# Reconfigurable Reflectarray Structure Based on Optimized Unit Cell for Wireless Communications

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**Abstract — This paper presents a 180 × 180 × 1 mm reconfigurable reflector array structure based on an optimized unit cell for wireless communication applications. The reflector array contains 144 unit cells placed on the FR4 substrate, and each unit cell structure uses a single layer based on multi-concentric square rings. The single layer is used to obtain negative $\varepsilon_r$ and $\mu_r$ values, while multiple rings provide a wide reflection bandwidth. The proposed structure is characterized by dual reflection bandwidth. The first band (2.6 GHz) ranges from 1.98 GHz to 4.6 GHz, while the other band (1.71 GHz), ranging from 7.41 GHz to 9.1 GHz. The reconfigurability of the structure is realized by using PIN diodes connected to each unit cell. Phase distribution in the proposed reflector structure changes according to state of the diodes, resulting in the reflection of the wave at different angles. The proposed solution was simulated in terms of S parameters, constitutive parameters and refractive index based on a full-wave analysis performed using CST Microwave Studio.**

***Keywords — constitutive parameters, metamaterial, reconfigurable reflectarray, unit cell***

## 1. Introduction

Reflectarray structures are currently receiving a great deal of interest when it comes to their use in wireless systems, due to their feature-rich capabilities. Compared with traditional reflectors, reflectarrays are characterized by light weight, low profile, flat surface and small volume. They are also easy and cheap to fabricate [1], [2]. Such features make reflectarray structures a preferred solution for satellite, radar, and long-distance wireless communication applications [3].

Recently, reflectarray structures with unit cells of a new geometrical shape have been developed to overcome their inherent disadvantage consisting in a limited phase variation range [4]. In [5], a reflector structure based on nine elements of different sizes is introduced for the purpose of reducing RCS level, while in [6] a reflectarray structure based on a stepped impedance resonator (SIR) supported on a frequency selective surface (FSS) is proposed for the purpose of lowering its radar cross-section. A compact reflectarray structure is introduced in [7] for performance enhancement, with the required phase delay compensated for by variable-size unit cell elements. Such elements are used to reflect/scatter the incident waves within the phase delay to achieve a desired shape of the beam, as presented in papers [8]–[12].

In this work, a reflectarray structure based on a single negative metamaterial, designed to achive a reconfigurable behavior, is presented. Metamaterials (MTMs) are substances based on properties not found in nature. Their parameters – such as $\mu_r$ and $\varepsilon_r$ – depend on the structure, shape, arrangement, orientation, and size of the unit cell, and may also assume negative values [13]–[16]. Materials with negative $\mu_r$ and $\varepsilon_r$ parameters are called left-handed materials (LH MTM). Their phase velocity is antiparallel to the Poynting vector and opposite to the propagation of waves in natural materials [17]–[20].

In this design, the unit cell utilizes a single layer-based, multi-concentric square-ring structure. A single layer is used to achieve a negative $\varepsilon_r$ or $\mu_r$, while multiple rings are used to provide wide reflective bands for sub-6 GHz band 5G applications. First, the reflectarray size is designed and optimized using the trust region algorithm. Then, a full-wave analysis is conducted and the obtained results are discussed. The CST Microwave software package is used to design and analyze the proposed structures [21].

## 2. Unit Cell Design

The optimized single negative metamaterial unit cell based on the reflectarray behavior is shown in Fig. 1. The dimensions of the unit cell are 15 × 15 × 1 mm and as the base substrate, the FR-4 material with $\varepsilon_r = 4.3$ and $\tan\delta = 0.02$ is used. For reconfigurable behavior, two PIN diodes are inserted at

