2022 IEEE 72nd Electronic Components and Technology Conference (ECTC) | 978-1-6654-7943-1/22/$31.00 ©2022 IEEE | DOI: 10.1109/ECTC51906.2022.00025

Compact frequency reconfigurable array antenna based on diagonally placed meander-line decouplers and PIN diodes for multi-range wireless communications

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Abstract— **In this paper, a compact frequency reconfigurable 2 × 2 array antenna based on diagonally placed meander-line (ML) complementary split-ring resonator (CSRR) decouplers and PIN diodes has been demonstrated. The ML-CSRR structured on the ground plane helps to reduce the mutual coupling between closely located patches (2 mm, 0.015 λ_0). The PIN diodes which act as switches have been located over the gap between neighboring patches. The antenna operates at 2.4 GHz when PIN diodes are reverse-biased (off-state), while it is reconfigured to operate at 914 MHz when the PIN diodes are changed to forward-biased (on-state). Design is fine-tuned with High Frequency Structure Simulator (HFSS, ANSYS Inc.). The antenna has been fabricated and characterized. The simulated and measured results have been compared. At 2.4 GHz, when the switch is in off-state, the antenna can be used for short-range wireless communications such as Wi-Fi and Bluetooth while at 914 MHz, when the switch is in on-state, it can be planned for the usage of Public Protection and Disaster Relief (PPDR) with the long-range wireless communication technology including low power wide area networks (LPWAN).**

Keywords- Reconfigurable antenna, 2 × 2 Array Patches, PIN diodes, Meander-line Complementary Split Ring Resonator, Multi-range wireless communications

I. INTRODUCTION

With the increased number of IoT devices and the advancement of its application these days, the demands for using multiple frequency spectra in a single device are rapidly growing [1] – [3]. However, a number of antennas to meet the demands require large device areas, which are not getting along with the current technology trend for minimized and lightweight gadgets in 5G communications era. Such an issue may be mitigated by designing an antenna that can have its operating frequency reconfigurable, and thus it is able to reduce the weight, dimension, and cost while meeting broadband frequency coverage.

In particular, requests for multi-range communication equipment are increasing in many fields such as smart cities, agriculture, and security. However, short-range wireless communication devices which are mainly produced in modern systems can cover only limited spans and need a high-power source. Meantime, low power wide area networks (LPWAN) technology such as LoRaWAN and Sigfox has been getting attention in recent wireless communication systems because it has several advantages, such as low power requirement, low deployment cost, and extended coverage compared with other IoT applications. LPWAN ensures communications from 10 to 40 km in the rural area and up to 5 km in the urban area [4]. In this sense, LPWAN technology fits well to be mounted on the unmanned aerial vehicle (UAV) and adapted for tracking assets, logistics, transportation, and smart cities [5].

Especially, when a disaster strikes, LPWAN technology can help recover communications in disaster areas by substituting the dysfunctional base station. In particular, an unexpected disaster such as flooding, tornado, hurricane, earthquakes, or terrorism causes to disable network operation, which leads to people being trapped in a dangerous situation and missing their 72 golden hours for rescue. On December 10, 2021, a violent tornado hit Western Kentucky, producing severe damage in numerous towns including death and missing cases. Mobile and internet communication was obliterated. To make it worse, the emergency operation center lost the ability to transmit radio communications, preventing the trapped people from reaching the rescue team. Deepak et al. [6] has reported that the aerial base station (UAVs) would replace the failed base station in a disaster area and directly connect to USER within the ISM band spectrum (915 MHz in North America).

