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Genetic Algorithm Optimized X-Band Absorber Using Metamaterials

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Abstract—This paper presents a novel, Genetic Algorithm (GA) optimized X-band absorber using metamaterials. The unit cell of this structure consists of several square patches, each having a dimension of 2.5 mm × 2.5 mm. Their positions are optimized using the GA such that the X-band absorption is maximized. Simulation results and the subsequent experimental validation affirm that the structure offers absorption of 97% from 10.42 GHz to 11.98 GHz and absorption of 90% over the entire X-band from 8 GHz to 9 GHz and also from 9.35 GHz to 12 GHz, with peak absorption of 99.95% at 10.52 GHz. The results are compared with the existing ones, to demonstrate the superiority of the proposed design.

1. INTRODUCTION

Metamaterial based absorbers have received considerable attention from the electromagnetic community over the past few decades. Metamaterials [1] are artificially engineered materials and have several unusual electromagnetic properties that are not found in ordinary materials such as negative refractive index, and artificial magnetism. They have myriad applications [2–4], and one of them is the design of X-band absorbers or radar absorbing material [5, 6]. Several X-band absorbers have been proposed in the literature [7–16] that can be broadly classified into two categories: polarization dependent absorbers [7, 8] and polarization independent absorbers [9–16]. The polarization independent absorbers are generally symmetrical structures and are insensitive to polarization states with a narrow absorption bandwidth [13]. The polarization dependent absorbers can be sensitive to the polarization state, but have relatively higher absorption bandwidth [8]. The first metamaterial absorber was proposed in [7]. However, this structure was polarization sensitive and offered a very low absorption bandwidth. A wide-band absorber using RLC screen that absorbs TEM polarized fields was presented in [8]. Similarly, via array absorber was proposed in [9] which exhibited polarization insensitivity, but is difficult to design due to the presence of vias. Several multiband absorbers were proposed in [11–13], but had a low peak absorption and narrow absorption bandwidth. Similarly, the structures proposed in [14–20] have narrow absorption bandwidths in the X-band.

The objective is to design a low cost FR4 based absorber for the entire X-band. This structure is obtained using a well-known optimization technique, the Genetic Algorithm (GA) [21]. Use of optimization techniques for design of electromagnetic structures is not pristine. Several such structures have been designed for different applications. This unconventional design technique is not frequently employed as it involves large computational time, but the results may be rewarding.

An ideal absorber works for all polarization states and over wide incident angles. However, we design the unit cell for TE polarization state, as increasing the number of polarization states increases the computational time. The other reason for opting a polarization sensitive absorber is that the optimized structure is unlikely to be symmetrical and hence cannot work for all the polarization states.

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The paper is organized as follows. The next section discusses the optimization process and the design of the structures. The unit cell of the proposed structure is presented in the third section. The results of simulation and the subsequent experimental validation are presented in the fourth section. A comprehensive comparison of the proposed structures with the recent publications is also presented in this section, and finally the conclusions are presented in the last section.

2. STRUCTURE DESIGN

HFSS is commercially available electromagnetic software which runs on VB script. This script can be written and executed from the MATLAB. This combined with the genetic algorithm toolbox of MATLAB, can be used for the design of optimized structures [22].

The general process involves the design of the structure's unit cell, assignment of periodic boundary conditions and the use of floquet ports for obtaining the coefficients, 's_{11}' and 's_{12}'. The absorption '$A(f)$' as a function frequency 'f' is related to these coefficients by the expression given in the Equation (1).

$$A(f) = 1 - |s_{11}(f)|^2 - |s_{12}(f)|^2 \tag{1}$$

The GA toolbox of MATLAB generates population whose chromosomes are binary numbers. GA uses these numbers to generate the VB script for the unit cell structure. If a bit is '0' in the bit string, a metal patch of 2.5 mm × 2.5 mm is placed on the substrate at the given position else no metal is placed. The coordinates are updated and the process is repeated until all the bits in the bit string are used. GA then assigns the boundary conditions and the floquet port excitation using the VB script and subsequently calls the HFSS to simulate the unit cell. After the simulation, the results are sent back to the MATLAB for calculation of the fitness value, which is given by Equation (2).

$$fitness := f_H - f_L \tag{2}$$

where '$f_H - f_L$' is the range of frequencies over which the structure offers the desired absorption. Fig. 1(a) shows the corresponding unit cell generated by the VB script for a given input bit string and the flowchart for the design of optimized structures using the GA is shown in Fig. 1(b).

