Novel 1-bit Hybrid Reconfigurable Intelligent Surface With Mitigated Quantization Lobe

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***Abstract*— This paper proposes a novel 1-bit hybrid reconfigurable intelligent surface (HRIS) designed to sense the incident signal's angle of arrival (AoA) and redirect it toward desired directions. This device consists of independently tunable resonant patch elements loaded with PIN diodes. To introduce sensing capabilities to this geometry, a portion of the signal incident on each element is coupled to a parallel plate waveguide through small rectangular slots. Two coaxial connectors then measure the signal coupled from all elements to the parallel plate waveguide. We use compressive sensing techniques to analyze this signal and detect AoA. Further, pre-coded phase randomization is implemented by varying slot sizes to suppress undesired quantization lobes. The proposed HRIS is simple, low cost, can operate without feedback loops, and may find application in intelligent wireless communication, power transfer, and sensing systems.**

Keywords—reconfigurable intelligent surface; compressive sensing; AoA detection; beamforming.

I. Introduction

Reconfigurable Intelligent Surfaces (RISs) have gained significant attention in wireless communication networks due to their ability to shape and control the propagation environment. They can redirect electromagnetic waves to overcome signal blockage, mitigate interference, or increase security. To realize their benefits, RISs require knowledge of the environment, to adjust their reflection patterns accordingly [1],[2]. To address this need, [1] and [2] proposed an RIS structure with integrated sensing capabilities called hybrid RIS (HRIS). The key innovation in HRISs is modifying the HRIS's meta-atoms to couple a portion of the incident signal into a waveguide, allowing it to be sampled and analyzed for information about the propagation environment, e.g., incident angle of arrival (AoA). However, adding sensing units behind each element can significantly increase the HRIS's cost and complexities. Previous HRISs used only a few hybrid elements connected to substrate-integrated waveguides (SIWs) to address this issue [2]. This configuration suffered from low signal strength since the sensing SIWs were usually near cutoff due to limited space. Overall, previous HRISs required a complicated multi-layer implementation.

Most previous RIS designs place elements at half-wavelength spacing with binary tuning (1-bit coding) to ensure simplicity and low cost. However, 1-bit coding results in quantization lobes, which reduces the RISs' efficiency by half and can be a source of interference. To overcome that, one may use more bits to tune the RIS (e.g., using varactor diodes) or utilize phase randomization. In the latter case, elements' geometries (or, equivalently, their resonance frequencies) are deliberately modified randomly to prevent periodic patterns that result in quantization lobes when using 1-bit coding. The 1-bit RIS with mitigated quantization lobe thus holds promise for a simplified overall configuration.

This paper introduces a novel HRIS that can detect AoA with minimal complexity. This design also incorporates phase randomization to avoid quantization lobes. Our proposed HRIS comprises patch elements positioned at half-wavelength spacing and tuned by a PIN diode. For detection purposes, we have added small slots to the ground plane of each patch, allowing a small portion of the signal to be coupled to a parallel plate waveguide (PPWG) that shares the same ground plane. To introduce phase randomization, we have randomly varied the size of the slots below each element along the HRIS. We will use full wave simulation to design the proposed HRIS, show its ability to steer its beam in prescribed directions without quantization lobes, and detect the AoA of incident signals using a compressive sensing technique.

II. Proposed Metasurface Element Design

The general configuration of the building block of the proposed HRIS is shown in Fig. 1. It consists of a square patch element (a=12mm side) implemented on a substrate of Rogers 4003 (1.624mm thickness, ϵr = 3.55) and loaded with a PIN diode. The diode's on state is modeled as 0.15 pF effective capacitance, and the off state is modeled as 0.1 ohm. This element shares the ground plane with a PPWG made of the same substrate and thickness. A small rectangular slot is added to the shared ground plane to couple a portion of the incident wave to the PPWG. We designed this element by simulating it in Ansys HFSS using the configuration illustrated in Fig. 1. In our study, the design was optimized for operation at 5.6 GHz, but it can be easily adapted to other frequencies by modifying the geometry or the switchable components. The simulated reflection coefficient for the element with and without the slots is shown in Fig. 2. We see that adding the slot decreases the reflection coefficient by less than 0.1 dB, which indicates only a small portion of the signal coupled to the PPWG. In these simulations, the slot was at an offset of -3mm from the center of the substrate in the x direction. To introduce phase randomization, which is later required for beamforming, we needed two different slot lengths that realize the four states with about 90° phase difference with respect to each other. As shown in Fig. 2 (b), 2mm and 6mm slot lengths realize this condition at 5.6 GHz.