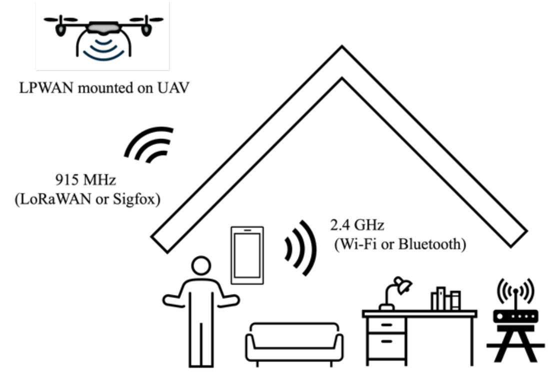


Fig. 1. The illustration of the proposed antenna for the multi-range wireless communications system

In this work, we present a compact frequency reconfigurable 2 x 2 array antenna operating at 914 MHz (LPWAN) and 2.4 GHz (Bluetooth and Wi-Fi) as we can choose depending on the situation as shown in Fig. 1. The reconfigurability can be realized with PIN diodes connected between the patch elements. PIN diodes have several advantages compared to varactor diodes and MEMS switches. They have a fast response time, low insertion loss, good

2377-5726/22/$31.00 ©2022 IEEE
DOI 10.1109/ECTC51906.2022.00025

isolation, high power handling capacity, simple biasing circuitry, and low cost [1]. Nonetheless, for resonating at both frequencies, the patches are designed to be closely placed than a typical distance (0.5 λ_0) between patches. However, the close proximity causes large mutual coupling and interference with neighboring patches. To suppress such coupling between the neighboring patches, a meander-line complementary splitring resonators (ML-CSRR) is placed under each patch in a diagonal direction. This array antenna is expected to show good multi-input multi-output (MIMO) antenna performance.

II. ANTENNA DESIGN AND SIMULATION RESULT

Fig. 2 shows a schematic of a frequency reconfigurable 2 x 2 array antenna based on diagonally placed ML-CSRRs and PIN diodes drawn with Full-wave 3D electromagnetic software, High Frequency Structure Simulator (HFSS, ANSYS Inc.). The patches are placed on a printing circuit board (PCB, FR-4) with a dielectric constant of 4.4 and a loss tangent of 0.02. The patches are placed closely (2 mm, ≅ 0.015 λ_0) where it is much smaller than a typical distance (0.5 λ_0) and is designed so to reduce the footprint of the antenna operating at target frequencies. The reduced gap between the patches causes severe interference to each patch, and the antenna resonant frequency would be changed with the different distance between patches. Several papers have addressed how to reduce mutual coupling using electromagnetic bandgap (EBG) structures, defected ground structures, and metamaterials [7] – [9]. In this paper, we have used meander-line (ML) slots since they have shown good performance to block the surface waves and good antenna efficiency than other approaches [9]. An ML-CSRR structure with a gap of less than 200 µm performs well as a band stop filter and enhances effective capacitance and inductance.

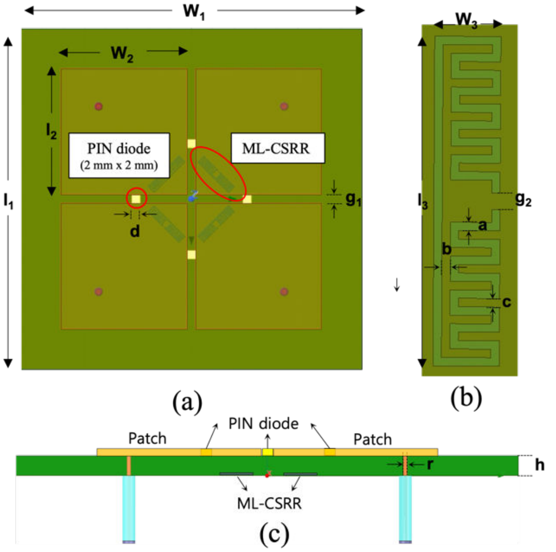


Fig. 2. Designed patch array: (a) top view, where W_1, l_1 = 80 mm, W_2, l_2 = 29.5 mm, d = 2 mm, g_1 = 2 mm, (b) ML-CSRR slots, where W_3 = 1.39 mm, l_3 = 7.06 mm, a = 0.16 mm, b = 0.16 mm, c = 0.2 mm, (c) front view, where r = 0.298 mm, h = 3.175 mm

