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Varactor-Based Reconfigurable Intelligent Surface with Dual Linear Polarisation at K-Band

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***Abstract*—Full polarisation coverage is necessary for reconfigurable intelligent surfaces to be suitable for deployment in real-world wireless communication networks. This work explores a dual-linear polarisation unit cell design for operation at the European mmWave Pioneer band covering 24.25 - 27.5 GHz. A microstrip patch coupled to two orthogonally-arranged parasitic patches through two varactor diodes facilitate a 1-bit reflection response with a periodicity of $0.27\lambda_0$. A -40 dB cross-polarisation level is enabled across the band by offset-tuning varactor placement and vias. The reflection responses are ascertained with manufacturer-provided S-parameter component data to ensure realistic simulations.**

I. Introduction

The potential for significant wireless channel improvement through programmable radio environments has led to a great deal of interest in reconfigurable intelligent surfaces (RISs) throughout academia and industry. RISs are near-passive programmable reflectors which can act to redirect and focus incident electromagnetic waves to meet wireless communications or wireless sensing goals [1]. These quasi-periodic structures consist of many, typically hundreds of, tuneable unit cell elements. The sheet impedance crafted by the collection of unit cells presents a discontinuity to incident EM waves, resulting in reradiation consistent with Huygen's principle and the surface equivalence theorem [2].

Due to the simplicity of the available tuning mechansisms and lower volume of biasing circuitry, two-state tuneable elements consisting of a means of switching between inductive and capacitive reactances have been widely utilised and are known as 1-bit unit cells [3]. A 1-bit unit cell design ideally provides a phase difference between two biasing states of 180 degrees, with minimal reflection loss. Several recent works have explored 1-bit RIS designs at mmWave frequencies [3] [4] [5]. Gros et al. introduced a dual-polarised PIN diode-based RIS design facilitated by strong coupling between a patch and switchable parasitic element [4]. This design demonstrated significant throughput enhancement of a non-line of sight indoor mmWave communication link over a 5 GHz bandwidth [3]. Employing varactor diodes, on the other hand, results in a lower power consumption due to the voltage-driven tuning mechanism and negligible current consumption. This is usually at the expense higher forward resistance with associated increased reflection loss [6]. Compounding the issue of high loss is the higher voltage requirements of varactors, complicating bias voltage distribution with off-the-shelf components. Rotshild and Abramovich recently introduced a programmable metasurface at K-band utilising GaAs varactor diodes for continuous sheet impedance tuning with a single linear polarisation [7]. Measurements with a prototype consisting of an arrangement of 16×40 unit cells revealed high spatial resolution beamsteering capability of up to 60 degrees from broadside over a 2.5 GHz bandwidth.

In this work, we introduce a varactor-based dual linear polarisation unit cell design operating within the 5G mmWave pioneer band, centered at 26 GHz. The design employs the minimal two active components per element and requires tuning voltages of 0V and 8V for 1-bit operation. A periodicity of $0.27\lambda_0$ is maintained and a maximum -42 dB cross polarisation level is exhibited.

II. Unit Cell Design

The proposed unit cell architecture is depicted in Fig. 1 with dimensions in Table I. The design consists of a single square copper patch and two orthogonally arranged parasitic patches printed on a grounded RT/Duroid 5880 dielectric substrate. The substrate dielectric constant and loss tangent used for simulation are $\epsilon_r = 2.2$ and $tan\delta = 0.0009$, respectively. The degree of coupling between the parasitic patches and the square patch is controlled by two varactor diodes, as labelled in Fig. 1(a). The varactor diodes are reverse-biased by applying DC voltages to the parasitic patches through two RF choke inductors. A common DC ground connection is maintained through a grounded via on the central patch. All vias have a diameter of $0.2\ mm$. MACOM MAVR-011020 varactor diodes and AVX Accu-L0201 choke inductors with a self-resonant frequency of 26 GHz were chosen for their low capacitance and high isolation, respectively. Simulations were performed in CST Studio Suite with unit cell boundary conditions and a Floquet port with 2 orthogonal modes at broadside. The RF chokes were simulated as lumped components with the associated S-parameter data. The varactor diodes were simulated by applying discrete ports at the varactor positions, followed by post-processing in MATLAB to include the varactor S-parameter data for varying reverse-bias voltage levels.

