m is calculated with formulas (4.37 and 4.38) which are in [12].

3. CFDTD/PSO METHOD

The FDTD method is widely used in electromagnetic, microwave and photonic structures. The FDTD is more suitable for modeling dielectric and magnetic materials of finite regions. In structures with curved areas such as antipodal Vivaldi antennas, the accuracy of the FDTD results decrease. In order to overcome this problem, rather than increasing mesh size which requires too large a memory, we use conformal FDTD. The CFDTD is more accurate and numerically stable for modeling the PEC objects.

The CFDTD code developed for antipodal Vivaldi antenna includes the convolutional PML (CPML) boundary conditions introduced in [13]. CPML is used to truncate the geometry in all directions. The space lattice is terminated with 6-cells from the outer dimensions of the antenna geometry. The matrix of the problem is about $20 \times 145 \times 116$ cells. The spatial step sizes, Δx, Δy and Δz have to be suitable, furthermore, the spatial step sizes should be much less than smallest guided wavelength λ_g [14]. Spatial size steps were chosen to be $\Delta x = 0.35\,\mathrm{mm}$, $\Delta y = 0.21\,\mathrm{mm}$ and $\Delta z = 0.4\,\mathrm{mm}$ and the time step is chosen to be:

$$\Delta t = \frac{0.95}{c\sqrt{\left(\frac{1}{\Delta x}\right)^2 + \left(\frac{1}{\Delta y}\right)^2 + \left(\frac{1}{\Delta z}\right)^2}} \tag{4}$$

Particle swarm optimization (PSO) models the solution process of searching for food after the natural movement of groups such as a swarm of bees. Each particle's position in the N-dimensional solution space represents one solution. A problem-dependent fitness function determines the quality of each solution relative to other solutions. Each

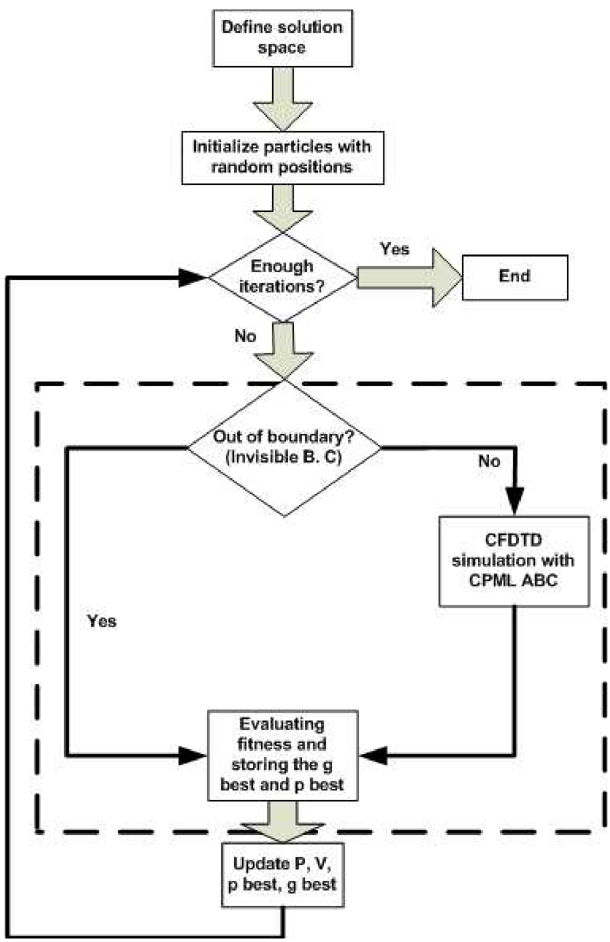


Figure 2. Flowchart of CFDTD/PSO algorithm.

particle remembers the location of its personal best (p_{best}) fitness, as well as the global best (g_{best}) among all particles.

A PSO algorithm is implemented to optimize the geometry of the proposed antenna. Because of optimizing the geometrical parameters, real PSO was chosen.

Figure 2 shows a flowchart of the CFDTD/PSO algorithm. To reduce the amount of time taken to analyze, the CFDTD code is written in FORTRAN 77 language. The code very quickly performs analysis. Four thousand steps of simulation are performed in 154 seconds, running the code on a CPU E6550 2.33 GHz having 4 GB of RAM. The PSO algorithm is written in MATLAB, and the MATLAB program is then linked with FORTRAN language to run Optimization.

In optimization, 3741 of 4000 maximum positions are encountered in the solution space. All would be stimulated by CFDTD. The investigation shows that only 2710 ($4000-259-1031 = 2710$) positions are not repeated, while 1031 positions are repeated. The total time of optimization is about 6955 minutes.