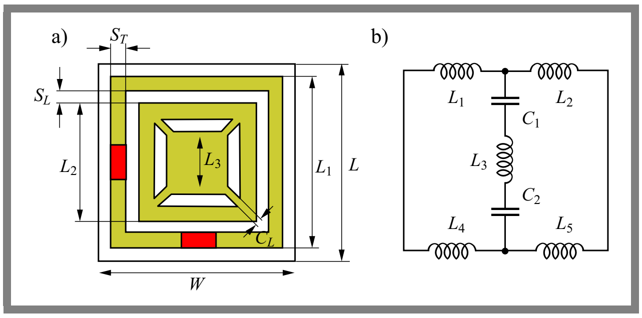


**Fig. 1.** Reconfigurable metamaterial structure: a) unit cell design and b) equivalent circuit.

**Tab. 1.** Dimensions of the unit cell.

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| $L$ | 15 mm | $L_3$ | 4.8 mm |
| $W$ | 15 mm | $S_T$ | 1.19 mm |
| $L_1$ | 13.2 mm | $S_L$ | 0.9 mm |
| $L_2$ | 13.2 mm | $C_L$ | 0.636 mm |
| $h$ | 1 mm | $t$ | 0.035 mm |

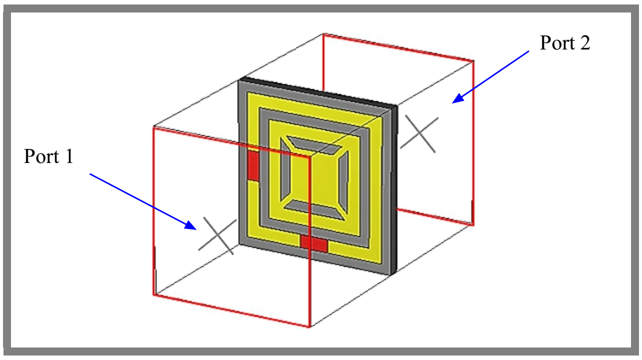


**Fig. 2.** Fictual waveguide with port excitation entries and boundary conditions settings.

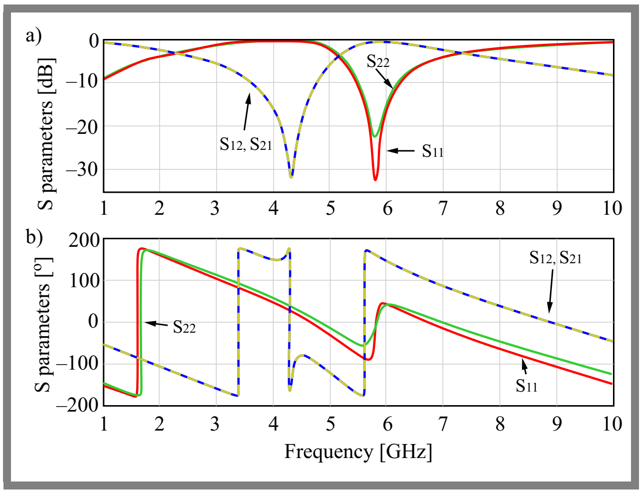


**Fig. 3.** S parameters of the unit cell: a) magnitude and b) phase.

each unit cell, with a rectangular strip used as the PIN diode switches between on and off states. The equivalent circuit of the proposed unit cell is presented in Fig. 1b, while other geometric details are shown in Tab. 1.

A full-wave analysis technique was applied to analyze the single unit cell. As illustrated in Fig. 2, the unit cell structure is placed in the center of a fictual waveguide. To mimic the wave's propagation through an infinite unit cell array, two ports are inserted, in addition to the boundary conditions provided by perfect electrical conductors (PECs) and perfect magnetic conductors (PMCs). In Fig. 3, the S parameters of such a unit cell are introduced in a set of magnitude and phase curves vs. frequency.

