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-URSI52054.2024.10685974

A Modified 1-Bit Unit-cell for mmWave RIS Optimized at Extreme Incident Angle

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***Abstract*—This paper presents a modified wideband reflective unit-cell for Reconfigurable Intelligent Surface (RIS) operating at millimeter-wave (mmWave) n257 band. The unit cell is specifically optimized at extreme incident angles and utilizes dual-polarization reflection with p-i-n diodes for a 1-bit RIS control. The design exhibits superior reflective phase difference close to 180° across most of the 3 GHz bandwidth (26.50–29.45 GHz) and reflects over 74% of the energy even at extreme angle of incidence as high as 70° from the RIS boresight. The enhanced reflectivity minimizes losses, and precise phase control improves beam pointing accuracy crucial for low-complexity 1-bit RIS. Full-wave electromagnetic simulations confirm effective performance. The unit cell is compared with the current state-of-the-art unit cells, in terms of bandwidth, polarization, phase accuracy and operation in extreme angles of incidence.**

***Index Terms*—antennas, mmWave, RIS, unit-cell, reconfigurable**

I. Introduction and Contribution

Reconfigurable Intelligent Surfaces (RIS) have revolutionized wireless communication by intelligently redirecting radio waves from base-stations (BS) to non-line-of-sight user equipment (UE). Manipulating reflected signals enhances network performance, offering improved signal coverage, higher data rates, and energy efficiency gains. Specifically in millimeter-wave (mmWave) frequencies, it mitigates one of the most important challenge, i.e., high free-space path loss (FSPL) which leads to poor link connections [1]–[3]. Integrating RIS smoothly into wireless networks comes with its own set of challenges. These include making sure the surfaces reflect signals well across a wide range of angles, ensuring the RIS devices use energy efficiently, and figuring out practical ways to put them into action. One underexplored aspect of RIS involves the impact of extreme (steep) incident and reflection angles on its performance. While numerous investigations focus on unit-cell reflection responses, this paper specifically addresses scenarios where the angle of incidence to the unit-cell is extreme. Illustrated by an example indoor mmWave communication in Fig. 1(a), this setting emphasizes the prevalence of extreme incident angles. To overcome this limitation, a modified 1-bit unit-cell for mmWave RIS is studied, providing dual-polarization, low diode loss, and coverage of the entire n257 band, even when operating at extreme angles of incidence.

II. RIS Unit-cell design and Analysis

Operating as reconfigurable metasurfaces, RIS utilizes meta-atoms with varactors or p-i-n diodes to create unit-cells.

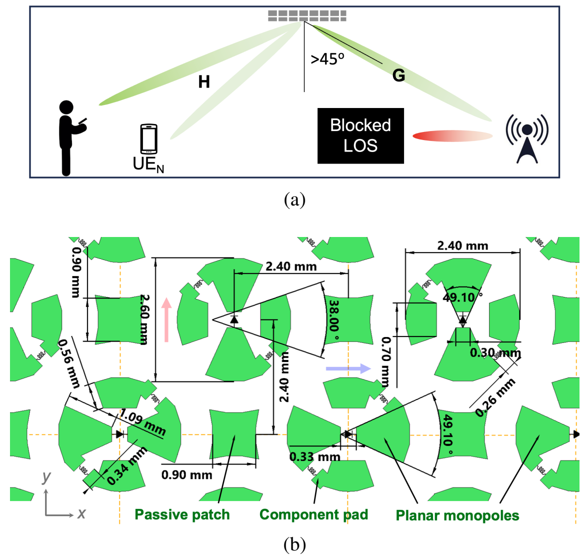
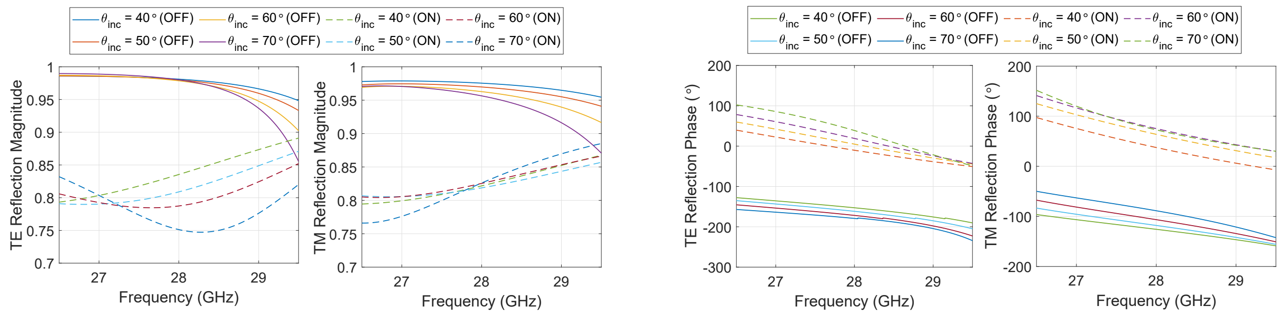


Fig. 1. (a) RIS-assisted indoor mmWave environment where the extreme incident and reflections angles are inevitable. (b) Modified RIS unit-cell with planar dipole radiator and a passive parasitic patch design and dimension.