The surface-mounted PIN diodes are located over the gap between the neighboring patches. The PIN diode (SMP1304-085LF, Skyworks Inc.) is used as a shunt connected PIN diode and is operated in a frequency range of 10 MHz - 6 GHz. Fig. 3 shows a lumped element model of the diode, which is formed with a turn-on resistance of 2 Ω under forward-bias (Fig. 3b), otherwise, a parallel combination of 1.5 kΩ resistance and 0.3 pF capacitance under reverse-bias (Fig. 3a):

$$|Z| = |jwL| = (2\pi \times 2.4 \times 10^{9}) \times 100 \times 10^{-9} = 1{,}500\,\Omega \quad (1)$$

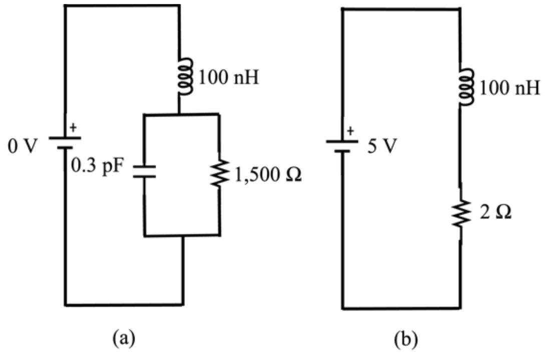


Fig. 3. Equivalent circuit model of the PIN diode under (a) reverse-biased condition ('off' state), (b) forward-biased condition ('on' state)

When PIN diodes are reverse-biased ('off' state), the patches function as a 2 x 2 array antenna with each patch of 29.5 mm x 29.5 mm. On the other hand, when PIN diodes are forward-biased ('on' state), the four patches are electrically connected and the current flows on all the patches, acting as a 61 mm x 61 mm single patch antenna as shown in Fig. 4. Specifically, when port 1 is excited and terminated with 50 ohms and other ports are 50 ohms terminated, the current from port 1 cannot flow to other patches when the PIN diodes are in 'off' state as shown in Fig. 4-(a). In contrast, when the PIN diodes are in 'on' state, the current flows all the patches as shown in Fig. 4-(b).

