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New Reconfigurable Transmitarray Unit Cell Design at Ku-Band Using PIN Diodes

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Abstract: Beam reconfigurable Transmitarray antennas require the unit cell phase variation capability. This paper presents a new reconfigurable Transmitarray unit cell design using PIN diodes at the Ku-band. The unit cell is comprised of three layers having four PIN diodes used in every unit cell layer. This results in phase controlling by switching the PIN diodes on every layer individually. The unit cell s-parametric analysis shows a high transmission coefficient magnitude (> -3.6dB) at a design frequency of 12.5GHz and maximum wide impedance bandwidth (17.5%). Four different switching states configurations are used, which result in phase variations over the range of 150.5 degrees. The transmission coefficient magnitude remains high for all four switching states. The proposed reconfigurable unit cell can be used in designing beam switched Transmitarray antennas for satellite communications and beam steering applications.

Keywords: Transmitarray, Unit cell design, Reconfigurable, PIN diode, Switching

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1. INTRODUCTION

High gain antennas are required for long-distance wireless communications. Different array antennas are designed to increase the gain of antennas whereas keeping the size compact [1]. Reflectarrays and transmitarrays are attractive options to overcome the size issue while achieving high gain simultaneously. However, transmitarrays have the advantage of avoiding feed blockage as it appears in reflectarrays [2]. Moreover, the transmitarray layers can enhance the gain of the feeding source antenna by phase adjustment and high transmission coefficient magnitude. Also, the feeding losses can be avoided in large microstrip array antennas with complex feeding and power division mechanisms [3, 4].

Beam steering has been an attractive option in designing antennas for applications like satellite communications and RADARs. To obtain the beam switching, different phased array antennas have been designed. These require the use of phase shifters with the fixed beam antennas to achieve the phase difference required for beam tilting. However, this increases the complexity of the overall design, especially when large arrays are required for higher gain applications [5]. Transmitarray antennas incorporate arrays comprised of a large number of unit cells. The unit cells designs can be frequency selective surface (FSS), metamaterial, or receiver-transmitter type. However, to achieve beam switching in Transmitarray antennas, the phase difference between consecutive unit cells is required, similar to the phased array antenna design [6]. The difference, in this case, is that the complex feeding networks and phase shifters are avoided. Beam switching can be obtained by incorporating switching devices like Varactors and PIN diodes in the structure of the unit cell [7]. By controlling these devices through biasing networks, beam switching can be performed by introducing an incremental phase between consecutive unit cells.

In this paper, a new type of transmitarray unit cell is designed using frequency selective surface configuration. The unit cell has a multi-layer structure to increase the phase range of transmitarray. In this case, three layers structure is used by keeping the transmission coefficient magnitude high and achieving a wide phase range. In order to obtain the beam tilting, four PIN diodes are used in each layer of the unit cell. The number of PIN diodes is optimized for the maximum phase difference obtained for three-unit cell layers. The proposed design can be used in beam steering of transmitarray antennas.

2. RECONFIGURABLE TRANSMITARRAY UNIT CELL DESIGN

The conventional transmitarray antenna designs used the receiver-transmitter configurations. In this type of Transmitarrays, phase shifting can be performed using biasing layer phase shifting circuits. However, for the FSS type transmitarrays, phase shifting can be achieved by unit cell parametric variations or incorporating physical switching devices such as PIN diodes and varactors. The Figure below shows the regular operation of the transmitarray antenna using FSS and beam tilting phenomena.

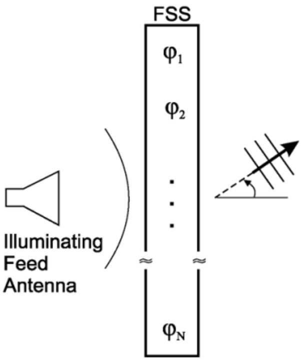
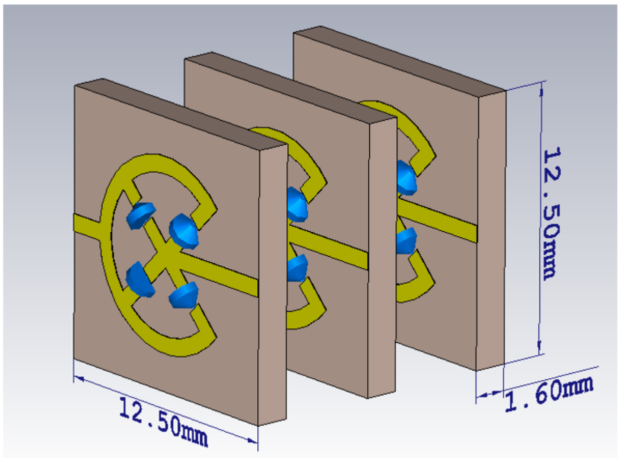


Figure 1. Beam switching principle using FSS Transmitarray configuration [7]