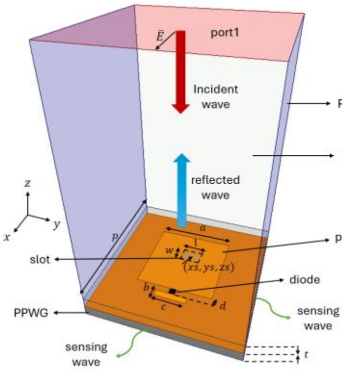

Figure 1. Simulation configuration of the building block of the proposed HRIS. Geometrical dimensions are as follows: $a = 12mm$, $b = 1mm$, $c = 5mm$, $d = 1mm$, $l = 6mm$, $p = 24mm$, $t = 1.624mm$ $w = 2mm$, and $(xs, ys, zs) = (-3,0,-1.624)$ which is a vector from the patch's center to the slot's center. Port 1 is de-embedded to the surfaces of the patch.

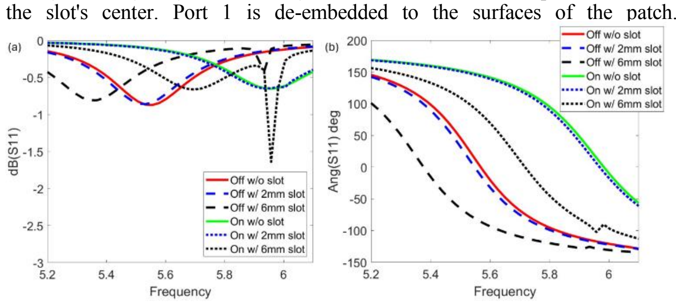

Figure 2. (a) Amplitude and (b) de-embedded phase of the reflection coefficient of the proposed building block.

III. RESULTS

First, we analyze the beamforming capability of the proposed HRIS. To do that, we simulated a 1D HRIS consisting of 19 of the proposed elements (Fig. 3). For simplicity, the beamforming and sensing capabilities are analyzed only in the yz plane, assuming an infinite periodic array in the other direction. To suppress quantization lobes, the length of the slots beneath elements is randomly chosen between 2mm and 6mm values. For each desired steering angle, we decide which elements should be in the "on" state or "off" state based on minimizing the Euclidian distance in the complex domain between the required phase of the element in the array and the available reflection phase from the simulation of the elements (Fig. 2(b)). Fig. 4 shows the simulated beamforming for different desired angles, verifying the proposed HRIS capability to redirect beams without quantization lobes even when using 1-bit coding.

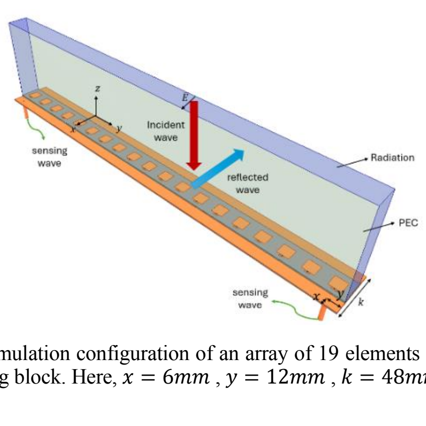

Figure 2. Simulation configuration of an array of 19 elements made of the proposed building block. Here, $x = 6mm$, $y = 12mm$, $k = 48mm$.

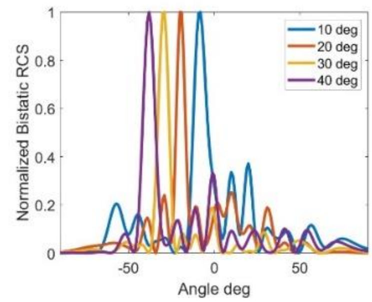

Figure 3. Beamforming results for 10°, 20°, 30°, and 40° desired angles.

Next, we examine the proposed HRIS's sensing capabilities. To minimize RF chains, we implement the AoA detection with only two coaxial connectors for collecting the sensing signal (Fig. 5). To form the sensing matrix, first we calculate the difference between the voltages on the coaxial connectors caused by the incident waves arriving from reference angles of $-60°$ to $60°$ (with $5°$ step size) for 16 masks of random "on/off" distribution. This sensing matrix is used in a process similar to the one in [2] to detect AoA. Fig. 5 shows the detected angle versus the actual incident angle for all the reference angles used to form the sensing matrix, and four test angles which are not in the reference set. It can be concluded that the proposed HRIS is capable of detecting the AoA with ±3 degrees of accuracy.

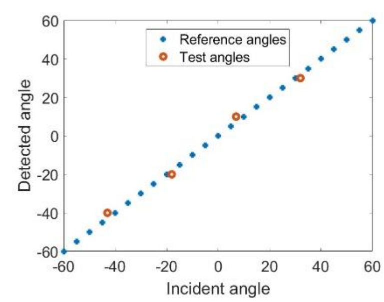

Figure 4. The angle detected by our proposed HRIS versus the actual incident angle.

CONCLUSION

This paper presented a novel metasurface that combines the benefits of phase randomization and hybrid RISs to realize a smart surface with integrated sensing and beamforming capabilities. This simple, low-cost HRIS may find applications in smart wireless communication and sensing systems.

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