The dimension of the optimization problem is three. In the proposed balanced antipodal Vivaldi antenna, a return loss (S_{11}) of less than -10 dB bandwidth covering the entire frequency band from 3.1 to 10.6 GHz is desired. The fitness function is applied as:

$$f = 50 + \max(S_{11 \text{ from } 3.1\,\text{GHz to } 10.6\,\text{GHz}}) \tag{5}$$

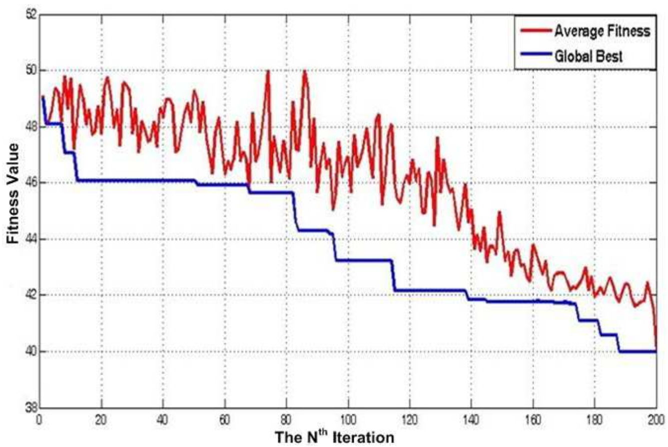
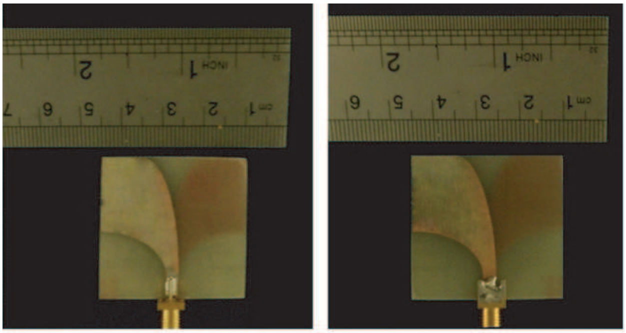


Figure 3. The convergence performance of the optimization for the BAVA.

The solution space is defined as (all dimensions are in mm):

$$L \in (18, 52),\ r \in (5, 25),\ d \in (0, 15) \tag{6}$$

As shown in Fig. 3 a swarm of twenty and a maximum iteration of 200 is used to achieve reasonable convergence. The algorithm was implemented with the utilization of "invisible boundary condition" [15].



(a) (b)

Figure 4. Photograph of the fabricated antenna (a) top layer, (b) bottom layer.

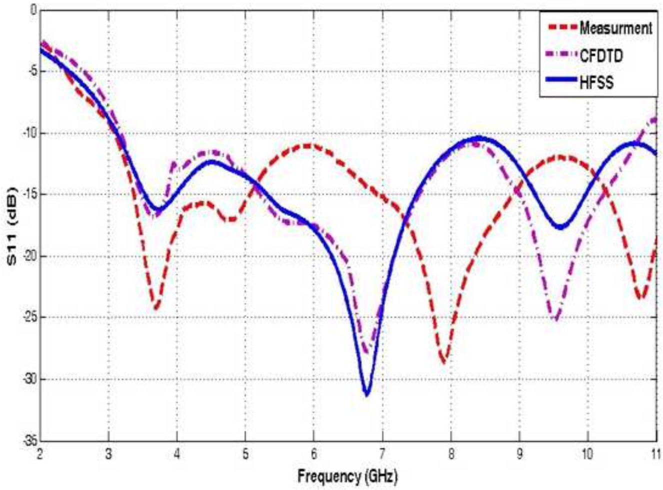


Figure 5. Simulated and measured return loss of the BAVA antenna.

4. NUMERICAL RESULTS

The fabricated proposed antenna is shown in Fig. 4. The simulation and measurement return losses of compact ($32 \times 35\,\text{mm}^2$) antipodal Vivaldi antenna is shown in Fig. 4. The result indicates that the area of the proposed antenna is reduced by about 62% in comparison with [5] and 21% in comparison with [6].

The return loss covers the required UWB band of 3.1–10.6 GHz which is shown in Fig. 5. All dimensions of the balanced antipodal Vivaldi antenna investigated in this optimization are: $L = 32\,\text{mm}$, $W = 35\,\text{mm}$, $W_m = 3\,\text{mm}$, $L_1 = 5\,\text{mm}$, $r = 19.6613\,\text{mm}$, $d = 9.9603\,\text{mm}$.

The simulated far-field radiation patterns, E-plane and H-plane, at 4, 6, 8, and 10 GHz are shown in Fig. 6. The measured far field radiation patterns, co- and cross-polarization for both planes