Figure 4 presents the constitutive parameters ($\mu_r$ and $\varepsilon_r$) of the proposed unit cell. One may notice that it has negative permittivity and permeability in multifrequency bands. A

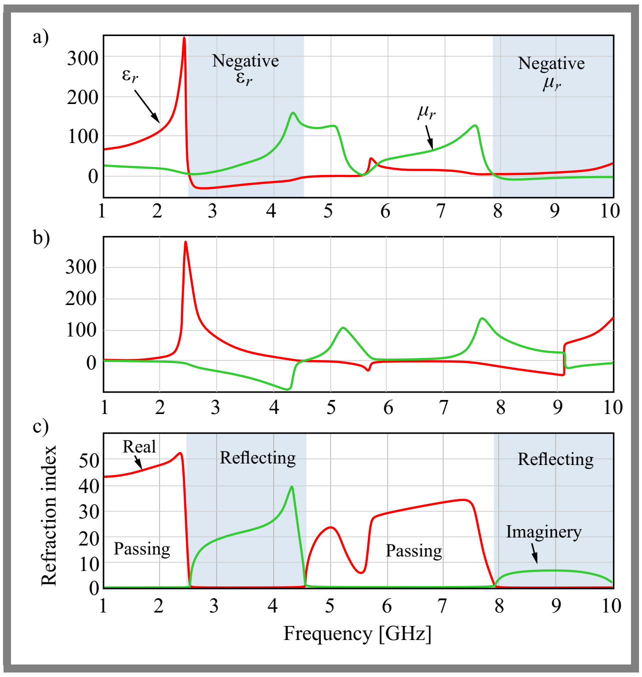


**Fig. 4.** Constitutive parameters ($\varepsilon_r$, $\mu_r$): a) real, b) imaginary component, and c) refraction index.

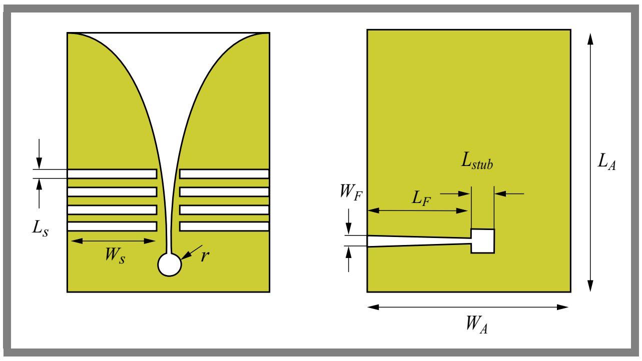


**Fig. 5.** Geometry of the MVA structure.

negative $\varepsilon_r$ has been achieved in the range of 2.51 to 4.56 GHz, with its maximum value reaching 2.73 GHz. A negative $\mu_r$ has been achieved in the frequency range of 7.91 to 10 GHz, with a maximum value of 8.25 GHz. Figure 4c illustrates the refraction index $n = \sqrt{\varepsilon_r \, \mu_r}$ with passing and reflecting frequency ranges of the designed unit cell.

### 2.1. Modified Antenna Design

In the next step, a modified Vivaldi antenna (MVA) was designed to generate the electromagnetic waves that will be incident on the reflectarray structure. The dimensions of MVA are 45 × 35 mm with a substrate thickness of 1 mm. Slit lines are etched along the outer edges to reduce surface current values. As a result, the antenna's performance is enhanced. Geometric details of the MVA structure may be found in Tab. 2, while Fig. 5 shows the proposed layout.

The $S_{11}$ of the designed antenna (Fig. 6) shows that the antenna covers a range of frequencies from 3 to 12 GHz with $S_{11} < -10$ dB, as seen in Fig. 6a. Furthermore, the MVA antenna shows endfire radiation with its maximum gain

**Tab. 2.** Dimensions of the unit cell.

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| $L_A$ | 45 mm | $L_{stub}$ | 4 mm |
| $W_A$ | 35 mm | $L_S$ | 1.5 mm |
| $L_F$ | 17.86 mm | $W_S$ | 15.5 mm |
| $W_F$ | 1.945 mm | $r$ | 2 mm |

