Numerical Investigation of a Symmetric-Unit-Cell-Based Tunable Frequency Selective Surface with Stable Angular Response

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***Abstract*—This work presents a preliminary design of a novel switchable frequency selective surface (FSS) unit cell with an embedded biasing network that preserves electromagnetic symmetry under both TE and TM polarizations. The proposed design addresses the symmetry-breaking limitations commonly caused by conventional control network (CN) layouts in tunable FSSs employing PIN diodes. The unit cell integrates four PIN diodes, all configured in the same state, either ON or OFF, and exhibits a distinct frequency shift along with a switchable band-stop response across the 3–13 GHz band. Full-wave simulations confirm stable angular performance and polarization-independent behavior. The proposed approach offers a compact, planar, and symmetric architecture suitable for future applications in programmable and reconfigurable metasurfaces.**

Keywords— FSS, switchable metasurface, PIN diode.

I. Introduction

Tunable frequency selective surfaces (FSSs) are widely employed in modern RF and communication systems due to their capability to provide dynamic spatial filtering, shielding, and polarization control [1]. These planar, periodic structures can be designed to allow or suppress electromagnetic wave transmission within predefined frequency bands. The integration of active components or materials, such as PIN diodes [2-5], Liquid Crystals (LC) [6] or varactors [7-10], enables reconfigurability and real-time control, which are particularly attractive for applications such as beam steering, adaptive filtering, intelligent reflecting surfaces for 5G and beyond, among others.

However, the inclusion of control networks (CNs) necessary for diode biasing, typically implemented as microstrip lines or wires, often disrupts the symmetry of the unit cell, resulting in polarization-sensitive behavior and degraded angular stability [2]. This limitation is critical in scenarios where robustness under both TE and TM polarized incidence is required.

Recent studies have addressed this issue by embedding the CN into the FSS structure [3] or employing multilayer or balanced topologies [4], [7]. Nonetheless, maintaining full electromagnetic symmetry while preserving planar fabrication remains a challenge.

In this work, we propose a modified FSS unit cell that mitigates the symmetry-breaking effects introduced by conventional CN layouts. The proposed unit cell consists of two square ring resonators of different dimensions, printed on opposite faces of a dielectric substrate. This dual-layer configuration enables dual-band operation, as each ring contributes to a distinct resonance within the 3–13 GHz range. The rings are electrically connected by four symmetrically placed PIN diodes that pass through the substrate, forming vertical interconnects between the front and back layers.

To enable switchable behaviour, a biasing network is integrated within the geometry of the cell itself, distributed on both sides of the substrate. The network is designed to deliver DC control to the PIN diodes without affecting the RF symmetry of the structure. This configuration ensures compactness, compatibility with planar fabrication, and polarization-insensitive performance under both TE and TM excitation.

A preliminary and comprehensive numerical characterization of the proposed configuration is performed. The performance is evaluated through full-wave simulations considering the ON and OFF states of the diodes, demonstrating improved symmetry and suitability for future reconfigurable metasurface platforms. These initial results validate the feasibility of the proposed configuration and provide a solid foundation for future physical prototyping and performance optimization.

II. Unit Cell Layout and Working Principle

The layout depicted in Fig. 1(a) is adopted to design a switchable FSS unit cell. The proposed structure consists of two square ring resonators of different side lengths, L_T and L_B, and a common ring width W, printed on opposite faces of a dielectric substrate. In the figure, the larger ring is placed on the front side (top layer), while the smaller one is on the back side (bottom layer), enabling dual-band operation by generating distinct resonance frequencies.

The two resonators are electrically interconnected through four vertical vias, each incorporating a through-hole PIN diode [8, 11]. These diodes are symmetrically distributed across the substrate, passing through the dielectric to connect the front and back resonators. This vertical interconnection ensures compactness while maintaining electromagnetic symmetry under both TE and TM polarizations.

