Dual-polarized Unit-cell of Continuous Reflective Phase-shift for Reconfigurable Reflectarrays

M. T. Zhang[1,2], S. Gao[1], J. X. Wan[2], B. N. Tian[2], and C. B. Wu[2]

[1]School of Engineering and Digital Arts, University of Kent, Canterbury, CT2 7NT, UK
[2]Xi'an Institute of Space Radio Technology, Xi'an, Shaanxi 710100, China

Abstract— This paper presents a Ku-band dual-polarized patch unit-cell of continuous phase shift for reconfigurable reflectarray antennas, which can twist the polarization of incident wave. This cross-polarized unit-cell can be applied in the folded reflectarray configuration for beam-scanning, and its performance is validated by the full-wave simulations under periodic boundary conditions. The scattered phase of the cross-polarized field varies continuously by approximate 300° as the capacitance in the varactor diodes is varied, and the magnitude of the cross-polarized field is higher than that of co-polarized field. The calculated results confirm that the dual-polarized multi-layer unit-cell consisting of dual-polarized H-shaped aperture coupled microstrips and vararctor-based reflection-type phase-shifter can be used as a reconfigurable reflectarray unit-cell to reflect the incident wave with a continuous phase shift after polarization twist.

1. INTRODUCTION

Recently, as one approach for high-directivity antennas of flexible functions, reconfigurable reflectarrays are becoming increasingly important for future wireless system applications. In space applications, the antennas of high-directivity are generally employed, and reflectarray antennas as strong candidates can form highly-directive beams by spatial feeds without beamforming network. The architecture of reflectarrays provides low-cost and high-efficiency beamforming. Electronically reconfigurable reflectarrays [1] have been nominated and demonstrated for beamscanning or other agile performance. The reflectarray can utilize reconfigurable technologies, and the varactor diode that can govern the scattered field from the unit-cell, is preferred in the electronic tuning design because of its continuous tuning and easy integration. In the classic folded reflectarray [2] for fixed-beam, the cross-polarized unit-cell is generally used to realize polarization twist for low profile structure and convenient feeder line. For electronically beamscanning, the reconfigurable unit-cells [3] can be used and meanwhile the polarizing grid in the folded reflectarray that can implement polarization selection demands the unit-cell can twist the polarization of the plane wave incident broadside to the unit-cell. The reflected wave after polarization twist can pass through the polarizing grid, if the phase calibration is performed in the reflectarray aperture according to the expected beam direction, the power originating from feed and distributed directly by the polarizing grid can be focused into a coherent beam in free space.

So the electronically tunable phase-shift unit-cells of polarization twist are necessary for this reconfigurable reflectarray, and the model based guided-wave approach has advantages in the design. Reflection-type phase-shifter based on hybrid coupler and varactors can be integrated with dual-polarized radiator to absorb the incident power and then re-radiate the power with an arbitrary phase-shift. The varactor-loaded transmission line can reflect the wave with a continuous reflective phase shift [4, 5], and in the phase-shifter the reflected waves from two identical varactor-loaded transmission lines can cancel out at the input port, while can be aggregated at the output port, the phase of the transmission coefficient can be manipulated dynamically by the embedded varactors. By connecting the ports of the dual-polarized radiator to the ports of the phase-shifter with transmission lines, the dual-polarized unit-cell of continuous reflective phase-shift can be built for cross-polarized reflectarray design where the input and output polarizations are orthogonal, which ordinarily characterizes the folded reflectarray. This unit-cell designed at Ku-band frequencies here is suitable for the implementation in the dual-reflective configuration using the polarizing grid.

In this paper, a cross-polarized unit-cell consisting of dual-polarized H-shaped aperture coupled microstrip and reflective phase-shifters is proposed. The scattering characteristics for this proposed reflectarray unit-cell with tuning the varactors are obtained using HFSS simulation.

