Fabrication and Characterization of a 900-Element 222.5 GHz Single-bit Reflective Surface with Suppressed Quantization Lobes

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***Abstract*— We present a topology for suppressing quantization lobes in 1-bit reconfigurable reflective surfaces (RRSs). RRSs are planar surfaces that redirect the imping waves to the desired direction through phase modulation. For single-bit modulation, plane-wave illuminated RRSs exhibit quantization lobes due to the limited number of available phase bits. To eliminate such lobes, we randomize the quantization error by employing a fixed but random phase delay in every unit-cell of the RRS. Specifically, we focus on the fabrication and characterization of a mmWave single-layer, 1-bit, 30×30 randomized RRS designed at 222.5 GHz. The quasi-optical RCS characterization of the fabricated RRS demonstrates the successful suppression of the quantization lobe using the proposed technique.**

I. Introduction

Reconfigurable reflective surfaces (RRSs) with their attractive characteristics of low-profile, low-RF losses, low-power consumption, and high-gain capabilities [1] are aptly suited for future high-frequency wireless communication applications. Particularly, with the evolution of intelligent reflective surfaces (IRSs), the RRSs are being integrated with mmWave/THz wireless communication systems to improve signal coverage and/or to enable new types of sensing. In such installations, RRSs are typically deployed as relays to redirect the incoming waves from the base station to the non-line of sight users [2]. As such, the RRSs are illuminated by plane waves from different directions and redirect them to desired directions by modulating the phase of the impinging waves through activation of the integrated switches (Fig.1). The phases of the individual elements are usually quantized using 1-, 2-, or 3-bit phase modulation schemes to reduce the design complexity. This method of phase rounding causes periodic quantization errors, which results in undesired quantization lobes. The effect is particularly aggravated for a 1-bit quantization scheme due to the limited number of phase bits. However, as the 1-bit quantization offers the advantages of design simplicity and low implementation cost, it is critical to devise methods to break the periodicity of the quantization errors and mitigate the undesired quantization lobes.

In this work, we present a technique for suppressing quantization lobes in single/multi-bit RRSs using phase randomization, originally proposed in phased arrays [3]. Specifically, by introducing random but fixed phase delays in each unit cell of a single-layer, 1-bit RRS, we randomize the quantization errors and thus, suppress the quantization lobes. A single-layer design is chosen here as it reduces the fabrication complexity and losses due to airgaps, bows, and warpages commonly seen in multilayer implementations. Some preliminary results of a 20-element linear RRS designed on a 20 μm Si substrate were presented in [4]. Herein, we focus on the design and characterization of a 222.5 GHz 30×30 two-dimensional (2D) RRS designed on a 45 μm thick alumina ribbon ceramic substrate from Corning Inc.

II. 2D RRS Design and Fabrication

In this section, we outline the design methodology and the fabrication technique employed for the proposed 2D 30×30 RRS. The unit cell of the RRS (Fig.1) consists of a linearly polarized patch antenna embedded with an integrated switch incorporated in a coplanar waveguide (CPW). The random phase shifts are implemented by varying the delay line length, Δl.

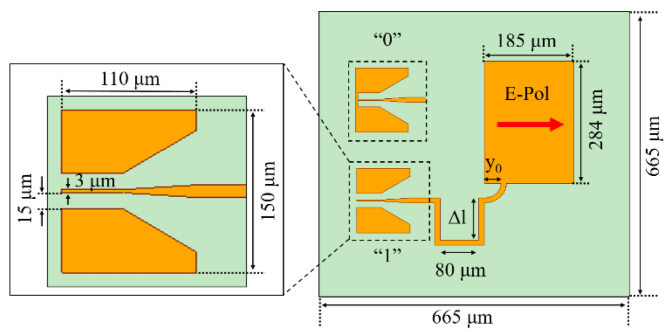
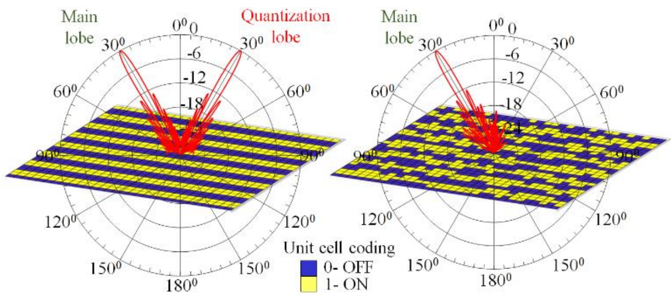


Fig. 1. A unit cell of the designed RRS.

When no randomization is employed, the quantized phases used to design the surface are periodic, as depicted by the unit cell coding of Fig. 2a. The resulting radiation pattern has a quantization lobe at $+30^0$ in addition to the desired main lobe at -30^0. This is because the phase modulation required for radiating at $+30^0$ is the same as that needed for radiating at -30^0. Consequently, the quantization lobe has the same magnitude as the main lobe in this case. On the contrary, when randomization is introduced, the periodicity of the quantization errors is broken and the quantized coding scheme is no longer symmetric as illustrated by the unit cell coding of Fig. 2b. Adopting the recommendation for choosing the range of randomization as proposed in [4], a phase randomization range of $0\text{-}180^0$ is selected for designing the randomized 2D RRS in this work. As such, for the same illumination scheme, the random delay lines have varying lengths, Δl and the resulting radiation only has the desired main lobe at -30^0 and no quantization lobe.