The biasing network is carefully integrated into the unit cell geometry and distributed on both sides of the substrate. It is designed to supply the necessary DC voltage to switch all the PIN diodes simultaneously to the same state, either ON or OFF, without interfering with the RF response.

The biasing lines are narrower than the resonators, with a reduced width denoted as W_{CN} (see Fig. 1(a)), in order to minimize their impact on the RF performance. Although high-impedance RF chokes and DC-blocking capacitors are not included at this stage, they are essential in practical implementations to isolate the control and RF paths, thereby preserving the symmetry and polarization insensitivity of the design.

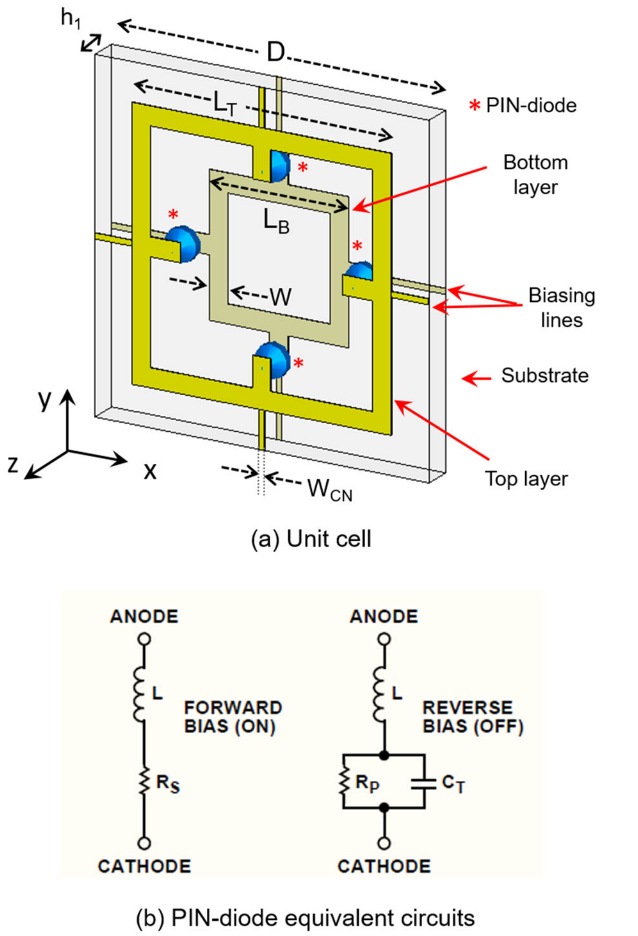

Fig. 1. Proposed FSS configuration: (a) unit cell geometry; (b) PIN-diode equivalent circuit model [12].

To evaluate the fundamental switching behaviour, the diodes are initially modelled using an idealized approach: a perfect short circuit in the ON state and an open circuit in the OFF state (see Fig. 2). This approximation simplifies the electromagnetic analysis while capturing the resonance shift between the two diode states.

In practical RF and microwave applications, however, PIN diodes behave as current-controlled resistors [12]. When forward biased (ON), they exhibit a low resistance R_S, typically below 1 Ω, allowing current to flow between the front and back layers. Conversely, when reverse or zero biased (OFF), the diode presents a high resistance R_P, typically greater than 10 kΩ, in parallel with a small junction capacitance C_T, effectively behaving as an open circuit at high frequencies. This behavior is represented by the equivalent circuit shown in Fig. 1(b).

Future simulations will incorporate this equivalent circuit model to account for non-idealities and parasitic effects, thereby improving the accuracy of performance estimation.

At this initial stage, the ideal open/short model has been considered sufficient to validate the switchable and symmetric nature of the proposed FSS cell.