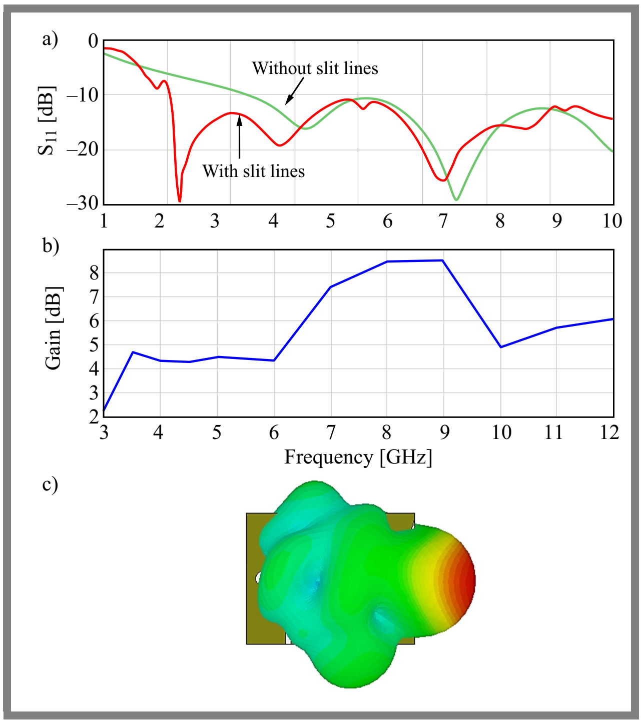


**Fig. 6.** Performance of the MVA antenna: a) reflection coefficient, b) gain value at different operating frequencies, and c) radiating pattern.

equal to 8.55 dB, varying from 4.29 to 8.55 dB in the desired band, as seen in Fig. 6b-c.

### *2.2. Reconfigurable Reflectarray Based on Optimized Unit Cell*

In the third step, an array of optimized unit cells was designed, as illustrated in Fig. 7. It was of the reflectarray variety and consisted of 12 × 12 unit cells, with an overall size of 180 ×180 × 1 mm. The dimensions were optimized based on separation distance $d$. A trust region algorithm was applied and used to achieve the best result. As seen in Fig. 8, the best separation distance $d$ was found to be equal to 0 mm in terms of a wider reflected band with the minimum size of the array compared to the other distance.

The proposed reflectarry solution was then reconfigured, with the unit placed parallel to the direction of propagated waves in order to prevent the propagation of electromagnetic waves through the proposed reflectarry structure, which has led to the most efficient reflection of radiation power. The reconfigurable unit cells based on the PIN diode in the reflectarray structure were divided into 4-groups, as seen in Fig. 9, with each group

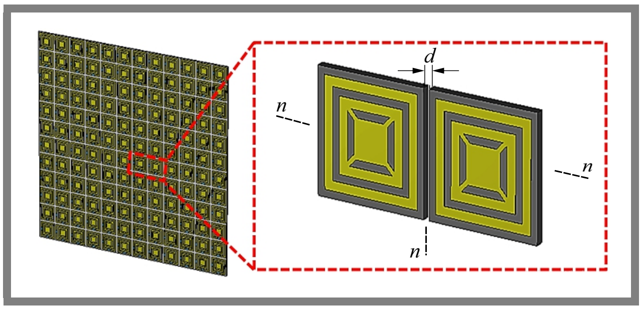


**Fig. 7.** Optimized unit cell-based array.

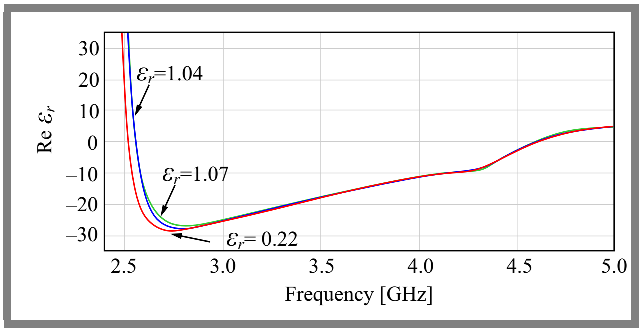


**Fig. 8.** Real $\varepsilon_r$ component at different separation distances.

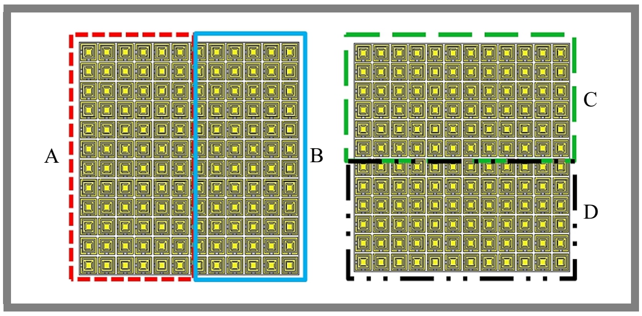


**Fig. 9.** Proposed final reflectarray structure.

of unit cells being responsible for different reflection direction angles.