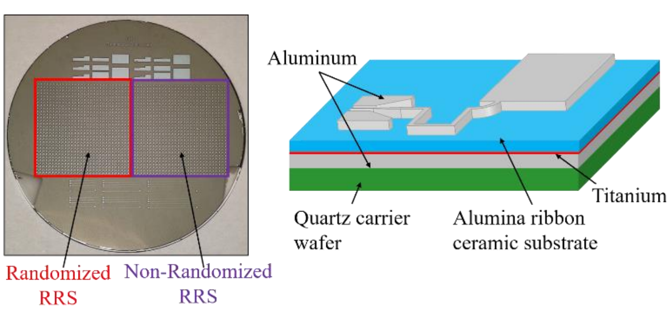


(a) (b)

Fig. 2. 2D RRS with (a) 1-bit phase modulation results in a periodic phase distribution with an undesired quantization lobe (b) randomization perturbes the periodicity and the resultant radiation pattern consists of a single main lobe.

Both the RRSs are fabricated side-by-side on a 45 µm thick, 2″ diameter alumina ribbon ceramic substrate ($\epsilon_r = 10$, $tan\delta = 0.8 \times 10^{-3}$) from Corning Inc. to demonstrate the proposed phase randomization technique. At first, a thin layer of titanium is deposited on one side of the alumina substrate, followed by a thicker layer of aluminum. This serves as the ground plane for the RRSs. Owing to its fine grain, dense microstructure, and low thickness, the alumina wafer it flexible. As such, to impart the sturdiness required by the wafer for further fabrication steps, the metallized side of the wafer is permanently bonded to a 500 µm thick quartz wafer.

Post bonding, the wafer is spin-coated with two-layered photoresists. It is followed by contact photolithography, which is used to expose the resists to ultraviolet radiation and develop the patterns of the radiating structures. We then use a second metallization process to deposit aluminum to form the antennas. Finally, the resists are stripped off to obtain the finished RRSs. The prototype of the fabricated wafer and its unit cell depicting the different layers of the fabricated RRS are shown in Fig. 3a and 3b, respectively.

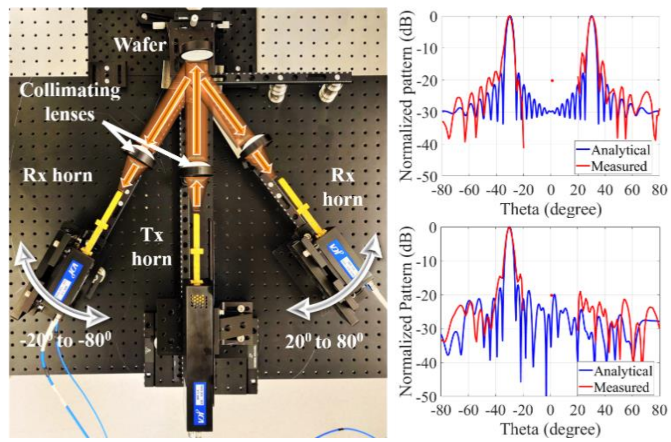


(a) (b)

Fig. 3. (a) Prototype of the fabricated wafer and (b) unit cell depicting the RRS layered structure.

III. RRS Characterization

A quasi-optical setup shown in Fig. 4a is used to characterize the fabricated reflective surfaces. As such, to measure the RCS of the RRSs, we utilize the Teflon lens to collimate the diverging beam from the horn and illuminate the RRS with a plane wave. The wafer is mounted on a sliding pedestal to align the RRS under test with the fixed transmitter beam at broadside, and the scattered fields are measured by rotating the receiver radially covering [-20^0, -80^0] and [+20^0, +80^0], only restricted by the geometrical limitations of the setup. To ensure that there is no significant reflection in the broadside direction, the back-reflected signal is also measured. The resulting RCS patterns of both the RRSs at 222.5 GHz are plotted together with their analytical patterns, as shown in Fig. 4b. A good agreement is seen between the measured and analytical patterns where the non-randomized RRS has both the main lobe and the quantization lobe as expected, while the randomized RRS only has the main lobe in the desired direction of -30^0. Thus, the proposed technique demonstrates the suppression of quantization lobes with a quantization lobe level of -18 dB.



(a) (b)

Fig. 4. (a) Quasi-optical measurement setup used for the characterization of the fabricated RRSs and (b) normalized RCS pattern v/s the scan angle theta at 222.5 GHz for non-randomized RRS (top) and randomized RRS (bottom).

IV. Conclusion

We presented a topology for mitigating quantization lobes in a single-layer, 1-bit RRS using the technique of phase randomization. The random phase delays implemented using physical delay lines break the periodicity of the quantization errors and suppress the quantization lobes. We have detailed the design, fabrication and characterization of a 900 element 2D RRS. The RCS characterization demonstrates the successful mitigation of the quantization lobes using the proposed technique that paves the way for efficient single beam IRSs.

References

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