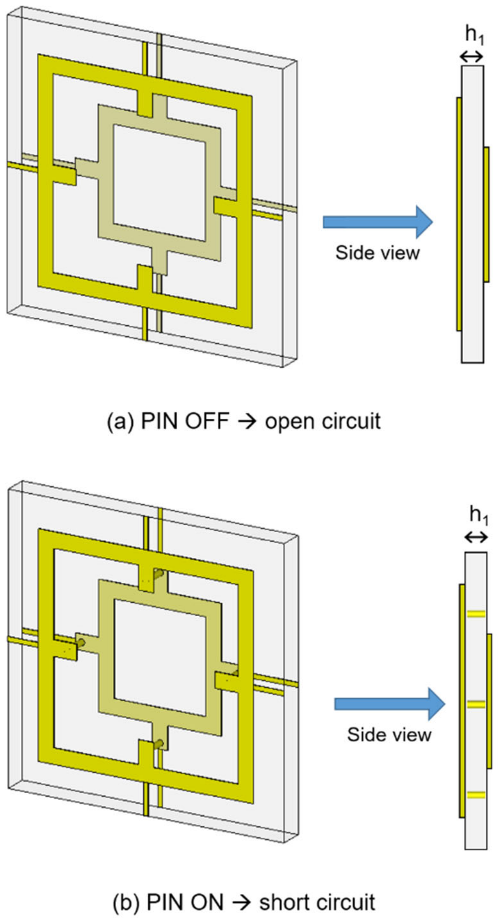

Fig. 2. Operation states of the PIN loaded unit cell: (a) OFF-state; (b) ON-state.

III. Unit Cell Design and Simulation

In order to give a preliminary validation of the proposed structure, a unit cell is designed and simulated within the 3–13 GHz band. The structure's dimensions, as defined in Fig. 1(a), are as follows: the unit cell size D is 15 mm; the larger ring has an external length L_T=14 mm and a trace width W=1 mm, while the smaller ring, located on the bottom side, has an external length L_B=8 mm and the same trace width. The rings are separated by a substrate of thickness h_1=1.58 mm, made of FR4 with a relative permittivity of ε_r=3.9 and loss tangent tan δ= 0.025. Four through-hole PIN diodes with leads designed to pass through the PCB for soldering on both opposite sides are integrated into the unit cell (Fig. 1(b)).

The control network, used to bias the PIN diodes, is implemented as a set of thin crossed metallic traces embedded within the FSS layout. These traces are symmetrically patterned on both the top and bottom layers of the substrate, closely following the resonators' geometry to preserve overall electromagnetic symmetry (see Fig. 1(b)). Each bias line has a width W_{CN}=0.4mm, carefully chosen to ensure reliable DC conduction while minimizing any perturbation to the RF response.

Full-wave electromagnetic simulations are carried out in CST Studio Suite [13], applying periodic boundary conditions along the x and y directions and Floquet ports along the z-axis. Both x-polarization (TM incidence, with the electric field polarized along x) and y-polarization (TE incidence, with the electric field polarized along y) are considered.

Figures 3 and 4 show the simulated transmission coefficient of the proposed structure for both diode states, plotted under normal incidence ($\theta = 0°$, $\phi = 0°$), where θ and ϕ are the spherical coordinates angles associated to the reference system in Fig. 1(a). The results highlight the tunability and band-stop characteristics of the FSS unit cell, demonstrating an identical reconfigurable behaviour for both x- and y-polarizations.

In the ON state, two transmission nulls occur around 7.86 GHz and 11.48 GHz, with attenuation levels exceeding 15 dB, effectively blocking electromagnetic waves at these frequencies (see Fig. 3). When the PIN diodes switch to the OFF state, these nulls shift to lower frequencies, approximately 6.78 GHz and 11.05 GHz (see Fig. 4), confirming the reconfigurable nature of the surface. One can observe an almost fixed frequency response for one of the passing frequencies (notch), while the other exhibits steering behaviour, a feature that can be useful in various applications.

Furthermore, the transmission responses for x- and y-polarizations are closely matched, demonstrating the polarization-insensitive behaviour enabled by the symmetric unit cell design and uniform diode placement.

