Experimental Characterization of 2×2 Electronically Reconfigurable 1 Bit Unit Cells for a Beamforming Transmitarray at X Band

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Abstract

This paper proposes a reconfigurable unit cell for a transmitarray operating at the X band. The unit cell consists of an active patch, a passive patch, and a phase shifter. The active patch has two PIN diodes that change the phase of 180° of the transmitted waves. The passive and active patches both have circular slots to enhance the bandwidth of the transmitted wave. We also propose a new type of experimental characterization technique to measure the performance of the unit cells at the X band without fabricating the entire transmitarray. Instead of a 1 unit cell as described in the literature, we propose 2×2 unit cells to measure the performance of unit cells using the X band waveguide. The waveguide consists of a WR-90 section and a rectangular to square waveguide transition section that can be fit to our proposed structure. A good agreement between simulated and measured results was found.

Key Words: Beamforming, PIN Diode, Reconfigurable Unit Cell, Transmitarray.

I. INTRODUCTION

Transmitarrays are one of the promising candidates for beam steering and polarization conversion at microwave and millimeter waves instead of the traditional phased arrays, which suffer from large insertion loss. Automotive radars, 5G networks, and some advanced military equipment require electronic scanning and a polarization converted beam. These types of antennas were extensively investigated in the last few years [1–12], and in [13], the first transmitarray was proposed, connecting upper patch and lower patch through a via for beam steering operation. Since then, different types of transmitarrays have been proposed by different authors. Transmitarrays consist of several periodical

identical elements known as unit cells. The unit cell can be based on a frequency selective surface or microstrip patches, or they can be inspired by metamaterial structures. Transmitarrays can be fabricated using conventional printed circuit board (PCB) technology by etching different layers and then connecting those layers. They are very lightweight and planar, which makes them suitable for integration with other planar devices. Moreover, the feeding antenna for a transmitarray is kept separated and at a distance, making transmitarrays ideal for a greater degree of modularity in comparison to conventional phased array antennas. A simple design, low fabrication design costs, greater flexibility, low losses, and low-profile characteristics make the transmitarray antenna system ideal for beam steering and polariza-

Manuscript received November 14, 2020 ; Revised January 9, 2021 ; Accepted February 14, 2021. (ID No. 20201114-183J)

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tion conversion of waves, and they are preferable in comparison to phased array. The transmitarray antennas are also more attractive when compared to reflect arrays [14–16] because waves are passed through the transmitarray, so they have no feed blockage. To achieve electronic beam steering, polarization conversion, or frequency tuning characteristics, transmitarrays require different types of elements, such as PIN diodes, varactor diodes, microelectromechanical systems, liquid crystals, and more. Several types of unit cells have been proposed in recent years using PIN diodes [1, 3, 5, 10, 11], varactor diodes [7, 17], microfluidics [18], or MEMS [19], and it is crucial to understand the performance of the unit cell before fabricating a complete transmitarray structure.

In this paper, a new type of very wideband 1 bit ($0^\circ/180^\circ$) electronically reconfigurable unit cell is proposed using PIN diodes. The size of the unit cell at X band is not comparable to the size of the X band waveguide. Thus, it is difficult to fabricate a waveguide transition section from X band WR-90 to the size of the unit cell [1]. To overcome this, we propose a new type of experimental characterization procedure based on an X band waveguide rectangular to square transition section where we have used 2×2 unit cells instead of a 1 unit cell. The design of the rectangular to square waveguide transition section is very easy, and the proposed method is useful for determining the performance of unit cells at the initial stages, without having to fabricate the entire transmitarray.

The remainder of this paper is arranged as follows. In Section II, the configuration and operating principle of the unit cell are discussed, and then the simulated performance of the unit cell is described in Section III. The waveguide transition section is a vital part of our design, and we describe the performance of the waveguide transition section with a WR-90 waveguide in Section IV. Similarly, biasing lines for our 2×2 unit cells are crucial, so biasing lines and the configuration of the 2×2 unit cells are explained in Section V. The performances of the 2×2 unit cells with an X band WR-90 waveguide and the rectangular to square waveguide transition work are discussed in Section VI. Finally, a conclusion of the total work is presented in Section VII.