In the "on" state, the radiation pattern of the proposed structure is presented in Fig. 10a. One may notice that the incident waves will be reflected from the reflectarray and no waves will be passed through the array.

The radiation pattern of the proposed array, where the diodes are on in group A, is introduced in Fig. 10b. It is found that the incident wave is reflected from the reflectarray structure at an angle of 20° to the left-hand side. With diodes in group B switched on (Fig. 10c), it is noticed that the incident waves are reflected to the right-hand side, at an angle of 21°. Moreover, when group C is activated, as seen in Fig. 10d, the waves are reflected at an angle of 30° upwards. The reflected waves are redirected at an angle of 37° downwards when group D diodes are on, as seen in Fig. 10e. Depending on which group of diodes is switched on, the waves will be reflected in different directions and at different angles. Finally, 2D radiation patterns are introduced in Fig. 11, for different states of the diodes.

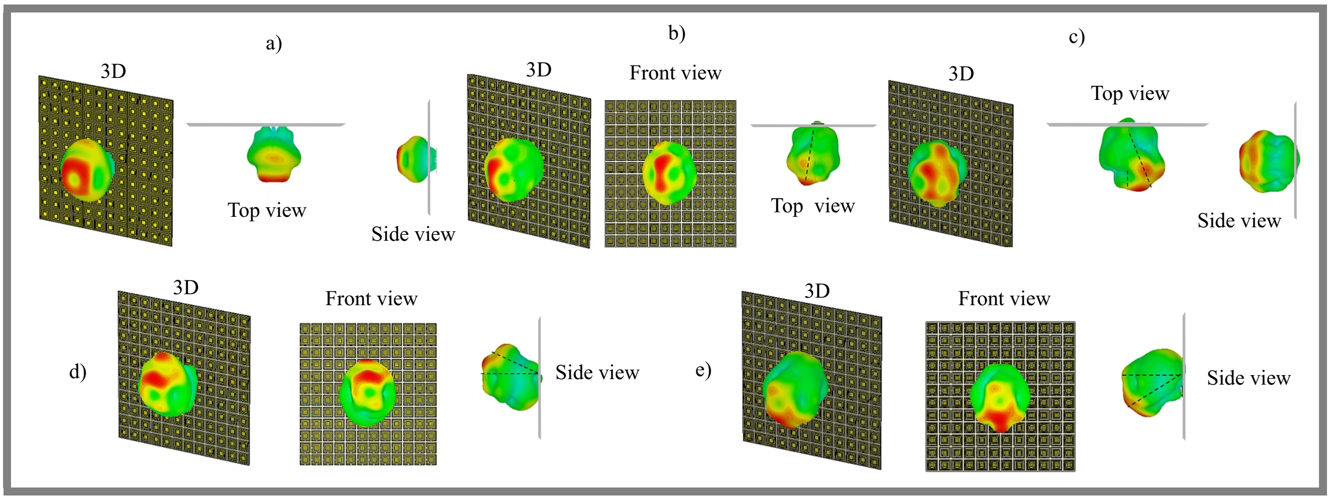


**Fig. 10.** Radiation pattern of the proposed structure in the case of: a) all diodes in on state, b) group A being in the on state, c) group B being in the on state, d) group C being in the on state, and e) group D being in the on state.

