Reconfigurable Metamaterial Antenna based an Electromagnetic Ground Plane Defects for Modern Wireless Communication Devices

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ABSTRACT In this paper, a design of a microstrip antenna based on metamaterial (MTM) and electromagnetic band gap (EBG) arrays. The patch is structured from 5×3 MTM array to enhance the antenna bandwidth gain product. The individual unit cell is structured as a split ring (SRR) with a T-resonator. The ground plane is defected with an EBG to suppress the surface waves diffraction from the substrate edges. The antenna is printed on a Roger substrate with permittivity of 10.2 and 1 mm thickness. It is found that the proposed antenna provides a frequency resonance around 2.45 GHz and 3.5 GHz with another band between 4.6 GHz to 5.6 GHz which are very suitable for Wi-Fi and 5G networks. Nevertheless, the antenna gain is found to vary from 3.5 dBi to less than 6 dBi. The antenna size is reduced enough to λ/5 of the guided wavelength to fit an area of 12 mm×20 mm. The proposed antenna performance is controlled with two PIN diodes for reconfiguration process. The antenna frequency resonance bands are found to be well controlled by stopping the current motion at the particular band. The antenna is fabricated and tested experimentally. Finally, the simulated results are compared to those obtained from measurements to provide an excellent agreement to each other with error of less than 3%.

INDEX TERMS Microstrip Antenna, Reconfigurable Metamaterial, Spilt Ring Resonator (SRR), Wireless devices.

I. INTRODUCTION

RECENTLY, personal wireless communication systems were applied in different directions including wireless sensor networks, internet of things, wearable and implantable electronic devices [1]. Such research aspects became an urgent need for different reasons, such as real-time based continuous monitoring processes, biological function detection and sensing, personal RF-harvesting base maker devices [2]. However, such technologies still suffer from different limitations most of them come from the antenna size criteria [3]. This is due to the frequency bands of such applications mostly in the range of sub 3 GHz [4]. On the other hand, these antennas must be biomedically applicable in the near use of the human body [4]. Therefore, many researchers conducted their designs to establish different techniques for antenna size reduction that realizes an acceptable size with acceptable performance for short and medium communication distances [5]. For example, an antenna based on a meander patch design was proposed for wearable and implantable communication devices at 611MHz [6] and [7]. A further development was conducted on that antenna design to produce an array for MIMO systems at Wi-Fi bands [8]. Another design was proposed in [9] for the applications of wearable MIMO systems at the frequency bands of Wi-Fi systems. The antenna array size was reduced enough by conducting the use of EBG defects on the ground plane. The authors in [10] produced an antenna design for wearable MIMO systems based on four antenna elements; their design was miniaturized by using ground plane defects and a folded substrate. In [11], the authors designed a miniaturized antenna array with two monopoles. Later on, the use of a metamaterial patch with a partial ground plane to realize an UWB performance-based wearable and portable modern systems were developed significantly. For this, the authors in [12] proposed an antenna patch based on Hilbert fractal shaped MTM with a defected ground plane to obtain a high gain-bandwidth product. The authors conducted their research in [13] to realize a Vivaldi antenna patch with the same ground plane defects for portable and wearable applications at the frequency bands from 1.5 GHz to 3 GHz. The proposed antenna in [14] was designed for self-powered wearable systems in the frequency range from 1 GHz to 10 GHz.

In this paper, a microstrip antenna design based on an MTM patch with EBG ground plane defects is proposed for portable wireless devices. The proposed MTM unit cell is designed as SRR with T-stub resonator. The ground plane is defected with EBG cross slots. The antenna operation is found to be changed to sub-6 GHz. The antenna provides gain values from 3.5 dBi to 5.5 dBi that suits the applications of short and medium communication distances. The rest of the paper is organized as following; Section 2, the antenna design is presented and discussed with all geometrical details. The MTM and the EBG characterizations are discussed in section 2.1. In section 2.2, the design methodology is presented. The PIN diodes switching scenarios are discussed in section 2.3. The results validation and discussion are explored in section 3. The paper is concluded in section 4.