3. METAMATERIAL ABSORBERS

The low-cost epoxy FR4 substrate has a dielectric constant of 4.4, loss tangent of 0.02 and thickness of 1.58 mm. The dimensions of the unit cell are taken as 30 mm × 30 mm, and the parameters of the GA, considered in the optimization, are maximum generations: 30, population size: 20, mutation rate: 0.35, and desired absorption: 97%. The unit cell of this structure obtained after the optimization is shown in Fig. 2. The orange colored portion indicates the conductive portion and the blue color indicates the substrate. The dimensions of the unit cell are: $a = 2.5$ mm, $b = 2.5$ mm, $h = 1.58$ mm and $c = 30$ mm. The ground plane is considered as a perfectly conducting surface, and so '$s_{12}(f)$' is taken as zero.

The simulation results of an infinite array of these unit cells, obtained using the periodic boundary conditions and floquet port excitation are shown in Fig. 3. Also shown in the figure are the results of normal incidence, i.e., $\theta = 0°$ and for $\theta = 30°$.

From the simulation response, it can be observed that the proposed absorber offers a reflection lower than −10 dB over the entire X band, i.e., from 8 GHz to 10 GHz, and can be represented using a parallel RLC circuit [23] as shown in Fig. 4(a). The values of these circuit elements are $R_1 = 2800\,\Omega$, $L = 0.2$ nH, $C = 1.05$ pF, $R_2 = 58\,\Omega$ and $R_3 = 50\,\Omega$. The circuit is designed using Agilent's Advanced Design System (ADS), and the response is shown in Fig. 4(b).

The impedance of this equivalent circuit is given by Equation (3), and the resonance frequency 'f_r', lower cutoff frequency 'f_L' and upper cutoff frequency 'f_U' are given by Equation (4), Equation (5) and Equation (6), respectively.

$$\frac{1}{Z} = \frac{1}{R_3} + \frac{R_1\left(1 - \omega^2 LC\right) + j\omega L}{j\omega L\,(R_1 + R_2) + R_1 R_2\,(1 - \omega^2 LC)} \tag{3}$$