II. CONFIGURATION AND OPERATING PRINCIPLE OF THE UNIT CELL

Fig. 1(a) shows the cross-sectional view of the proposed unit cell, and Fig. 1(b) shows the 3D view of the proposed unit cell. A passive circular-shaped patch antenna with an 8.8 mm diameter that is loaded with a circular slot having a diameter of 3.1 mm on the receiving side were considered for our design. A similar circular patch and slot on the transmitting side were also considered. The transmitting side of the patch has two PIN

Fig. 1. (a) Cross-sectional view of the unit cell. (b) 3D view of the unit cell.

diodes (MA4GP907; MACOM, Lowell, MA, USA), which are shown in Fig. 1(b). The diagram shows two circular type microstrip patches connected by metallized via holes located at their centers and separated by a ground plane and bonding film with permittivity of 3.88, loss tangent of 0.0236, and thickness of 0.1 mm. The diameter and height of the metallized via holes connecting the active patch and passive patch are 0.4 mm and 3.3 mm, respectively.

As shown in Fig. 1(b), the active microstrip antenna loaded with a circular type slot has two PIN diodes for phase switching operation. The passive microstrip antenna in Fig. 1(b) also has a circular slot to enhance operational bandwidth. A Taconic RF-35 substrate with permittivity of 3.5, loss tangent of 0.0018, and height of 1.6 mm was considered for our proposed design. Table 1 shows the dimensions of the proposed unit cell. Although two metallized via holes are sufficient for our design, we used four metallized via holes to keep the structure symmetrical. This configuration also reduces the cross-polarization level. One metallized via hole shown in Fig. 1(b) (forming the top of the active path to the bonding film) was used with the bias line that connects the PIN diodes and the power supply. The bias line has a width of 0.21 mm. Another metallized via hole (forming the top of the active path to bonding film) was kept as a dummy via hole. Both metallized via holes have a diameter of 0.4 mm

Table 1. Main features of the unit cell

Parameter	Value
Unit cell size	15 mm $\times$ 15 mm
Patch diameter	8.8 mm
Slot diameter	3.1 mm
Substrate	Taconic RF-35 ($\epsilon_r = 3.5$, $\tan\delta = 0.0018$, $h = 1.6$ mm)
Bonding film	$\epsilon_r = 3.88$, $\tan\delta = 0.0236$, $h = 0.1$ mm
Diameter of connecting via	0.4 mm
Diameter of bias vias	0.4 mm

and a height of 1.6 mm. As shown in Fig. 1(b), the PIN diodes are connected in such a way that they always stay in opposite biased conditions for any single biasing signal. Therefore, the slot on the active patch always stays in a short-circuited condition on one side.

III. SIMULATED PERFORMANCE AND EQUIVALENT CIRCUIT OF THE UNIT CELL

The unit cell was simulated with the ANSYS Electronics Desktop simulator for both phase states. The unit cell was illuminated by a plane wave under normal incidence, with boundary conditions on the four walls of the boundaries. To present forward bias and reverse bias of the PIN diodes, an equivalent lumped RLC circuit model was used, and Fig. 2 shows the equivalent RLC circuit model of a PIN diode for the forward bias ($L_{11} = 0.05$ nH, $R_{11} = 5.2$ Ω for the forward bias condition, and for the reverse bias, $L_{22} = 0.05$ nH, $R_{22} = 300$ k Ω , $C_{22} = 25$ fF). In this paper, we used the label State1 when the PIN Diode 1 shown in Fig. 1(b) was in a reverse biased condition and PIN Diode 2 was forward biased. The opposite conditions were used for State2. The magnitude of transmission and reflection coefficients are depicted in Fig. 3, which shows that a -3 dB transmission bandwidth for State1 was 1.08 GHz (8.82–9.9 GHz), while it was 1.02 GHz (8.81–9.83) for State2. There was a slight difference between the simulated performance of the magnitude of transmission and reflection coefficients for State1

Fig. 2. Equivalent model of PIN diode for forward bias and reverse bias conditions.

Fig. 3. Magnitude of S -parameters of the unit cell, obtained from the ANSYS Electronics Desktop simulations.

and State2. This may be due to the effect of the opening diameter on the ground plane, weak signal interaction between active and passive patches, and the asymmetric structure of the passive patch. The phases of the transmission coefficient are shown in Fig. 4. It can be seen that there was a phase shift of around 180° for State1 and State2 of the unit cell. At 9.1 GHz, phases of the transmission coefficients for State1 and State2 were 35.2° and -147.4° , respectively. The insertion loss at 9.1 GHz was -0.7 dB.