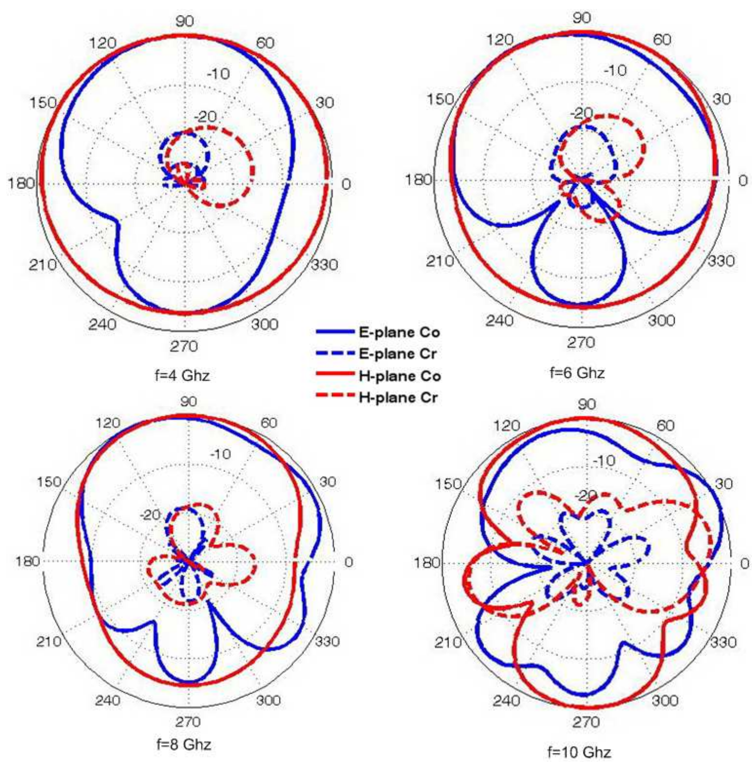


Figure 6. Simulated radiation patterns of the proposed antenna at 4, 6, 8, and 10 GHz.

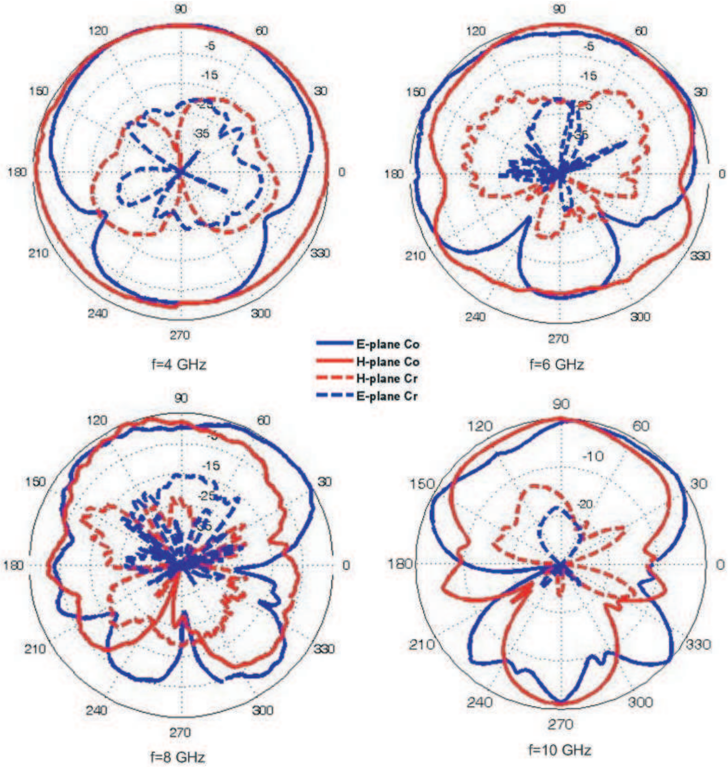


Figure 7. Measured radiation patterns of the proposed antenna at 4, 6, 8 and 10 GHz.

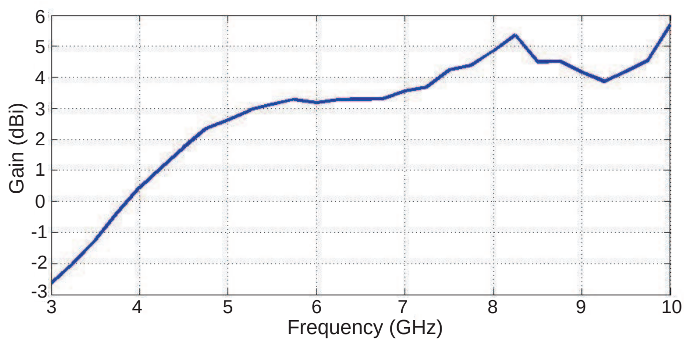


Figure 8. Measured gain of BAVA.

are presented in Fig. 7. The Plots show that the values of cross-polarization in the direction of the maximum radiation pattern towards the co-polarization are nearly -20 dB. The measured peak gain shown in Fig. 8 is 5.25 dBi at 8.24 GHz. Due to the size limitation, there is a trade-off between bandwidth and antenna gain in the lower end of frequency, which results in the low gain between 3.1 GHz and 3.8 GHz.

5. CONCLUSION

Based on the CFDTD method using PSO algorithm for optimization, a compact directive balanced antipodal Vivaldi antenna has been designed and fabricated. The CFDTD code, including CPML, is implemented. The designed and optimized antenna covers 3.1–10.6 GHz, which is suitable for UWB applications. The proposed antenna is printed on FR4 substrate which is easily integrated with circuits. The dimension of the antenna is reduced significantly. The reduction of size is about 21% in comparison with [6]. The peak gain of the proposed antenna at 8.24 GHz is 5.25 dBi and the front-to-back ratio is more than 15 dB.

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