II. ANTENNA DESIGN AND GEOMETRICAL DETAILS

The proposed antenna, see Fig. 1, is constructed from MTM array that is etched on the antenna patch structure to provide a plasmonic zero resonance frequency response [15]. The MTM patch is consistent of 3×5 unit-cells to provide a maximum dimension of 20×12 mm^2 as depicted in Fig. 1(a). Each unit cell is constructed from a T-resonator that is de-embedded inside an SRR as shown in Fig. 1(b). The advantage of embedding the T-resonator inside the SRR is to provides a capacitive coupling effect [16]; that realizes a frequency bandwidth enhancement along with surface waves reduction [17]; which maintains the radiation efficiency enhancement through the electromagnetic aperture matching with the free space impedance [18]. The resulted structure is surrounded with a closed loop to ensure the surface current excitation from the RF source. The antenna patch is printed on a semi-flexible roger substrate of ε_r=10.2 with tanδ= 0.0012. Such substrate is considered to satisfy the antenna applications for wearable electronic devices. The back panel of the substrate is covered with a partial ground plane defected with an EBG array. The proposed EBG array is designed to be a 5×7 unit-cell matrix to provide a sufficient reduction in the antenna back radiations that is very required in the applications of wearable and portable systems [10]. Such reduction is achieved, as will be seen later, by using cross slots that produce a composite right left hand (CRLH) structure to suppress the effects of skew waves on the back panel of the antenna [19]. Therefore, the back lobes from the antenna radiations, the antenna back radiation, would be significantly vanished [20]. For configuration purposes, the authors applied the use of two PIN diodes to control the antenna performance in terms of frequency band. Such application is found to be very urgent for different smart electronic wearable devices. The proposed antenna is fabricated, using a wet chemical etching process.

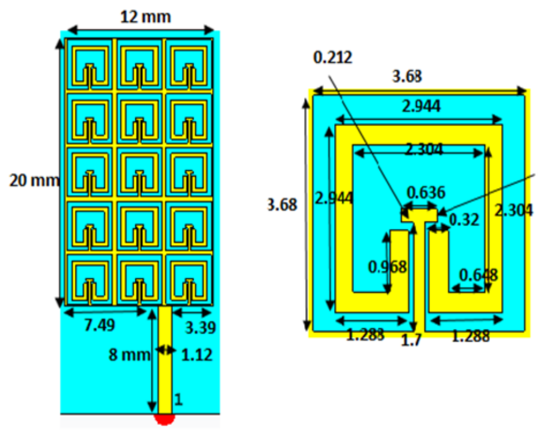

FIGURE 1. Antenna geometrical details: (a) Front view of patch structure, (b) unit cell dimensions.

A. MTM and EBG Characterizations

The proposed MTM unit cell, see Fig. 2, for this design is analyzed completely using a circuit model and a numerical analysis based on the effective medium theory based SRR structure. The circuit model of the proposed SRR is derived from the disused circuit in [21] with a modification of SRR part. As seen in Fig. 2, the unit cell is characterized equivalently with LC branches. In the circuit model analysis, the authors evaluated the lumped elements as listed in Table I.

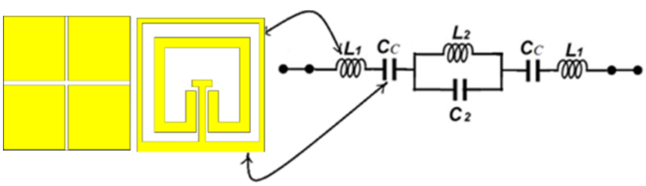

FIGURE 2. Circuit model of the proposed unit cell.

The relative lumped circuit element values of the proposed unit cell equivalent circuit model, see Fig. 2, are given in Table I.