In Fig. 5, an equivalent circuit for the proposed unit cell is depicted. The slot-loaded circular patch on the top layer can be modeled by two impedances Z_1 and Z_2 . Similarly, the slot-loaded circular patch on the bottom layer can be modeled by two impedances Z_6 and Z_5 . The patches on the top and bottom

Fig. 4. Phases of the transmission coefficient of the unit cell obtained from the ANSYS Electronics Desktop simulations.

Fig. 5. Equivalent circuit of the 1 bit transmitarray unit cell.

layers are in the free space, which can be modeled as an ideal transformer with 377Ω port impedance. The unit cell has two PIN diodes that are connected in such a way that while one PIN diode is in the forward bias condition, the other PIN diode is in a reversed bias condition. The forward bias and reverse bias conditions can be represented as equivalence impedances of Z_4 and Z_3 , respectively. Furthermore, the PIN diodes have a bulk volume that gives additional capacitance, and a series capacitance C_1 and shunt capacitance C_2 are needed to compensate for the bulk volume of the PIN diodes.

IV. DESIGN OF WAVEGUIDE TRANSITION SECTION AND ITS PERFORMANCE

The geometry of the waveguide WR-90 with transition section is shown in Fig. 6. The X band rectangular WR-90 waveguide has an opening area of $22.86 \times 10.16 \text{ mm}^2$. But our proposed 2×2 elements transmitarray has an area of $30 \times 30 \text{ mm}^2$, so it requires a transition section through which the signal can propagate at X band. Thus, we designed a rectangular WR-90 to square waveguide transition section. The cross-sectional view of the waveguide transition section is shown in Fig. 6. The cut-off frequency of the WR-90 waveguide for TE_{10} mode is 6.557 GHz, and the next highest order cut-off frequency for that waveguide is 13.114 GHz. The cut-off frequency for the $30 \times 30 \text{ mm}^2$ section for the lowest order and next low order modes were 4.99 GHz and 6.24 GHz, respectively. However, because of the very small length of the transition section, the signal for the TE_{10} mode can propagate at the edge of the transition section without any significant attenuation.

The transition section was fabricated with copper material and is shown in Fig. 7. In the ANSYS Electronics Desktop simulator, the complete waveguide setup was simulated, and it was measured with an Agilent vector network analyzer and rectangular to square waveguide transition section. The simulated and measured transmission and reflection coefficients with the rectangular to square waveguide transition section are shown in Fig. 8.

Fig. 6. The geometry of the waveguide transition section.

Fig. 7. Fabricated waveguide transition sections.

Fig. 8. Magnitudes of S_{11} and S_{21} with the transition section.

V. DESIGN OF 2×2 ELEMENTS UNIT CELLS WITH BIASING LINE

Before designing the whole transmitarray, it was necessary to fabricate and measure the performances of the unit cell using the waveguide. To do this, we designed and fabricated 2×2 1-bit unit cells instead of a single 1 bit unit cell because of the simplicity of the waveguide transition section for 2×2 1-bit unit cells. Fig. 9, the top view of our proposed unit cells, shows

Fig. 9. Schematic top view of the 2×2 1-bit unit cells.

that the total structure was $70 \times 70 \text{ mm}^2$. The large ground plane of $50 \times 50 \text{ mm}^2$ and two rows of metallized via holes with a diameter of 0.4 mm each ensured continuity of the waveguide wall through the prototype.

There are four circular patches, each of which has two PIN diodes. A 10 V power source was used to feed the biasing network for 2×2 unit cells. An inductor of 1.4 nH and a resistor of 200Ω (self-resonant frequency at 10 GHz) were used to suppress the effect of the bias network. Fig. 10 shows the biasing line of our design. The biasing lines were kept inside the structure to minimize their effect on the unit cell performances, and it was found through simulation that the biasing line had no significant effect on the unit cell performances. As shown in Fig. 9, there are five connection lines: four connect to eight PIN diodes, and one is for the ground plane.

Fig. 11 shows the bottom view of the proposed 2×2 1-bit unit cells with four passive patches that receive the signal from a source and send to the active patch through the central metallized

Fig. 10. Schematic of the biasing lines for our 2×2 1-bit unit cells.

Fig. 11. Schematic bottom view of the 2×2 1-bit unit cell.

via hole. The top and bottom views of the fabricated prototype, with PIN diodes, chip inductor, and chip resistor, are shown in Fig. 12(a) and (b), respectively.