2. UNIT-CELL CONFIGURATION AND DESCRIPTION

The proposed unit-cell is composed of two parts, one is the dual-polarized radiation part, and another is the electronically tuning reflection-type phase-shifter.

2.1. Configuration of Dual-polarized Radiator

The radiator is a multi-layer PCB structure, and consists of square patches and the H-shaped coupling slots in the ground, which supply the microstrip-patch transitions for dual linearly polarized radiation. The two ports of 50 Ω transmission lines for orthogonal polarizations are defined in this dual-polarized radiator. The arrangement [6] of the slots in the ground is specially selected, and the design to optimize the slots is completed, which saves the space for the reflection-type phase-shifter, as shown in Fig. 1. The multi-layer structure consists of Rogers Duroid 5880 substrate of different thickness with relative permittivity $\varepsilon_r = 2.20$ and low loss tangent and Rogers Duroid 6006 substrate of 0.254 mm thickness with $\varepsilon_r = 6.15$, on which the square patches and the transmission-line network for reflection-type phase-shifter are etched. The substrates of different permittivity can improve the radiating ability of patches, meanwhile can restrain the edge field for network miniaturization, two no copper-cladding substrates of the 0.787-mm thickness with excavated central square vacuums cavity is sandwiched to enhance the coupling among patches and the coupling between patches and slots in the ground.

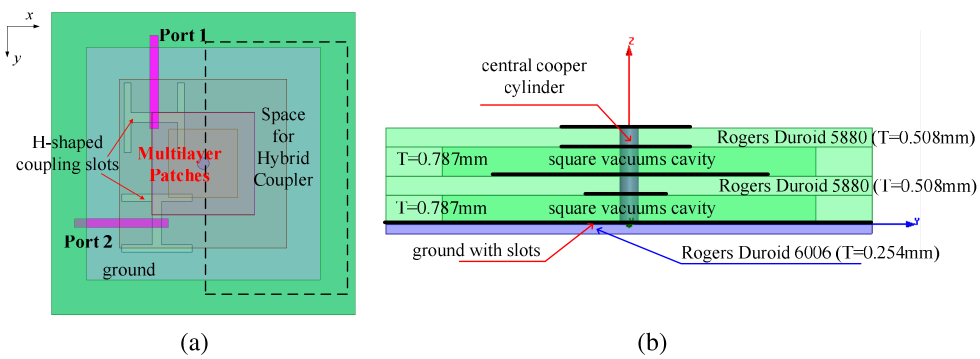

Figure 1: Configuration of dual-polarized H-slot coupled patch unit-cell for reconfigurable reflectarray. (a) Top view and (b) side view.

The performance of this radiator with the defined two ports is analyzed, and the scattering parameters are given in Fig. 2. It can be noticed that the broadband dual-polarized radiator can be matched in the range from 12.5 GHz to 14.5 GHz, and nearly 14% relative bandwidth (return loss ≤ -9 dB) is achieved, the decoupling level between two ports are approximate 20 dB. The scattering performance of this dual-polarized radiator is extremely important for the total unit-cell, cascading the radiator with the tunable phase-shifter will worsen the scattering parameters, and the dual-polarized radiator prescribe the potential limit for the total unit-cell.

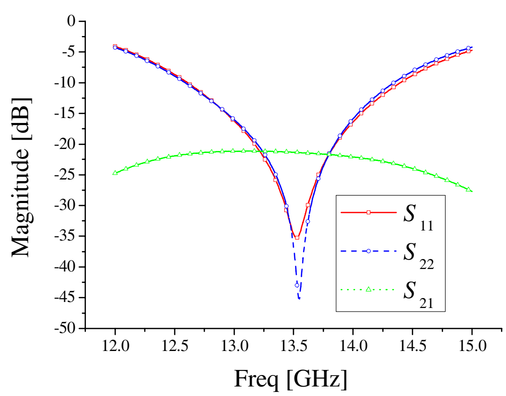

Figure 2: Scattering parameters of the designed dual-polarized radiator.