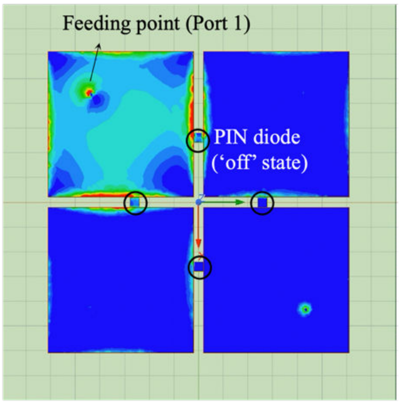


Fig. 4-(a). Current distribution when the PIN diodes are in 'off' state

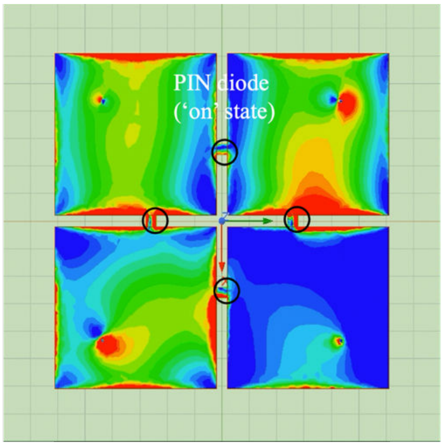


Fig. 4-(b). Current distribution when the PIN diodes are in 'on' state

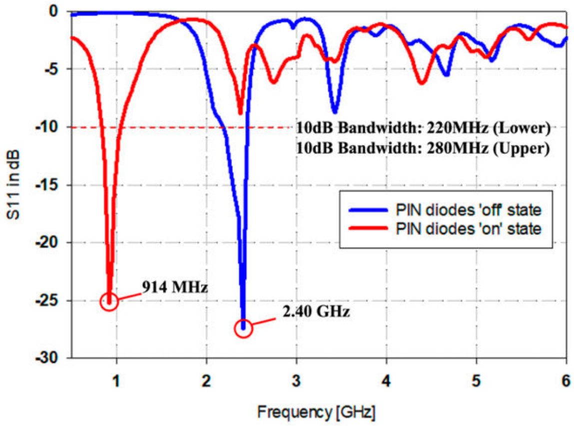


Fig. 5. Simulated radiation frequencies of the proposed antenna with the PIN diodes in 'on' (red) and 'off' state (blue)

Fig. 5 shows a simulated result using HFSS, where the resonant frequency is 2.40 GHz and the 10 dB bandwidth is 280 MHz with the PIN diodes in 'off' state, and it can be operated for Bluetooth or Wi-Fi applications. On the other hand, in 'on' state, the resonant frequency is 914 MHz, and the 10 dB bandwidth is 220 MHz, which can be used for LPWAN applications. The return loss at 914 MHz and 2.4 GHz is 25 dB and 27 dB, respectively.

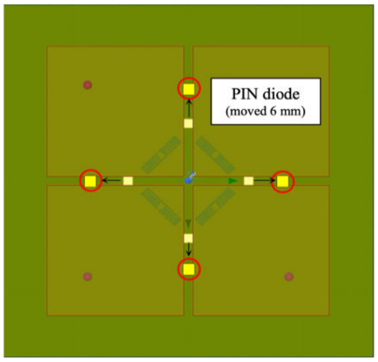


Fig. 6-(a). Top view of the proposed antenna by changing the PIN location

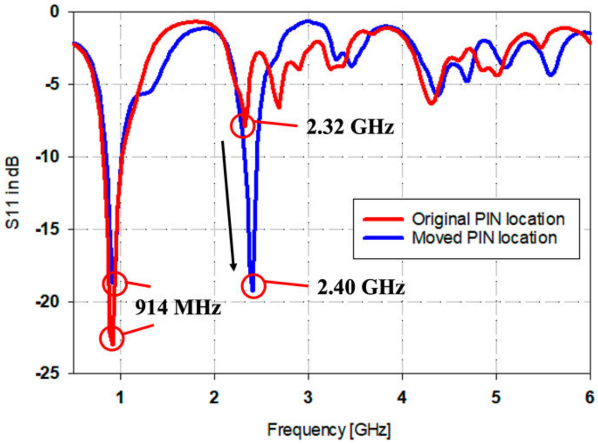


Fig. 6-(b). The simulation results compared to different PIN locations

Depending on PIN diode's location in the gap between patches as shown in Fig. 6-(a), the performance of the return losses is different. It shows a single peak at 914 MHz with PINs in its original position while showing dual peaks (dual-bands), i.e. 914 MHz and 2.4 GHz with PINs placed in shifted locations as shown in Fig. 6-(b). the new diode position is 6 mm away from its original location.

III. FABRICATION OF THE PROPOSED ANTENNA

The fabricated frequency reconfigurable 2 x 2 patch array antenna with ML-CSRRs and PIN diodes is shown in Fig. 7. The patches are placed on the top surface of the substrate and the ML-CSRRs are on the bottom side, i.e. the ground plane. The PIN diodes are placed over the gaps between patches and soldered using Sn63/Pb37 solder paste and heat [10]. After the PCB is heated in a stove, the solder paste melts, forming a mechanical and electrical connection. The total area of the frequency reconfigurable 2 x 2 array antenna is 61 x 61 mm^2. The antenna shows a compact size compared to other 2 x 2 patch array antennas operating at 2.4 GHz [11]-[13].