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{4}$$

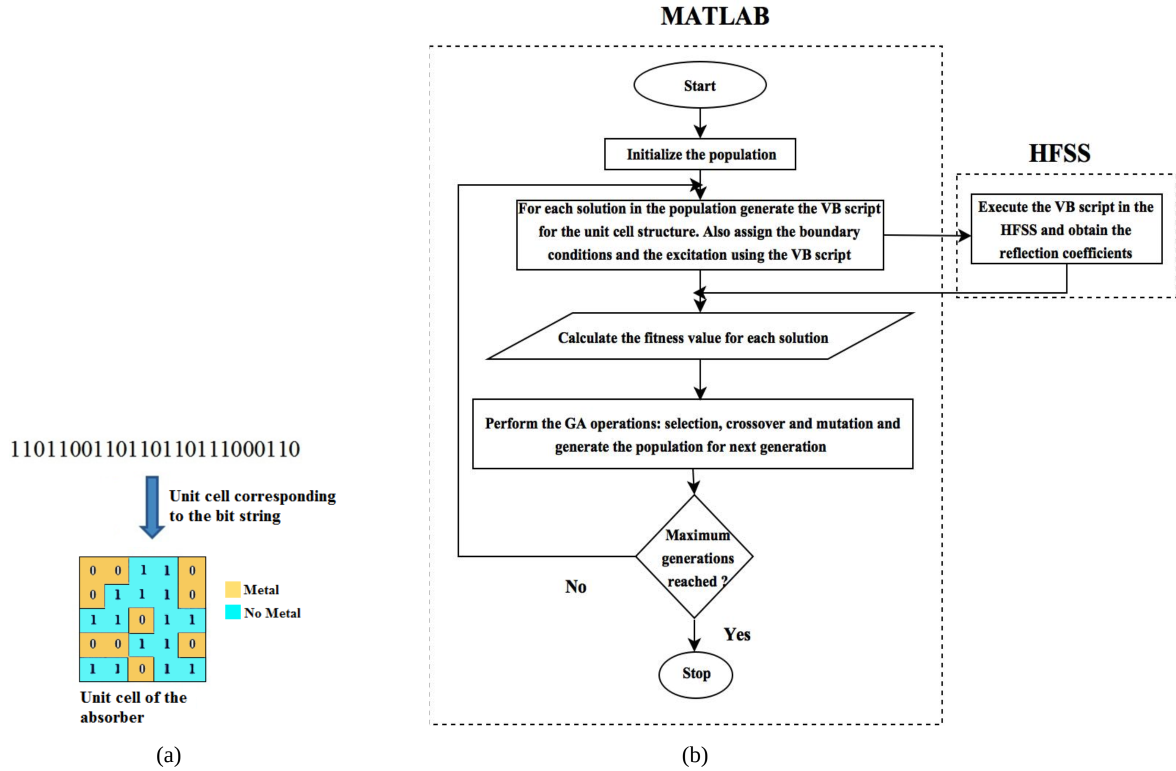


Figure 1. (a) Unit cell for the corresponding bit string. (b) Flow chart for the design process.

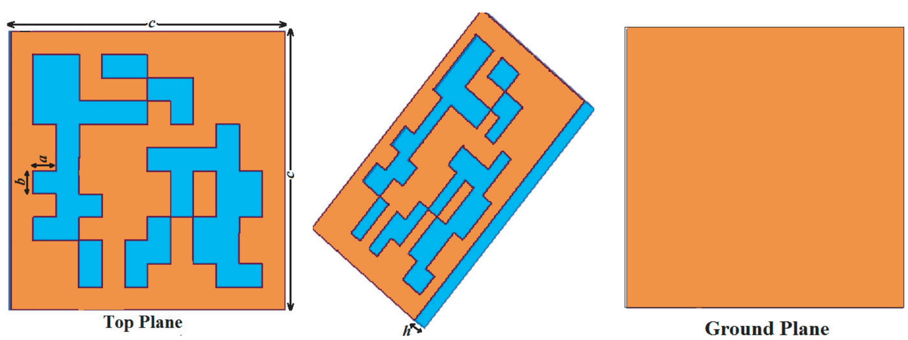


Figure 2. Unit Cell of the GA optimized FR4 absorber.

$$f_L \approx \frac{1}{2\pi\sqrt{LC}} - \frac{1}{4\pi\left(R_1 + R_3\right)C} \tag{5}$$

$$f_U \approx \frac{1}{2\pi\sqrt{LC}} + \frac{1}{4\pi\left(R_1 + R_3\right)C} \tag{6}$$

4. SIMULATION RESULTS AND EXPERIMENTAL VALIDATION

After obtaining the absorption characteristics of an infinite array of the optimized unit cells, a 25-cell metamaterial absorber [10] having dimensions of 150 mm × 150 mm is designed and fabricated. The structure is shown in Fig. 5(a). The structure was then placed into an anechoic chamber in order to validate its absorption characteristics. Two single mode (TE) X-band pyramidal horn antennas, one for transmitting and the other for receiving were placed 60° apart, such that the main beam could be