The resulting global reflection responses for 0V and 8V reverse-bias voltages are shown in Fig. 2. The co-polar (S11) and cross-polar (S12) magnitude is plotted in Fig. 2(a) with solid and dashed lines, respectively. The point of intersection of the S11 curves is approximately the design frequency of

TABLE I
UNIT CELL DIMENSIONS

Parameter	Length (mm)	Parameter	Length (mm)
w	3.1	h	0.6
g	0.1	a, b	2.2, 2.2
q, r	1.6, 0.4	u, v	0.4, 0.25

26 GHz, and a reflection loss of approximately 3 dB occurs for both states. A worst-case reflection loss at the band edges can be seen, with 9 dB at 0V and 5.1 dB at 8V, at 24.5 and 27.5 GHz, respectively. This loss is acceptable given the high scalability of this design approach and is compensated for by the aperture gain of the RIS. The cross-polarised components are plotted as the dashed curves in Fig. 2(a). Less than -40 dB S12 magnitude is maintained at both states at 26 GHz by tuning the offset of the varactors and central via. The phase response is plotted in Fig. 2(b) for 0V and 8V. Examining the phase difference curve shown by the dashed line, it can be seen that a phase shift in the region 180 ± 20 degrees is maintained between 24.7 and 26.6 GHz.

III. CONCLUSION

This work explores the viability of a varactor-based dual-polarised unit cell design for truly near-passive RISs at one of the designated mmWave bands for 5G in Europe. Future work will focus on the fabrication and characterisation of this unit cell design through waveguide-based measurements, followed by fabrication and field trials with a complete RIS.

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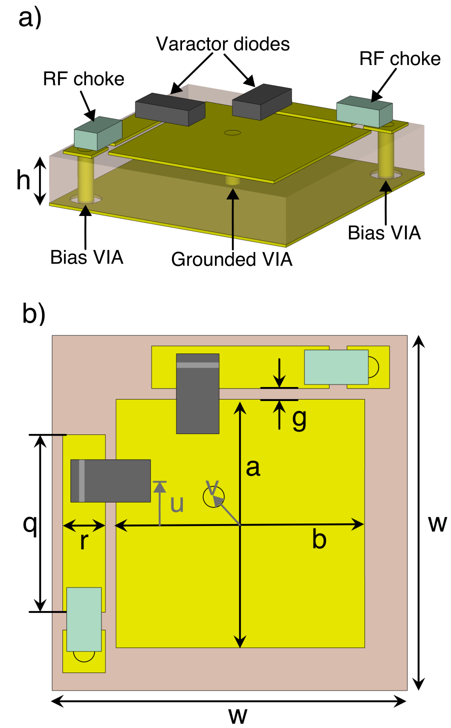

Fig. 1. Proposed dual linear polarised reflecting metasurface unit cell. Perspective view (a) and top view (b) of unit cell consisting of copper patches printed on a grounded Rogers RT/Duroid 5880 dielectric substrate. Dimensions are shown in table I. The central VIA offset and diode offset are labelled u and v, respectively.

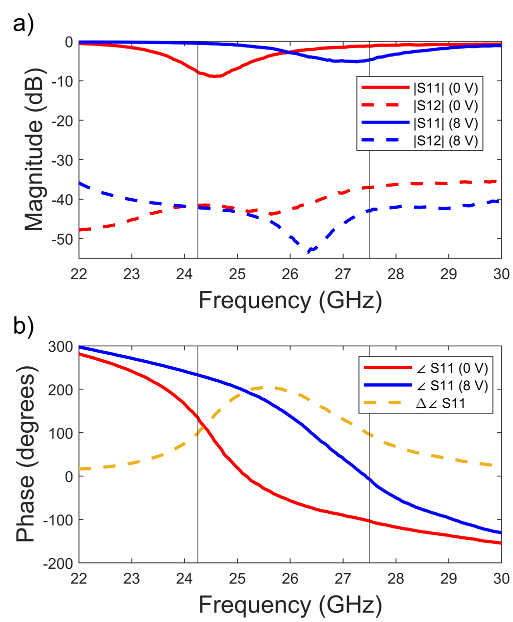

Fig. 2. Reflection magnitude (top) and phase (bottom) for the proposed unit cell design at 0V and 8V reverse-biased voltage after manual-tuning of the unit cell geometry. The curves apply to both linear polarisations due to mirror symmetry about the diagonal. Vertical lines mark the boundaries of the 24.25 - 27.5 GHz pioneer band.