2.2. Configuration of Reflection-type Phase-shifter

As discussed above, the reflection-type phase-shifter should be designed for this unit-cell, and for the sake of stability in the operating Ku-band frequency range the 2-step 3 dB quadrature hybrid is chosen here, shown in Fig. 3, the diagram describes the basic working principle of reflection-type phase-shifter. When the excitation E_i exists at the Port 3, the reflected field can be eliminated if the network is an ideal circuit, and Port 4 outputs a phase-tunable transmission field without loss. The network circuit is printed on the bottom side of Rogers Duroid 6006 substrate shown in Fig. 1, and the ground is same to the one in which the H-shaped slots are etched.

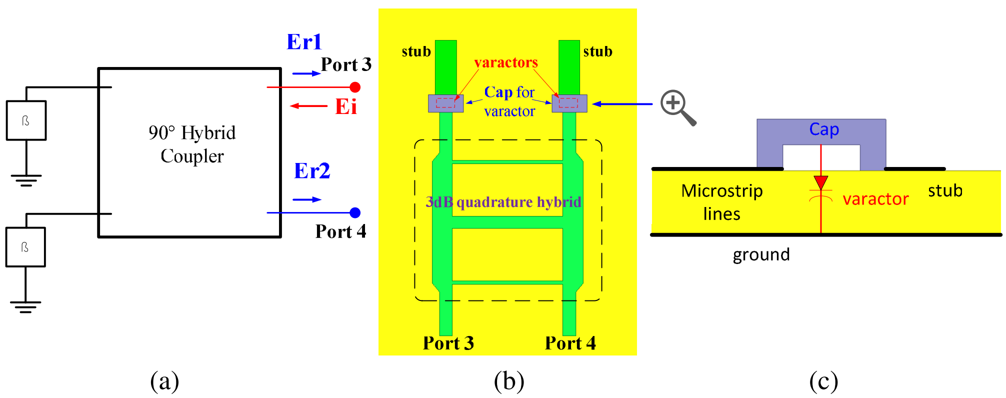

Figure 3: Diagram and Configuration of varactor-loaded reflection-type phase-shifter based on hybrid coupler for reconfigurable reflectarray unit-cell.

As shown in the Figs. 3(b) & (c), a pair of Microsemi GC15006-89 varactor diodes is used, which is silicon epitaxial mesa device. The junction capacity in the selected varactor diode, Cvar, varies in the range between 2.2 pF and 0.2 pF when reverse-biased between 0 and 30 V. The equivalent circuits including package effects are considered and modelled in the simulation. The Microsemi GC15006-89 is preferred in the design thanks to its very high quality factor and high total capacitance ratio. In the design of varactor-loaded reflection-type phase-shifter, the cap for the varactor is added for integration, the Fig. 3(c) is a side view after zooming in for the varactor. Each varactor is connected to the microstrip and the ground by the cap, a strip bridge over the microstrip and the stub.

The width and the length of the stub can be adjusted for the tradeoff between the loss and the phase range. In [7], the tunable load consists of a series LC lumped circuit, and in my design the distributed component is used because of its ease for practice and flexibility. This reflection-type phase-shifter is analyzed by tuning the capacitance in varactors, and the results are given in Fig. 4. It can noticed that the phase variation of about 300° is achieved, and the ports match well with a return loss of below −20 dB, and the maximum loss in the phase shift is about 1.5 dB at the frequency point 13.50 GHz. From the analysis, the design of the Ku-band reflection-type phase-shifter is confirmed, the performance is suitable for being integrated in the final reconfigurable reflectarray unit-cell based on guided-wave approach for continuous phase shift and polarization twist.