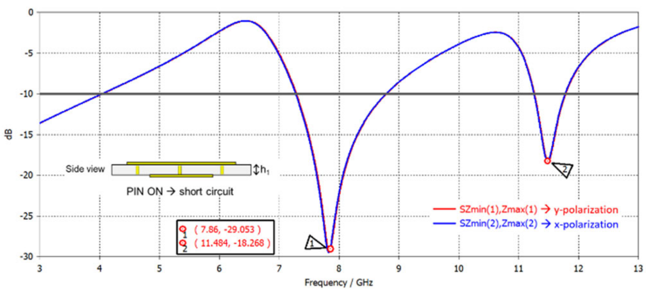

Fig. 3. Simulated transmission coefficient with the PIN diodes in the ON state, for x- and y-polarizations under normal incidence.

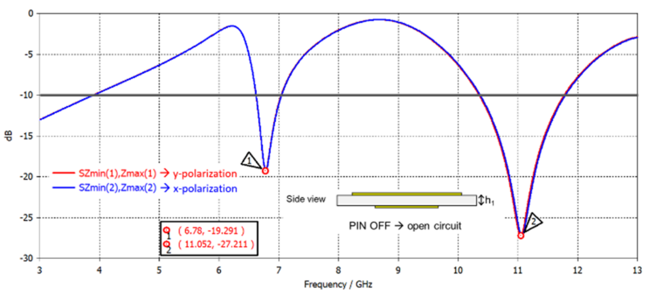

Fig. 4. Simulated transmission coefficient with the PIN diodes in the OFF state, for x- and y-polarizations under normal incidence

In addition, the TE-mode response has been analyzed under oblique incidence for both diode states, as shown in Figs. 5 and 6. The structure exhibits a reasonably good level of angular stability, with a slightly increased sensitivity observed when the PIN diodes are in the OFF state (Fig. 6). Further structural optimization is planned to improve performance at higher incidence angles.

These findings confirm the structural symmetry and effectiveness of the embedded control network, which avoids the typical drawbacks of conventional biasing schemes. This solution represents a promising step toward the development of compact and polarization-independent switchable FSS.

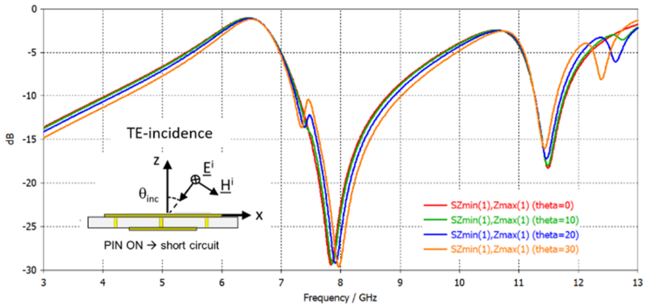

Fig. 5. Simulated transmission coefficient with the PIN diodes in the ON state, for different angle of incidence (TE-polarization).

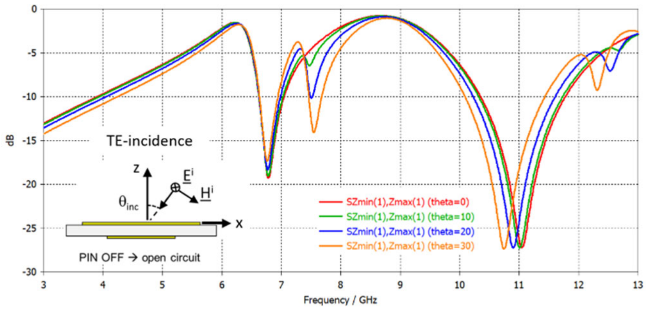

Fig. 6. Simulated transmission coefficient with the PIN diodes in the OFF state, for different angle of incidence (TE-polarization).