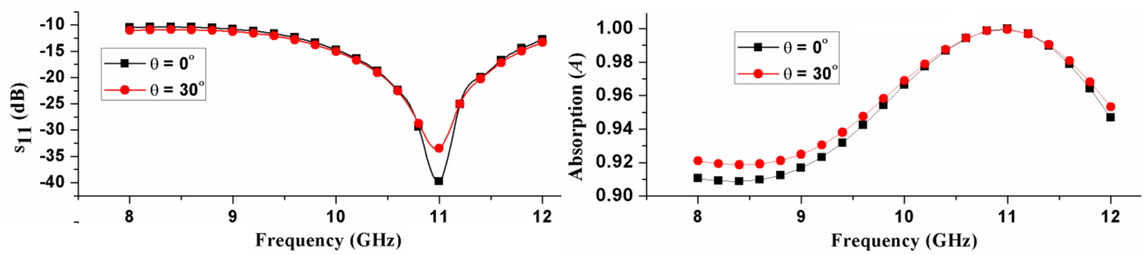
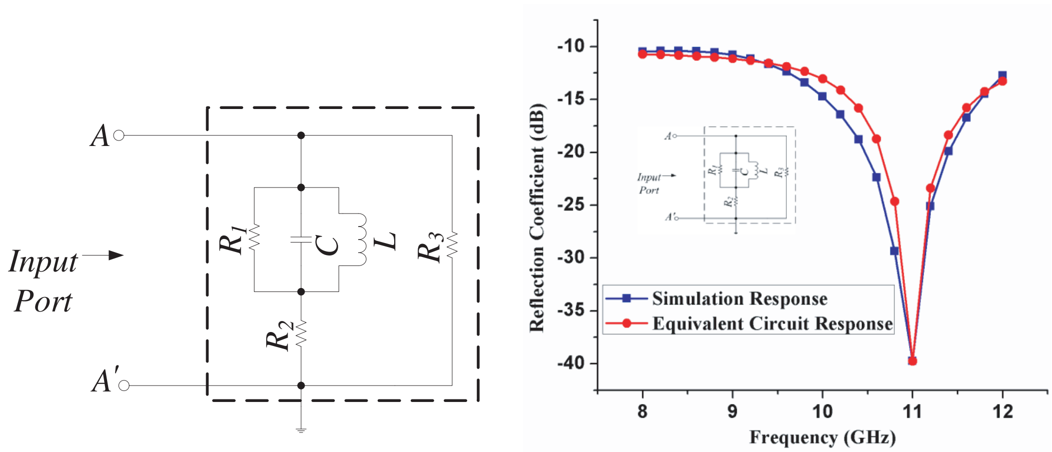
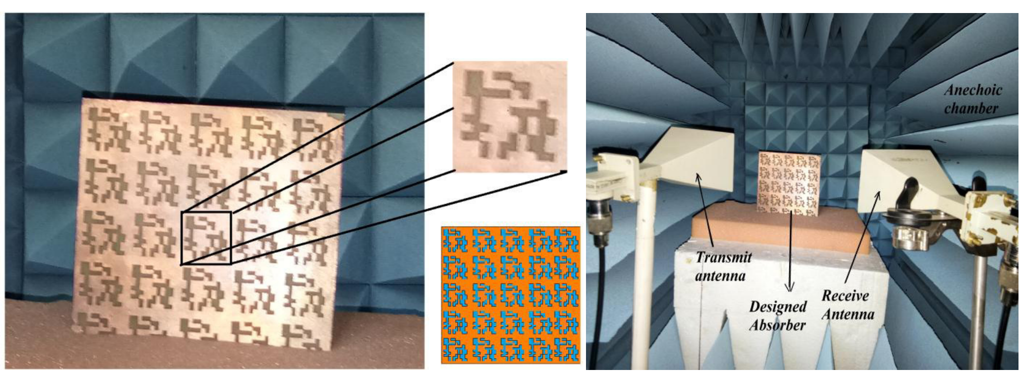


Figure 3. Reflection and absorption for $\theta = 0°$ and $\theta = 30°$.



(a) (b)

Figure 4. (a) Equivalent circuit, (b) s parameter response.