2.3. Integration for the Reconfigurable Reflectarray Unit-cell

After the design of the dual-polarized radiator and the reflection-type phase-shifter, the reconfigurable reflectarray unit-cell of continuous phase shift and polarization twist shown in Fig. 5 can be built by connecting Port 1 to Port 3 and Port 2 to Port 4 with transmission lines. The microstrip lines are assigned to maintain a decoupling of more than 30 dB between lines. It can be discovered

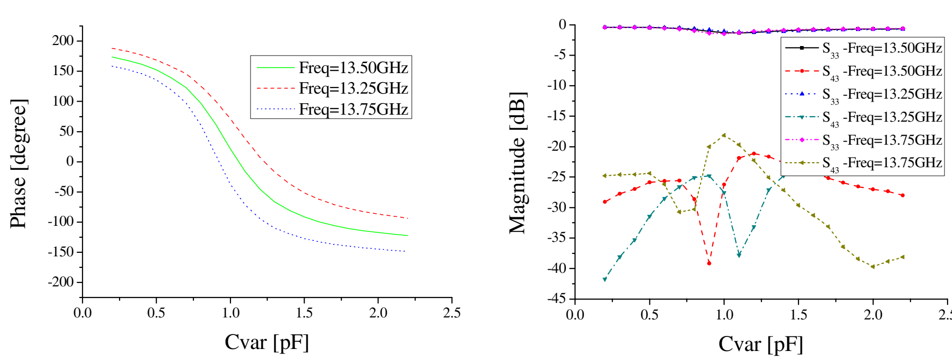

Figure 4: Phase and amplitude variation in the reflection-type phase-shifter with tuning capacitance in varactors.

that the special arrangement of the slots reserves enough space for the reflection-type phase-shifter's location. Due to the uncertainty of the output position and its stable performance, the dc biasing line connected to the network for controlling the varactors is hided, that consists of a high impedance line with an open-ended radial stub, as a RF-chock in the operational frequency band, and thanks to the metal connectivity one dc biasing line can control the two varactors together.

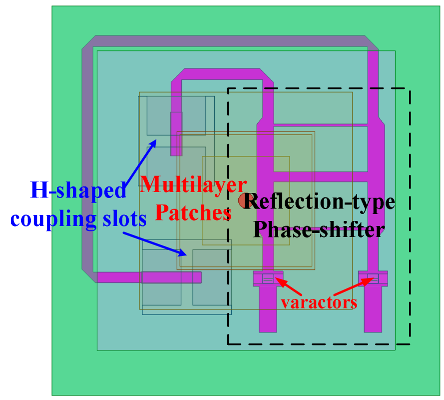

Figure 5: Configuration of the prosposed reconfigurable reflectarray unit-cell.

3. SIMULATATIONS AND DISCUSSIONS

The performance of the proposed topology has been assessed at the frequency point 13.50 GHz. Numerical characterisations with HFSS® commercial software have been carried out using Floquet Boundary approach for this square cell of size $13 \times 13\,\text{mm}^2$ with the consideration of coupling in the arrays. The cell is excited with the plane waves with the electric fields perpendicular to the grid of the array. In the simulations, results in the situations of the normal incidence (0°) and oblique incidence (30°) are calculated, and the phase and the amplitude variation in scattering parameters with tuning the varactors are illustrated in Fig. 6.

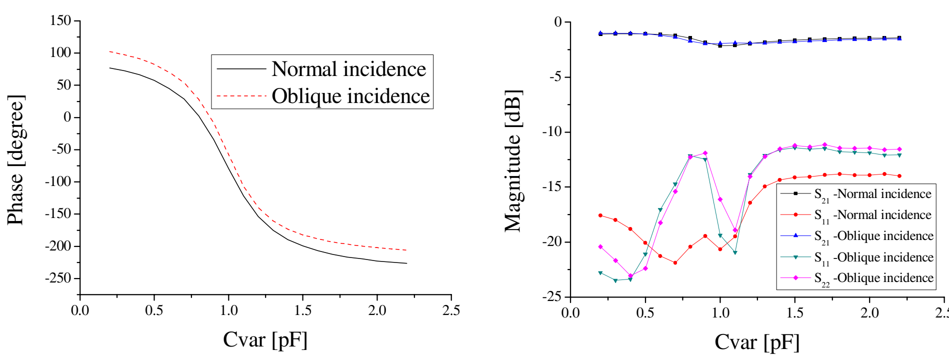

Figure 6: Phase and amplitude variation with tuning capacitance in varactors.