Design parameters, encompassing shape, dimensions, and thickness, significantly influence RIS reflection performance, a critical consideration for practical applications. The RIS unit-cell shown in Fig. 1(b), developed on a 1.52mm thick Rogers 4003C substrate ($\epsilon_r = 3.4$ and $\tan\delta = 0.0027$), coated with $35\mu m$ copper clad, uses a MADP-000907-14020P p-i-n diode for both vertical (V) and horizontal (H) control. For precise simulation, p-i-n diode LRC characteristics were measured at Queen's University Belfast, fitted to Keysight Pathwave ADS, showing agreement with [2]. Each unit-cell includes two L0201R82AHSTR 500 RF chokes, self-resonant at 28 GHz, behaving as a parallel LRC tank with $L_{ind} = 820$ pH, $R_{ind} = 4050\ \Omega$, and $C_{ind} = 13.12$ fF. Fig. 1(b) displays interlaced unit-cell polarisation being V (shown in red) and H (blue), while landing pads are designed for 0201 component placement and soldering. Here the reflecting components include two planar monopoles forming a planar dipole and parasitic patches interlaced between the V and H unit-cells. The dipole structure is active based on the electric field's orientation and biased by auxiliary elements isolated by RF chokes. The inclusion of the proposed passive parasitic structures constitutes the main novelty of this work,



(a)
(b)

Fig. 2. (a) Magnitude and (b) phase of the reflection coefficient at V and H polarised oblique incident signal at 28 GHz.

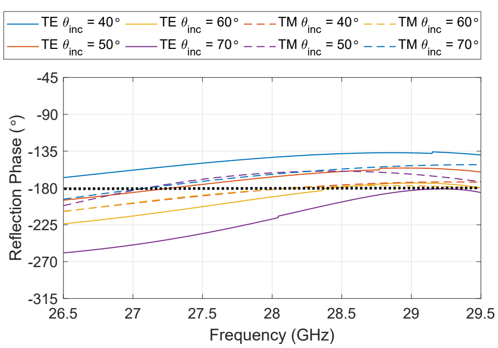


Fig. 3. Reflection phase difference comparison at multiple V and H polarization incident angles.

responsible for providing reflection phase stability to the unit cell at an extreme incident angle. The same phenomenon has previously been shown in [1] where optimizing the passive parasitic patches reduces the reflection phase variation at multiple incident angles. This work expands to propose a unique unit cell that provides superior reflection performance of RIS, achieving a good reflection coefficient while minimizing phase difference between states, crucial for 1-bit RIS. Our 1-bit RIS requires a 180° phase difference, reducing quantization error relevant for 1-bit architectures. Optimization of the unit cell involved substrate thickness, element dimensions, and placement.

The unit-cell, simulated in CST Microwave Studio 2023, utilized an infinite periodic surface boundary condition. A Floquet port excited the unit-cell, and the reference plane was adjusted to the copper surface for precise phase shift. Fig. 2(a) displays results for both polarizations, showing over 85% reflection in reverse bias and over 74% in forward bias. The reflection phase and phase difference, crucial for mmWave RIS performance, are illustrated in Fig. 2(b) and Fig. 3, respectively, for $40°$ to $70°$ incidence. The unit-cell exhibits less than $\pm10°$ difference between $26.5 - 29$ GHz and $< 20°$ at 29.5 GHz, at $50°$ incident angle aiding beam pointing accuracy and mitigating quantization error for 1-bit arrays [4]. The benefits of passive patches are two fold. First, they improve the reflection magnitude compared to the previous version of the unit-cell [5]. Second, it maintains the reflective phase at extreme angles of incidence up to $70°$. Bandwidth optimization involves RF substrate thickness adjustment, unit-cell dimension tweaking, inductor influence, and via placement. Table I compares our work with state-of-the-art, emphasizing bandwidth and loss advantages, and potential for RIS development. Notably, our dual-polarized unit-cell outperforms 2-bit architectures, showcasing its superiority in complexity and capability. Fabrication and measurements is the next step.

TABLE I
COMPARISON WITH THE STATE-OF-THE-ART MMWAVE RIS UNIT-CELLS

Ref.	Freq. band	Error	$\min.(\lvert\Gamma\rvert)$	Quantization	Pol.
[1]	26.25 GHz	N/A	-17.83 dB	2-bit	Single
[2]	$28.2 - 30$ GHz	20°	-1.3 dB	1-bit	Dual
[5]	$26.5 - 29.5$ GHz	20°	-1.8 dB	1-bit	Dual
[3]	$27.5 - 29.5$ GHz	36°	-6 dB	1-bit	Dual
[6]	29 GHz	N/A	-2.12 dB	2-bit	Single
This work*	$26.5 - 29.5$ GHz	25°	-1.8 dB	1-bit	Dual

* at 50° incident angle

ACKNOWLEDGMENT

This work was partially supported by Project REASON a UK Government funded project under the Future Open Networks Research Challenge (FONRC) sponsored by the Department of Science Innovation and Technology (DSIT), and by the Department for the Economy of Northern Ireland under US Ireland R&D Partnership grant no. USI 199.

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