The evaluated S-parameters from the circuit model are compared to their identical values from the numerical simulations based on CSTMWS. In the numerical simulation, the authors applied the effective medium theory using perfect electric and magnetic conductive walls to create a virtual waveguide as discussed in [22]. The created waveguide is excited with two ports to generate TEM modes with infinite bandwidth [23]. In this case, the proposed unit cell is centered inside the waveguide to evaluate the S-parameters as seen later. As seen in Fig. 3(a), the evaluated S-parameters in terms of S_{11} and S_{12} are compared to the evaluated results from the circuit model. It is found that the proposed unit cell provides excellent resonance mode at 6.86 GHz with S_{12} magnitude less than -36 dB. The bandwidth of the proposed unit cell covers the frequency band from 3.5 GHz to 7.5 GHz at $S_{12} < -10$ dB from the S_{12} spectrum. Next, the unit cell performance in terms of phase velocity variation at the first Brillion zone. At this analysis, the variation of the frequency and phase change is given in Fig. 3(b) by applying an Eigenmode solver of CST MWS. These results are compared from the analytical model based on the circuit analysis theory. It is found that the proposed results provide an excellent agreement to each other.

Table I. Circuit model of the proposed unit cell.

Parameters	Value
L1	2.2nH
Cc	1.5pF
L2	1.1nH
C2	1.7pF
Cc	1.1pF
L1	1.3nH

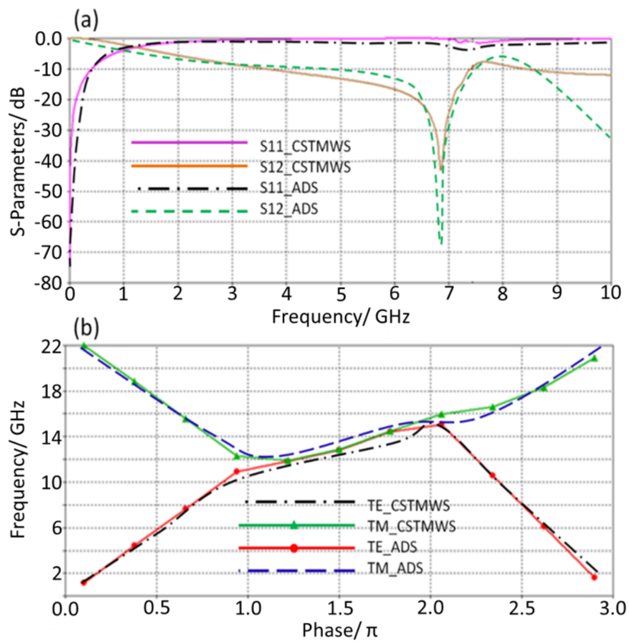

FIGURE 3. Unit cell properties: (a) S-parameters and (b) dispersion diagram.

B. DESIGN METHODOLOGY

1) PATCH WITHOUT MTM

The proposed antenna results, as shown in Fig. 4 in terms of S_{11} is constructed based on a rectangular patch with a mesh net geometry by etching a square area from the metallic layer of the patch. In this case, the authors eliminated SRR and without EBG layers to realize the fundamental properties of the plate form of their design.

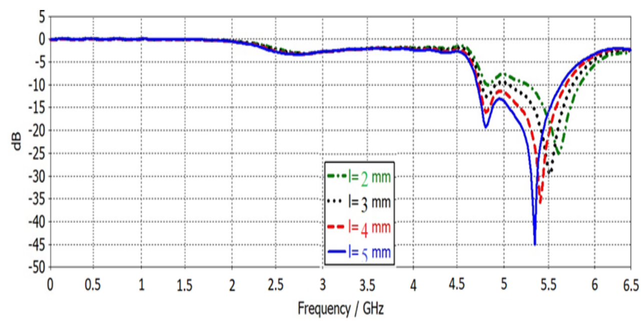

FIGURE 4. S_{11} spectra of the proposed design case.

