2024 IEEE International Symposium on Antennas and Propagation and INC/USNC-URSI Radio Science Meeting (AP-S/INC-USNC-URSI) | 979-8-3503-6990-8/24/$31.00 ©2024 IEEE | DOI: 10.1109/AP-S/INC-USNC-URSI52054.2024.10686452

Design and Analysis of a 1-bit Guided Wave Fed Transmitarray Antenna

Kevin K. Mutai and Qiang Chen
Department of Communications Engineering, Graduate School of Engineering, Tohoku University, Sendai, Japan (e-mail: mutai-k@ecei.tohoku.ac.jp; chenq@ecei.tohoku.ac.jp)

***Abstract*—In this paper we introduce a 1-bit guided wave fed transmitarray antenna based on the inherently low-profile substrate integrated waveguide (SIW) technology capable of one-dimensional, frequency independent and reconfigurable beam scanning. The antenna structure is composed of a 21-element, one-dimensional array of slot antennas whose radiating state is determined by PIN diodes soldered across the slots. The design of the antenna structure is discussed, and the beam scanning performance is verified by full-wave simulation.**

I. Introduction

The need for reconfigurable antennas capable of flexibly changing the radiation direction to overcome line of sight (LOS) limitations of fixed-beam antennas has given rise to the so-called reconfigurable intelligent surfaces (RISs) [1]. There has, therefore, been a significant amount of research into RISs, moreso into those of the 1-bit variety where the antenna elements comprising the surface are switched between a radiating (or ON) state and a non-radiating (OFF) state using PIN diodes [2], [3].

An intriguing design challenge apparent from contemporary space-wave fed RISs (both 1-bit and otherwise), is the relatively large physical profiles of these antennas as they require a separate feed. One solution to this challenge is to use a guided-wave fed topology in which the feed is integrated with the antenna structure and the structures are intrinsically low profile with the thickness of the antennas reduced to about $0.37\lambda_0$ [4] and $0.75\lambda_0$ [5]. To further reduce the physical profile, SIW technology may be employed in supporting the guided waves as was done in this work. The proposed concept and design of the proposed antenna structure is presented in Section II and full-wave simulation results are included in Section III.

II. Concept and Design of the 1-bit Guided Wave Fed Transmitarray

To accomplish the main functionality of the proposed structure, which is one-dimensional (1-D) beam scanning, holography is used where the status (ON or OFF) of each element is determined by the phase difference (φ_{diff}) between the object wave ($\mathbf{E}_{obj}$) and the guided wave propagating within the SIW which is denoted as the reference wave ($\mathbf{E}_{ref}$).

By traveling backwards from the desired radiation direction in the far field (See Fig. 1), the required phase at each element n on the RIS to radiate in that direction can be found which explains the positive $\boldsymbol{k}_0$ in

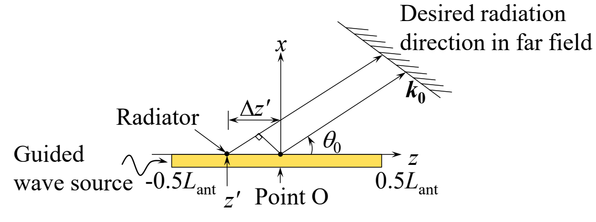

Figure 1. Concept of the proposed 1-bit reconfigurable guided wave fed transmitarray.

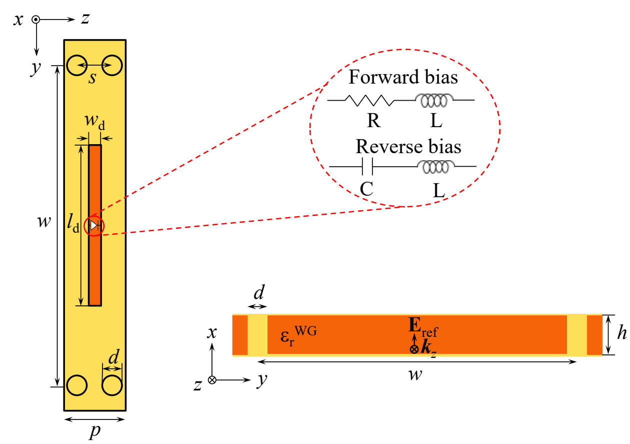

Figure 2. Unit cell of the proposed 1-bit reconfigurable 1-D array.

$$\mathbf{E}_{obj} = e^{j\mathbf{k}_0 \cos\theta_0 z'} \tag{1}$$

where θ_0 represents the desired radiation direction. By taking the phase at each element n as

$$\psi_n = \sum_{k=1}^{n} \beta \Delta z'. \tag{2}$$

in which β is the phase constant of the travelling wave within the SIW propagating along the z-direction, then

$$\mathbf{E}_{ref} = e^{-j\psi_n}. \tag{3}$$

The phase difference between the (1) and (3) is then

$$\psi_{diff} = \mathrm{Arg}\left\{\mathbf{E}_{obj}\mathbf{E}^*_{ref}\right\}. \tag{4}$$

The phase threshold was set at 70° such that if $\psi_{diff} \le 70^\circ$ the element is set to ON and OFF otherwise. This value of the