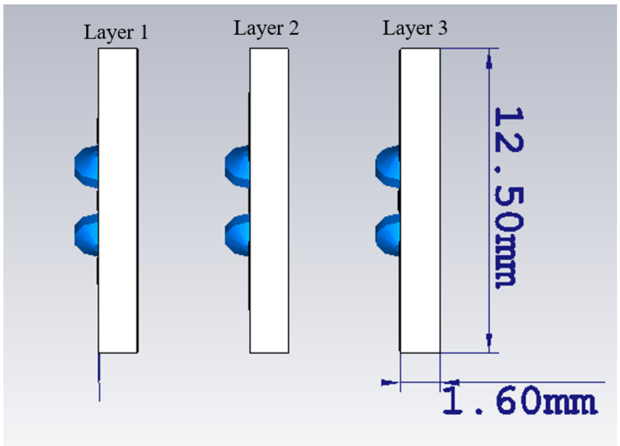
The new reconfigurable Transmitarray unit cell is designed using FR4 substrate (relative permittivity=4.4) as depicted in Figure 2. The unit cell is comprised of a combination of a circular arc and a cross-section. Two biasing lines on the left and right sides of the unit cell also are included. Four PIN diodes (D1-D4) are added to each arm of the cross-section to control the switching layers. The overall unit cell configuration has a three-layer FSS. These three layers are stacked together with an interlayer spacing of 6.25mm. The complete dimensions of the unit cell design are given in Table 1. The four PIN diodes in each layer will be switched ON or OFF simultaneously by controlling the voltage through biasing lines depending on the desired configuration or phase-shifting required. Four different switching configurations will be tested and are represented as states that are given in Table 2.

Table 1. Dimensions of the reconfigurable transmitarray unit cell design

Parameters	Description	Dimensions
Lt_Arm_L	Length of the left biasing line	1.7 mm
Rt_Arm_L	Length of the right biasing line	6.2 mm
Arc_Rad	The radius of the Outer Arc	4.5 mm
Rot_Ang	The angle between the cross arms	90 degrees
Strp_th	Width of Copper strip	0.8 mm
gap	A gap in cross arms for PIN diode	1 mm



(a)



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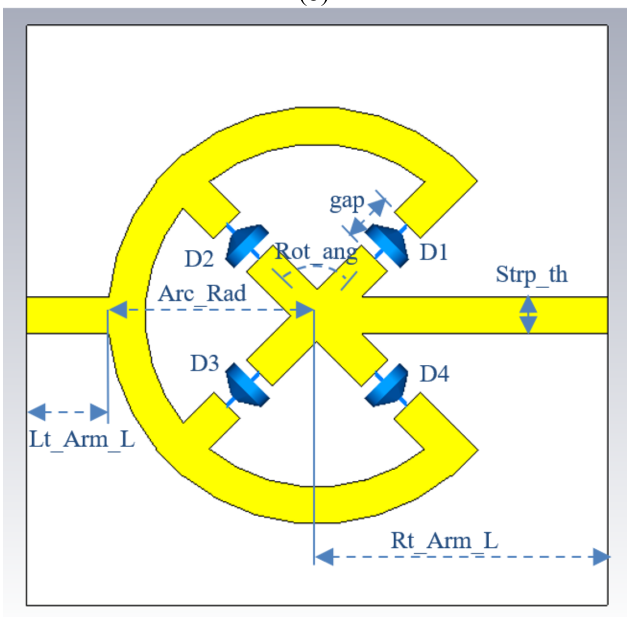

(c)

Figure 2. Reconfigurable unit cell design (a) Three-dimensional (b) Side view and (c) Front view for each layer

Table 2. Configurations of PIN diodes switching in each layer

State Number	Status of PIN diodes (D1-D4) in each layer
State-1	All layers switched OFF
State-2	Layer-1 ON, Layer-2 OFF, Layer-3 OFF
State-3	Layer-1 ON, Layer-2 ON, Layer-3 OFF
State-4	All layers switched ON

The unit cell designs are simulated and analyzed using CST studio. For CST Studio simulations, the PIN diode is represented with a serial Resistance (R_{ON}) of 2.3Ohm in the ON state and a parallel combination of resistance (R_{OFF}) value 3k Ohm and Capacitance (C_{OFF}) value 0.17pF in the OFF state. The effect of switching different layers using PIN diodes on Transmission coefficient magnitude and phase are shown in Figures 3 and 4, respectively. The results show a high transmission coefficient magnitude is obtained with a maximum value of -3.63dB and a phase of 258.22 degrees when all the PIN diodes in each layer are switched OFF (state-1). By sequentially switching from state-2 to state-4, magnitude curves move towards the left or low-frequency range. The phase is reduced to 182.08, 123.58, and 107.72 degrees, respectively. However, the transmission coefficient magnitude remains high (>-3.6dB) in each state for desired frequency of 12.5GHz. The maximum phase difference between state-1 and state-4 is obtained as 150.5 degrees. In addition, it can also be observed that transmission bandwidth becomes wider when we switch from state-1 to state-4. The complete results are shown in Table 3.