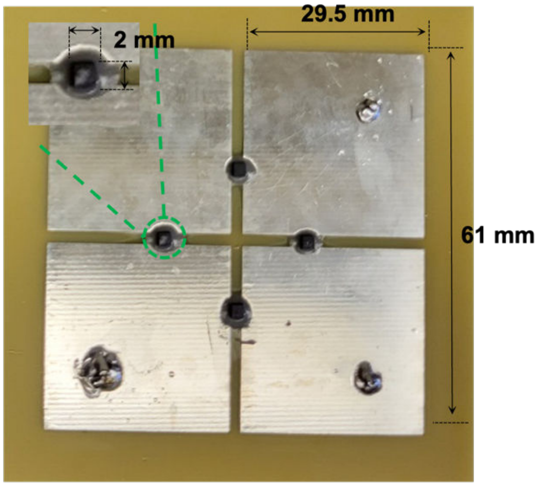


Fig. 7-(a). Top view of a fabricated frequency reconfigurable 2 x 2 array antenna with ML-CSRRs and the PIN diodes

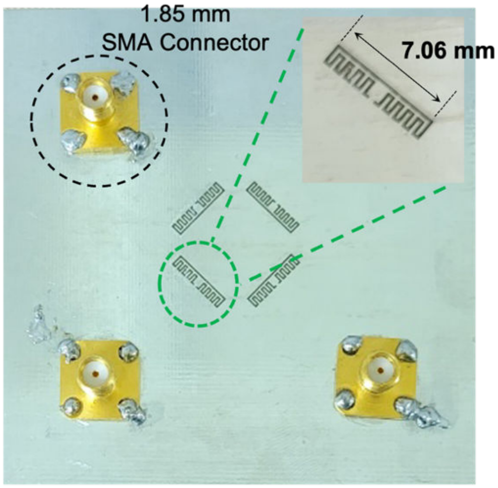


Fig. 7-(b). Bottom view of a fabricated frequency reconfigurable 2 x 2 array antenna with ML-CSRRs and the PIN diodes

A vector network analyzer (E5071C, Agilent Technologies) is used for measuring the return loss of the fabricated antenna. Fig. 8 shows the comparison of the measured return loss when the PIN diode is in 'on' and 'off' state. The measured resonant frequencies are 900 MHz and 2.23 GHz, and the return loss is 34 dB and 31 dB, respectively.

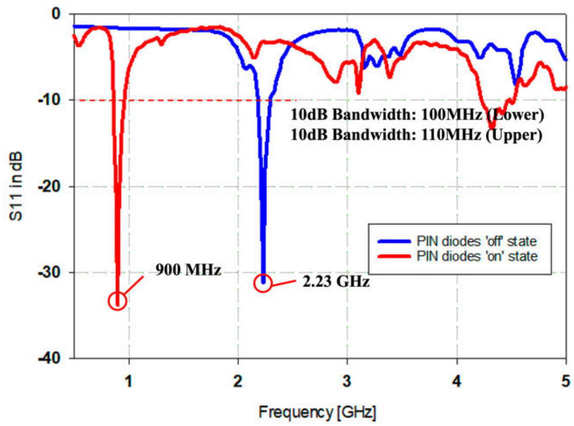


Fig. 8. Tested radiation frequencies of the fabricated antenna with the PIN diodes of 'on' and 'off' state

IV. COMPARISON OF RESULTS AND ANALYSIS

The measured result is downshifted from the simulated result by 14 MHz when the PIN diodes are reverse-biased as shown in Fig. 9. The measurement result with PIN diodes 'on' state (i.e. a forward-biased condition), the radiation frequency is also downshifted by 170 MHz as shown in Fig. 10. These shifts are attributed to fabrication and integration tolerance. Although there are slight shifts between the simulated and measured frequencies, overall, they show good matching between them, supporting a proof of concept that we can control the frequencies for the long- and short-range communications in the event of emergency.