2) PATCH WITH SRR AND WITHOUT EBG

Now, the proposed SRR unit cell is mounted in the etched slot on the patch to result an array of 3×5 as shown in Fig. 5. It is found from the achieved results, a significant enhancement in the antenna bandwidth. As seen in Fig. 5, the antenna matching bandwidth variation with changing the transmission line width (w) is studied. It is found that the proposed case provides a bandwidth from 4.7 GHz to 5.75 GHz with another band around 2.73 GHz.

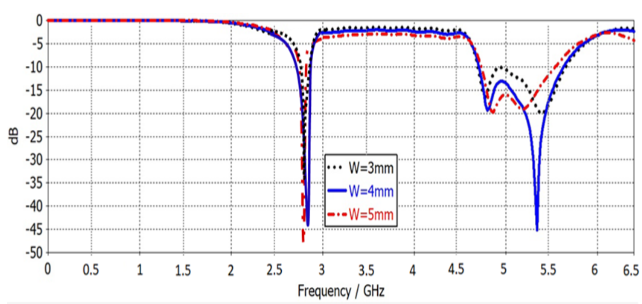

FIGURE 5. S_{11} spectra of the proposed design case.

3) PATCH WITH SRR AND EBG LAYERS

The proposed patch design is filled with the MTM inclusions to provide a plasmonic behavior [24]. This introduction increases the antenna bandwidth significantly. From the results in Fig. 6, it is found that the proposed antenna provides a bandwidth around 2.45 GHz with another band at 3.5 GHz. Such an increase is attributed to the surface waves suppressing by the single negative components of the proposed SRR unit cell. The effect of the distance between the ground plane and the EBG layer (l) is discussed by changing this distance from 1 mm to 4 mm with a step of 1 mm.

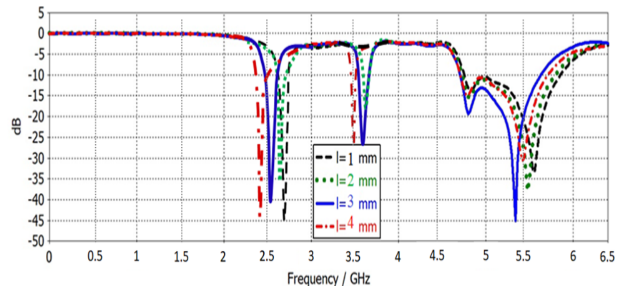

FIGURE 6. Effects of the ground plane separation distance from the EBG layer.

C. PIN DIODES SWITCHING SCENARIOS

In this section, the effects of switching the PIN diodes on the antenna performance are explored through a parametric study. Therefore, S_{11} and gain spectra are monitored concerning the PIN diodes switching process. As depicted in Fig. 7(a), varying the switching scenarios results in a significant variation in the first and second resonance modes of the proposed antenna. However, the antenna bandwidth at the third resonance is significantly altered without varying the frequency resonance location. In Fig. 7(b), the antenna gain spectra show a significant reduction when changing the switching scenarios due to the disappearance of particular frequency resonance caused by the effects of storing losses [21]. Thus, the impact of varying the diodes switching on the antenna performance is listed in Table II.

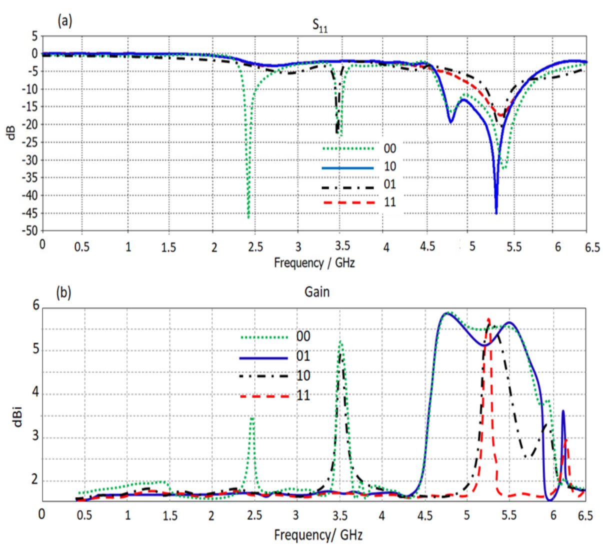

FIGURE 7. Antenna performance in terms of: (a) S_{11} and (b) gain.