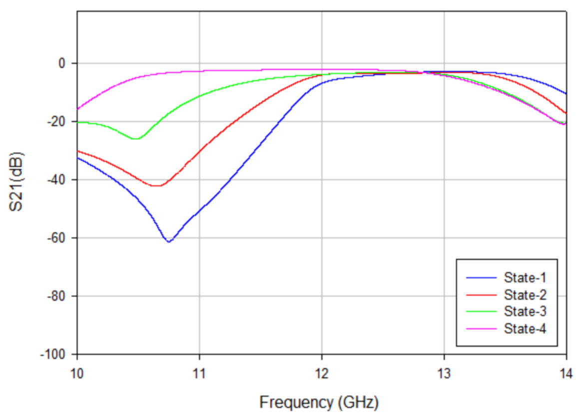

Figure 3. Magnitude versus frequency plots for different Pin diodes switching configurations

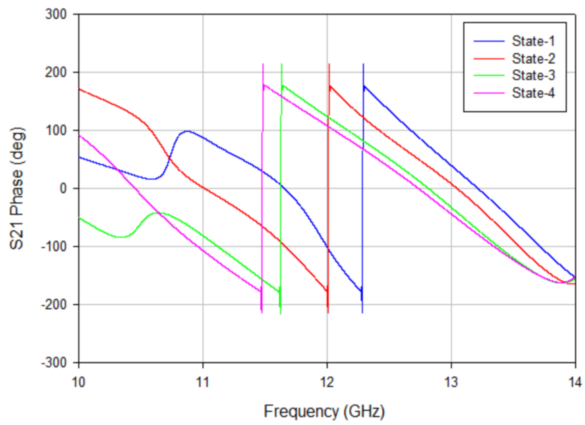

Figure 4. Phase versus frequency plots for different Pin diodes switching configurations

Table 3. Reconfigurable unit cell results at 12.5GHz for different switching states

State Number	S21 (Magnitude)	S21 (Phase)	Transmission Bandwidth
State-1	-3.63 dB	258.22 deg	0.6 GHz
State-2	-3.34 dB	182.08 deg	0.24 GHz
State-3	-2.96 dB	123.58 deg	0.33 GHz
State-4	-2.19 dB	107.72 deg	2 GHz

The comparison of different unit cell designs for beam switching transmitarray are presented in Table 4. The first design shows an FSS type transmitarray design with active unit cells. Varactors are used for tuning the transmission coefficient phase and producing a beam switching [7]. For single element. 03 layers are included and phase range of 120 degrees is achieved. However, the phase is increased to 410 degrees for 9-layer design with 3200 varactors. The second design has produced 185 degrees phase range [8]. However, the unit cell design is this case is based upon receiver-transmitter configuration which has the complex structure and interconnection issues. Another design with element rotations scheme has produced wide phase range of 190 degrees for 03-layer design [3]. However, the design has fixed configuration. This work presents an active FSS unit cell design with range of 151 degrees using 03-layer structure. However, this design has the advantage of simple fabrication method, low profile structure, electronically reconfigurable and a smaller number of active devices (PIN diodes) being used.

3. CONCLUSION

In this paper, a new reconfigurable transmitarray unit cell is designed at 12.5GHz. Each layer includes four PIN diodes, and a three-layer configuration is used. Every layer can be selectively switched using separate biasing lines to perform four different states. The simulation results show that all four states have a high transmission coefficient magnitude of (>-3.6dB) with transmission phase variations. The maximum phase range is obtained as 150.5 degrees. Moreover, changing from state-1 to state-4 will also increase the transmission bandwidth. The newly designed unit cell finds applications in beam reconfigurable transmitarray antennas for satellite communications.

Table 1. Comparison of Unit Cell Design for Beam Reconfigurable Transmitarrays

Unit Cell Design	Freq (GHz)	Phase Shift Range (degrees)	No. of layers / No. of Active elements / Type	Comments
Tunable FSS with Ferroelectric Varactors [7]	12 GHz	120 degrees (1 panel, 3-layers) 230 degrees (2 panels, 6 layers) 410 degrees (3 panels, 9 layers)	3, 6, 9 layers configurations. 3200 Varactors	Different phase ranges which can be tuned. Large number of varactors and layers required
Reconfigurable Unit Cell for TA Beam Scanning [8]	10 GHz	185 degrees	3 layers design	Complex receiver-transmitter configuration. Interconnection issues
Third-order Meta-FSS TA design [3]	10 GHz	190 degrees	3 layers design	Metasurface design with element rotations Fixed beam design with passive TA
New Reconfigurable TA FSS unit cell (This work)	12 GHz	151 degrees	3 layers FSS design	Low profile FSS-based design Avoid complex receiver-transmitter configuration Better switching technique

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