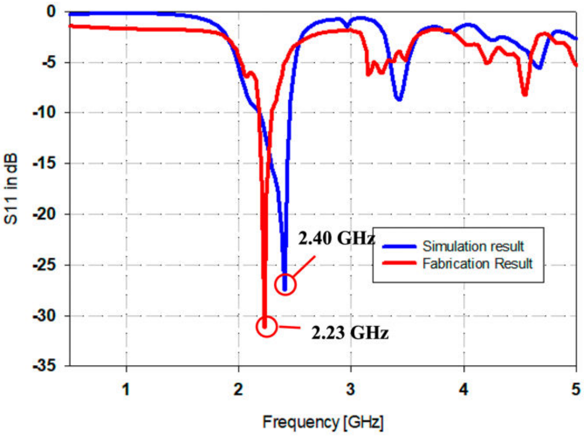


Fig. 9. Measured and simulated results of return loss when the PIN diodes are in 'off' state

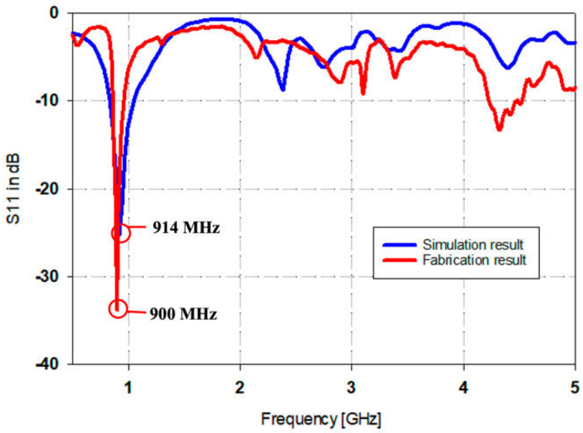
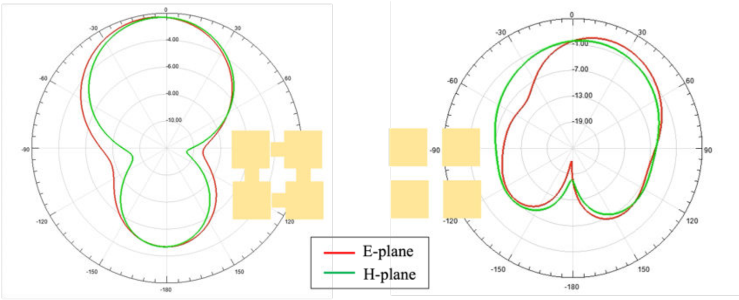


Fig. 10. Measured and simulated results of return loss when the PIN diodes are in 'on' state

The radiation patterns of the patch array at 914 MHz and 2.40 GHz are shown in Fig. 11. The total gains of the antenna are -2.4 dB and -0.9 dB, respectively.



(a) 914 MHz

(b) 2.40 GHz

Fig. 11. Radiation patterns of the patch array: (a) at 914 MHz, (b) at 2.40 GHz

V. CONCLUSION

In this work, a compact frequency reconfigurable 2 x 2 patch array integrated with ML-CSRR slots and PIN diodes is designed, fabricated, and characterized. The ML-CSRRs are placed on the ground plane for the reduction of mutual coupling between narrowly spaced neighbouring patches. Surface mount PIN diodes are connected between patches on the top surface and their on/off conditions are controlled by DC bias. The tuning capability between 2.4 GHz and 914 MHz bands has been demonstrated. It is applicable not only for multi-range wireless communications but also for the post-disaster scenario toward recovering communications by using a UAV-assisted base station. This type of reconfigurable device would also contribute to the enhancement of spectrum efficiency in the IoT era.

ACKNOWLEDGMENT

This material is based upon work supported by the National Science Foundation under Grant Number 2030122. The device has been fabricated by the Multidisciplinary nano and Microsystems (MnM) Laboratory at the University of Florida. S.Choi is supported by the Republic of Korea Army Abroad Training program.

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