Table II. Antenna performance with varying the diodes switching.

Scenarios	Frequency Resonance/GHz	Gain/ dBi
00	2.45, 3.5, 4.6-5.4	3.5,5.2, 5.5
01	4.6-5.4	0.011, 0.001, 5
10	3.5, 5.4	5, 5.5
11	5.4	5.7

III. RESULTS AND DISCUSSION

The proposed antenna is fabricated as seen in Fig. 8(a) using Nano sphere lithography and wet chemical etching processes that were used in [25]. The antenna structure is mounted on the Roger substrate to realize low dielectric material loss. The antenna is measured using a vector network analyzer (37347A) VNA to measure S_{11} spectra. The achieved results are presented in Fig. 8(b) in terms of S_{11} spectra with different diodes switching scenarios. We found that the achieved results agree with the simulated results from CST MWS.

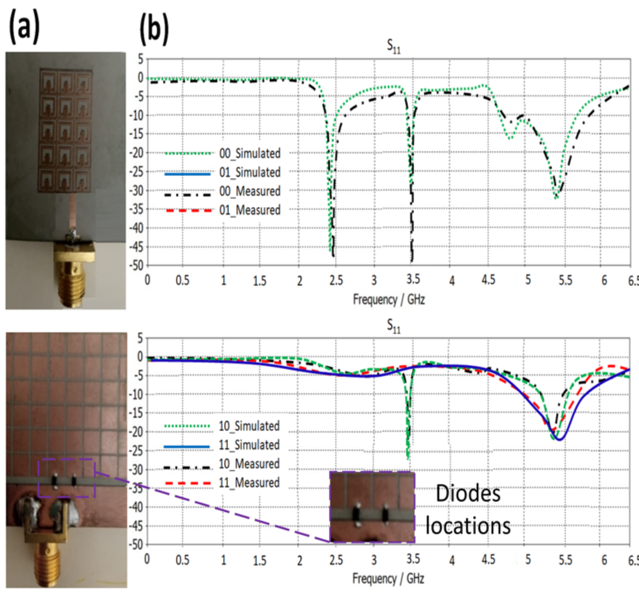

FIGURE 8. Fabricated antenna test with diodes locations: (a) Fabricated prototype and (b) S_{11} spectra.

IV. CONCLUSION

In this work, a novel antenna structure is proposed for the applications in portable modern wireless devices including 5G networks. The antenna is structured from an SRR patch with an EBG defected ground plane, and mounted on Roger substrate. Two PIN diodes are attached to the proposed antenna to control the performance in terms of radiation efficiency and frequency resonance. The antenna size is miniaturized to λ/5 to suit the portable devices. The antenna gain is found to be vary from 3.5 dBi to 6 dBi within the frequency range of interest. It is found that such gain is very useful for short and medium communication distances. Nevertheless, we obtained an excellent beam forming after varying the capacitive value that makes the antenna an excellent candidate for beam steering to suit many applications including the 5G networks and other smart wireless devices. The antenna shows a frequency resonance around 2.45 GHz, 3.4 GHz, and 5 GHz that makes it excellent fit to 5G communication networks. The obtained results from the simulation and the experimental measurements are agreed well to each other. Finally, as a future work of this research, the authors want to construct an antenna array of their proposed design for MIMO applications in the 5G networks. Therefore, as a part of that applying the practical measurements in real environments would part of this research.

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