(a) (b)

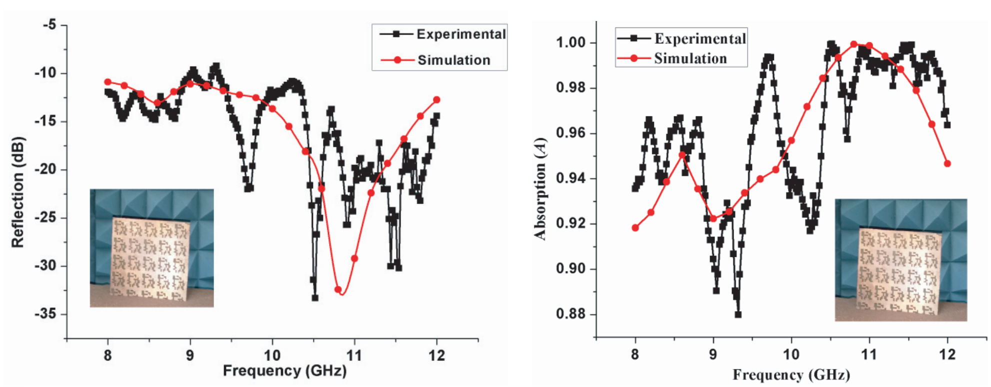
Figure 5. (a) A 25 cell absorber, (b) experimental setup.

focused onto the structure. The experimental setup is shown in Fig. 5(b). The energy transmitted by the transmit antenna gets reflected from the absorber and is received by the receive antenna. Both the antennas were connected to the vector network analyzer (VNA), and the reflection coefficient is obtained. The experimental and simulated results are found in good agreement and shown in Fig. 6.

From the experimental and simulated results shown in Fig. 6, we can observe that the optimized structure absorbs 90% of the incident energy over most of the X-band from 8 GHz to 9 GHz and from 9.35 GHz to 12 GHz. Also, it absorbs 97% of the incident energy in the range of 10.42 GHz to 11.98 GHz with a peak absorption of 99.95% at 10.52 GHz. A comparison of the absorption characteristics of the proposed structure with the recently published work is shown in Table 1.

Table 1. Comparison of results.

Reference	Size of unit cell (mm^3)	Absorption (%)	Absorption Bandwidth in X band (GHz)
Proposed	$30 \times 30 \times 1.58$	≥ 90 ≥ 90 ≥ 97 $= 99.95$	8–9 GHz 9.35–12 GHz 10.42–11.98 GHz 10.52 GHz
[8]	$9.6 \times 9.6 \times 3.2$	≥ 90 ≈ 100	8.36–12 GHz 10.93 GHz
[9]	$8 \times 8 \times 0.35$	≥ 90 $= 99.6$	11.14–11.46 GHz 11.6 GHz
[12]	$4.3 \times 9.2 \times 4$	≥ 92	$\approx$ 8–9 GHz
[13]	$9 \times 9 \times 0.8$	$= 97.3$ $= 91.84$ $= 90.84$	8 GHz 10 GHz 12 GHz
[16]	$8 \times 8 \times 2.7$	≥ 90	8–12 GHz
[17]	$6.67 \times 6.67 \times 0.75$	$= 97.95$ $= 98.4$	9.1 GHz 10.53 GHz
[18]	$15 \times 15 \times 0.017$	$= 99.84$	9.5 GHz
[19]	$4.59 \times 4.59 \times 0.8$	$= 99.97$	10.53 GHz
[20]	$5.6 \times 5.6 \times 2.4$	≥ 90	8.6–12 GHz



(a) (b)

Figure 6. Experimental and simulation result for (a) reflection coefficient, (b) absorption.

5. CONCLUSION

A novel GA optimized metamaterial absorber for X-band is presented. The structure is designed to offer the desired absorption of 97% over a maximum range of frequencies. The design offers absorption of 90% from 8 GHz to 9 GHz and from 9.35 GHz to 12 GHz and an absorption of 97% from 10.42 GHz to 11.98 GHz. The proposed method can also be used to design absorbers which are insensitive to polarization state and angle of incidence but requires intensive computational time. The authors wish to address this problem in their future work.

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