VI. EXPERIENTIAL CHARACTERIZATION OF 4-ELEMENT UNIT CELLS

Fig. 13 shows the complete setup used to measure the performance of the 2×2 1-bit unit cells. This included an Agilent vector network analyzer, two X band WR-90 waveguides, two rectangular to square waveguide transition sections, and a voltage source. The voltage source was set at 10 V so that sufficient current could pass through the forward-biased PIN diode. The vector network analyzer was calibrated using the through-reflect-line (TRL) method. Fig. 14 shows the simulated and measured magnitudes of transmission coefficients for State1, and Fig. 15 shows the simulated and measured magnitudes of transition coefficients for State2.

At 9.1 GHz, the simulated and measured magnitudes of transmission coefficients for State1 were -1.8 dB and -1.4 dB , respectively. At the same frequency, the magnitudes of transmission coefficients were -1.6 dB and -1.6 dB , respectively, for State2. Thus, there was little difference between the simulated and measured results across the bandwidth. This can be due to

Fig. 12. Fabricated 2×2 1-bit unit cells with PIN diode, chip inductor, and chip resistor: (a) top view, (b) bottom view.

Fig. 13. Measurement setup with VNA and power supply.

Fig. 14. Simulated and measured magnitudes of transmission coefficient for State1.

Fig. 15. Simulated and measured magnitude of transmission coefficients for State2.

fabrication errors in the unit cells and adding a coating material to the top and bottom layers during fabrication. The simulated and measured phases of the transmission coefficients for State1 and State2 are provided in Fig. 16. Using a Floquet mode approach, the simulated results showed -3 dB bandwidth for 1.08 GHz. Figs. 14 and 15 show narrowly different simulated and measured results using the waveguide and the rectangular to square waveguide transition. These differences were due to the imperfect rectangular to square transition section.

Fig. 16. Simulated and measured phases of transmission coefficients for State1 and State2.

We compared our proposed unit cell with the 1 bit unit cells (having PIN diodes) shown in Table 2, which were used in earlier studies found in the literature. Our proposed 1 bit transmitarray has two PIN diodes, while most of the previously proposed 1 bit unit cells had varactor diodes. However, to make a unit cell completely digital, one needs to use a PIN diode. Most 1 bit unit cells have very narrow transmission bandwidth. For instance, [1] reported a bandwidth of 1.50 GHz with an insertion loss of -1.87 . Our proposed transmitarray has a bandwidth of 1.08 GHz with an insertion loss of -0.7 dB. As shown in Fig. 17, the unit cell simulated in free space using the Floquet mode shows good agreement with the results of the unit cells simulated using a waveguide transition. This shows that measuring in this way gives accurate results.

VII. CONCLUSION

In this paper, a new type of electronically reconfigurable unit cell with two phase states was proposed. The proposed cell had a 1.08 GHz transmission bandwidth with constant phase shift and low insertion losses in the operating bandwidth. A circular patch and a circular type slot were used for this unit cell.

We also proposed a new method for experimental characterization of a transmitarray using the 2×2 1-bit unit cell. The prototype was tested successfully using an X band waveguide and rectangular to square waveguide transition section. This

Table 2. Comparison of our proposed unit cell with other unit cells (considering 1 bit unit cell with PIN diode)

	Transmission bandwidth (GHz)	Insertion loss (dB)	Unit cell size (mm ²)
Proposed unit cell	1.08	-0.70	$0.45\lambda \times 0.45\lambda$
Clemente et al. [1]	1.50	-1.87	$0.5\lambda \times 0.5\lambda$
Nguyen and Pichot [10]	n/a	n/a	$0.54\lambda \times 0.54\lambda$

Fig. 17. Simulated magnitudes of transmission coefficients for State1 in free space and in the waveguide model.

method allows for checking the performance of the unit cells initially without having to fabricate an entire transmitarray antenna. A large array of this unit cell placed in front of a conventional horn antenna or any other suitable antenna with a specific focal length to diameter ratio can be used as a beamforming module, and the unit cell characterization method described in this paper can be applied to any type of unit cell in a transmitarray. The proposed transmitarray is only our initial work. We would like to design a transmitarray with a horn antenna, which will have both beam steering and polarization conversion properties. The circular-shaped allows us to make polarization conversion happen at the same frequency band because of its symmetrical structure. This cannot be achieved using a rectangular patch, because it is impossible to obtain vertical linearly polarized and horizontal linearly polarized beams at the same frequency band.

This research was supported by Basic Science Research Program (No. 2020R1I1A3057142), the Priority Research Centers Program (No. 2019R1A6A1A03032988) through the National Research Foundation of Korea, and the research grant of the Kongju National University in 2020.

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