In the results, the phase of the cross-polarized component in the scattered field varies continuously by approximate 300°, and the magnitude of the cross-polarized component is higher than that of co-polarized component over the tuning range by 10 dB. It can be summarized that the continuous reflective phase-shift and the polarization twist are combined in the dual linearly polarized unit-cell for reconfigurable reflectarray antenna, and the unit-cell is preferred in the reconfigurable folded reflectarray antenna application.

4. CONCLUSIONS

For continuous phase tuning, the varactor-loaded unit-cell based on reflection-type phase-shifter and dual-polarized radiator is preferred and designed for the polarization twist in the reconfigurable folded reflectarray. The varactor's tuning in the reflection-type phase-shifter endow the unit-cell with a continuous reflective phase shift, further the cross-polarized unit-cell can transform the incident linearly polarized wave into the reflected wave of orthogonal polarization with a continuous phase tuning, and the reciprocity of the unit-cell can be demonstrated by the dual-polarized reflective transition. This proposed reflectarray unit-cell is able to offer a wide continuous phase tuning range, which is of critical importance for the reconfigurable reflectarray antenna performance improvement, and its performance is verified by the total model full-wave simulations instead of the network-based approach in [7]. The continuous phase shift in the unit-cell of polarization twist is required necessarily for high performance realization, which ensures the high aperture efficiency in the antenna radiation. Therefore, this unit-cell gives a good option for advanced reconfigurable reflectarray antenna.

ACKNOWLEDGMENT

This research is funded by China Scholarship Council, Xi'an Institute of Space Radio Technology. Also the authors would like to thanks the staff from China Scholarship Council, Xi'an Institute of Space Radio Technology and University of Kent for the support and help. Professor Yongchang Jiao from Xidian University in China is acknowledged for the care and concern.

REFERENCES

1. Hum, S. V. and J. Perruisseau-Carrier, "Reconfigurable reflectarrays and array lenses for dynamic antenna beam control: A review," *IEEE Trans. Antennas Propag.*, Vol. 62, No. 1, 183–198, Jan. 2014.
2. Tarn, I. Y., Y. S. Wang, and S. J. Chung, "A dual-mode millimeter-wave folded microstrip reflectarray antenna," *IEEE Trans. Antennas Propag.*, Vol. 56, No. 6, 1510–1517, Jun. 2008.
3. Montori, S., R. V. Gatti, R. Sorrentino, S. Dieter, and W. Menzel, "Reconfigurable and dual-polarization folded reflectarray antenna," *42nd European Microwave Conf., (EuMC 2012)*, 735–738, Amsterdam, The Netherlands, 2012.
4. Venneri, F., S. Costanzo, and G. Di Massa, "Reconfigurable aperture-coupled reflectarray element tuned by single varactor diode," *Electronics Letters*, Vol. 48, No. 2, 68–69, Jan. 2012.
5. Venneri, F., S. Costanzo, and G. Di Massa, "Design and validation of a reconfigurable single varactor-tuned reflectarray," *IEEE Trans. Antennas Propag.*, Vol. 61, No. 2, 635–645, Oct. 2012.
6. Wong, K.-L., *Compact and Broadband Microstrip Antenna*, John Wiley & Sons, New York, 2004.
7. Kishor, K. K. and S. V. Hum, "Modeling of active reconfigurable reflectarray elements," *13th International Symposium on Antenna Technology and Applied Electromagnetics and the Canadian Radio Sciences Meeting, (ANTEM/URSI 2009)*, Toronto, Canada, 2009.