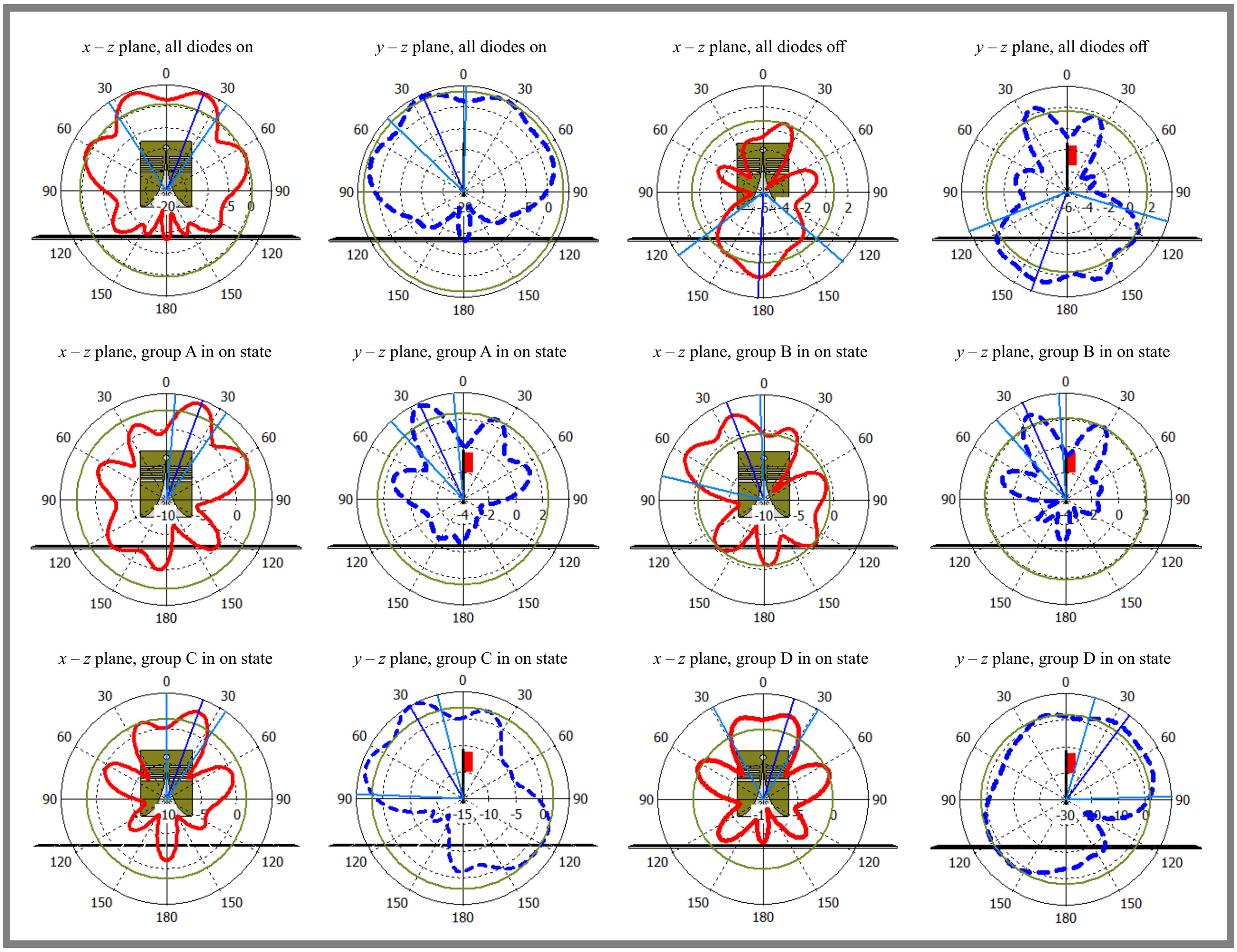


**Fig. 11.** 2D projection of radiation patterns of the proposed structure for different states of the diodes.

## 3. Conclusions

In this paper, an optimized reconfigurable reflectarry structure based on single negative unit cell metamaterials is proposed. A single negative metamaterial is used to reflect the waves. For reconfigurable behavior, two PIN diodes were used in the unit cell to manipulate its constitutive parameters ($\varepsilon_r, \mu_r$). A trust region algorithm was employed to optimize the reflectarry size area. By switching the PIN diodes, various reflection angles of the incident wave were achieved.

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