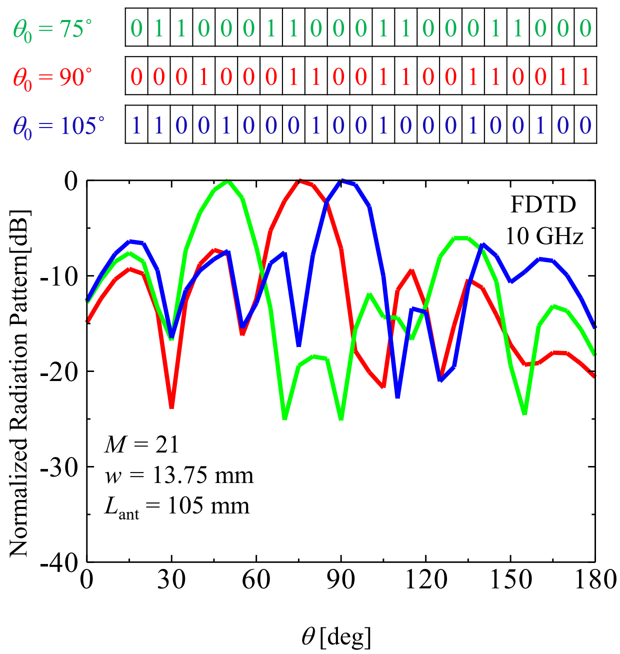

Figure 3. Normalized radiation pattern extracted from the simulation results for $\theta_0 = 75^\circ$, $\theta_0 = 90^\circ$ and $\theta_0 = 105^\circ$.

threshold was arrived at because at this value the SLL was lowest for several θ_0.

To actualize the logic explained thus far, the unit cell indicated in Fig. 2 was used. A full-sized array with L_{ant} = 105 mm (M = 21 elements) was then modelled in a full-wave simulation solver with the dielectric constant of the material within the waveguide ε_r^{WG} = 3.38 and $\tan\delta$ = 0.0027 to represent Rogers R4003C. The SIW width w = 13.75 mm and height h = 1.524 mm whereas the slot length l_d = 65 mm and width w_d = 0.5mm were selected to ensure the slot is resonant at 10 GHz (the desired operating frequency of the array). The SIW via diameter d = 0.8 mm and the separation width s = 1.25 mm were selected such that the equivalent rectangular waveguide broadwall width calculated from

$$a = w + \frac{d^2}{0.95s} \tag{5}$$

takes the value a = 14.3mm which can then be used to calculate β for the SIW operating in TE_{10} mode. Finally, the periodicity of the unit cell p =5 mm.

III. Simulation Results and Discussion

To evaluate the beam scanning capabilities of the proposed structure, three scenarios with $\theta_0 = 75^\circ$, $\theta_0 = 90^\circ$ and $\theta_0 = 105^\circ$ were investigated. In all three cases, the same phase difference threshold of 70° was used. To realistically simulate the switching performance of the 1-D array, the PIN diode across the slot indicated in Fig. 2 was modelled using its equivalent circuit. The modelled PIN diode was the MACOM MA4AGFCP910 flip chip diode with the biasing parameters set as R = 4Ω and L = 0.5nH in the forward biased (antenna element OFF or '0') state and L = 5nH and C = 0.02pF in the reverse biased (antenna element ON or '1') state.

The three cases were calculated using a finite difference time domain (FDTD) solver where a rectangular waveguide was used to feed the SIW through an aperture in the bottom of the SIW at one end and the radiation pattern extracted in each case at the design frequency of 10 GHz. The simulation results are presented in Fig. 3.

From the figure, it is readily apparent that the reconfigurable beam scanning is possible by the proposed structure as the radiation pattern was successfully changed. However, the radiation directions were shifted by about 15° to 20° which is attributed to the mutual coupling between the antenna elements which was not originally accounted for in the design calculations using the array factor. Further, the SLL is at about -7 dB which can be reduced by amplitude tapering and is to be considered in future designs.

IV. Conclusion

In this paper, an extremely low profile (thickness of about $0.05\lambda_0$) reconfigurable transmitarray antenna is introduced. The proposed antenna was shown to be capable of beam scanning by full-wave simulations thereby validating the proposed concept. Future work would therefore focus on overcoming the relatively high SLL and verifying the beam scanning performance experimentally.

Acknowledgment

This work was supported in part by the Program on Open Innovation Platform with Enterprises, Research Institute and Academic, Japan Science and Technology Agency (OPERA, JST) under grant JPMJOP1852 and in part by the 2023 IEEE APS Doctoral Fellowship.

References

[1] E. Björnson, Ö. Özdogan and E. G. Larsson, "Reconfigurable Intelligent Surfaces: Three Myths and Two Critical Questions," *IEEE Comm. Mag.*, vol. 58, no. 12, pp. 90-96, Dec. 2020.

[2] E. Carrasco, M. barba and J. A. Encinar, "X-Band Reflectarray Antenna with Switching Beam using PIN diodes and Gathered Elements," *IEEE Trans. Antennas Propag.*, vol. 60, no. 12, pp. 5700-5708, Dec. 2012.

[3] H. Yang, F. Yang, S. Xu, Y. Mao, M. Li, X. Cao and J. Gao, "A 1-bit 10 x 10 Reconfigurable Reflectarray Antenna: Design, Optimization , and Experiment," *IEEE Trans. Antennas Propag.*, vol. 64, no. 6, pp. 2246-2254, Jun. 2016.

[4] L. Huang, J-C. Chiao and M. P. De Lisio, "An Electronically Switchable Leaky-Wave Antenna," *IEEE Trans. Antennas Propag.*, vol. 48, no. 11, pp. 1769-1772, Nov. 2000.

[5] J. G. Nicholls and S. V. Hum, "Full-Space Electronic Beam Steering Transmitarray with Integrated Leaky-Wave Feed," *IEEE Trans. Antennas Propag.*, vol. 64, no. 8, pp. 3410-3422, Aug. 2016.