IV. CONCLUSION

This work presented a switchable FSS unit cell featuring dual metal layers, a symmetric layout and an embedded control network designed to maintain polarization insensitivity under both TE and TM incidence. The proposed structure leverages vertically integrated PIN diodes and symmetrically patterned bias lines to enable dynamic control of the transmission characteristics while preserving electromagnetic symmetry. Full-wave simulations demonstrated a tunable band-stop behaviour across the 3–13 GHz range, with clearly distinct resonance shifts between the diode states and robust performance under polarization variation. The adopted control network strategy successfully mitigates the symmetry-breaking issues commonly introduced by conventional biasing schemes, supporting the development of compact, planar, and reconfigurable metasurface designs. Future developments will include refined modelling of the PIN diodes and experimental validation through optimization and fabrication of prototypes.

References

[1] B. A. Munk, *Frequency Selective Surfaces: Theory and Design*, Wiley, 2000.

[2] A. Silaghi, F. Mir, A. De Sabata, L. Matekovits, “Design and experimental validation of a switchable Frequency Selective Surface with Incorporated Control Network,” *Sensors*, 2023, 23, 4561.

[3] F. Mir, L. Matekovits, A. De Sabata, “Symmetry-breaking manipulation in the design of multifunctional tunable frequency selective surface,” *AEU - International Journal of Electronics and Communications*, vol. 142, 2021.

[4] P. Fei, W. Guo, W. Hu, Q. Zheng, X. Wen, X. Chen, G.A.E.Vandenbosch, “A Transmissive Frequency-Reconfigurable Cross-Polarization Conversion Surface,” *IEEE Antennas Wirel. Propag. Lett.*, 2022, 21, 997–1001.

[5] W. Li, S. Xia, B. He, J. Chen, H. Shi, A. Zhang, Z. Li, Z. Xu, “A Reconfigurable Polarization Converter Using Active Metasurface and Its Application in Horn Antenna,” *IEEE Trans. Antennas Propag.*, 2016, 64, 5281–5290.

[6] J. A. Bossard, X. Liang, L. Li, S. Yun, D. H. Werner, B. Weiner, T. S. Mayer, P. F. Cristman, A. Diaz, I. C. Khoo, “Tunable Frequency Selective Surfaces and Negative-Zero-Positive Index Metamaterials Based on Liquid Crystals,” *IEEE Trans. Antennas Propag.*, 2008, 56, 1308–1320.

[7] X. Gao, W. L. Yang, H. F. Ma, Q. Cheng, X. H. Yu, T. J. Cui, “A Reconfigurable Broadband Polarization Converter Based on an Active Metasurface,” *IEEE Trans. Antennas Propag.*, 2018, 66, 6086–6095.

[8] F. Venneri, S. Costanzo, G. Di Massa, “Design and validation of a reconfigurable single varactor-tuned reflectarray,” IEEE Transactions on Antennas and Propagation, 61 (2), art. no. 6339007, pp. 635 – 645, DOI: 10.1109/TAP.2012.2226229.

[9] A. Ebrahimi, Z. Shen, W. Withayachumnankul, S. F. Al-Sarawi and D. Abbott, “Varactor-Tunable Second-Order Bandpass Frequency-Selective Surface With Embedded Bias Network,” in *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 5, pp. 1672-1680, 2016.

[10] B. Q. Lin, J. Guo, P. Chu, N. Li, N. Wu, X. Liu, “Varactor-tunable frequency selective surface with an appropriate embedded bias network,” *Radio Science*, vol. 53, pp. 535–543.

[11] S. Costanzo, F. Venneri “Tunable Reflector/Absorber Surfaces for Next Generation Wireless Communication Systems,” Lecture Notes in Networks and Systems, 988 LNNS, pp. 209 - 215, DOI: 10.1007/978-3-031-60224-5_22.

[12] Analog Devices Homepage, https://www.analog.com/en/analog-dialogue/articles/driving-pin-diodes-with-op-amps.html, last accessed 2025/07/31.

[13] CST Studio, Suite, Dassault Systemes, v. 2022; CST Studio: Clinton Township, MI, USA, 2022.