Rotman-Lens-Based Reconfigurable Intelligence Surface mmID with Energy Harvesting Capability

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Abstract — **This paper presents a low-power and potentially energy-autonomous Rotman Lens-based reconfigurable intelligence surface millimeter wave identification (mmID) that is able to harvest and communicate selectively with a power consumption of $159.6\,\mu\mathrm{W}$ at $28\,\mathrm{GHz}$. The prototype is inkjet-printed on a thin Rogers substrate using a masking technique followed by etching. Its harvesting performance is evaluated by its rectifier efficiency and the system is able to turn on at $2.5\,\mathrm{dBm}$ input power. Its communication ability is evaluated indoors in both close range and medium range. The system displays a medium-range communication capability up to $10\,\mathrm{m}$ with $41\,\mathrm{dBm}$ effective isotropic radiated power (EIRP) and can harvest $28\,\mathrm{GHz}$ signals up to $11\,\mathrm{m}$ and communicate up to $125\,\mathrm{m}$ with $75\,\mathrm{dBm}$ EIRP.**

Keywords — **Rotman Lens, Re-direction, Energy Harvesting, Backscatter Communications**

I. Introduction

Moving into the 5G and IoT era, millimeter wave (mm-Wave) presents a great option for communication because of its high data rates and small cell infrastructure. However, mm-Wave communications significantly deteriorate in non-line-of-sight (NLOS) conditions where the path between the transmitter and receiver is obstructed. Unfortunately, in 5G and IoT applications, such as smart cities, wireless links are highly prone to these conditions in a complex urban environment. Reconfigurable Intelligence Surface (RIS) aided wireless communication has been a promising candidate technology to overcome this challenge by dynamically controlling the propagation direction of electromagnetic waves to bypass physical obstacles and allow signal relays. Meanwhile, a lot of the current low-power 5G communication research explores co-polarized retrodirective backscattering devices that are limited in range due to the cross-talk between the co-located transmitting and the receiving antennas. Signal re-direction using RIS overcomes this challenge by spatially separating the transmitter and the receiver. Furthermore, RISs enable more complexity and coverage for communication between base stations that do not have a line-of-sight (LOS) link.

In [1], the authors revisited many computational results of RIS for energy-efficient IoT applications but emphasized the gap between theory and practical solutions. There have been very limited demonstrations of functional RIS prototypes. Reported designs either consume high power or are bulky in size due to the array structures that support beamforming ability, and none of those operates at the mm-Wave 5G band whose performance degrades severely in NLOS scenarios. Existing RIS designs such as [2] leverages metamaterials to support beamforming ability. The authors explored metasurfaces at $10.5\,\mathrm{GHz}$ and $4.25\,\mathrm{GHz}$ by using extra low power varactor diodes and mW scale PIN diodes per unit cell, but the design requires $10\,\mathrm{W}$ and $0.72\,\mathrm{W}$ for the system controller circuits respectively. [3] presented a high-gain 16×16 structure at $2.3\,\mathrm{GHz}$ that realizes 2-bit phase shifting by consuming $153\,\mathrm{W}$ of power. However, none of the reported solutions tackle the mm-wave/5G band, where the re-direction system could solve the fundamental problem of NLOS blockage. It is important to highlight that implementing these systems at mm-Wave frequencies would result in even higher power consumption because components are less efficient at higher frequencies. Therefore, there is clearly a need for a system that is power autonomous and capable of communicating and re-directing the beams in the mm-Wave regime.

There are some existing technologies that can be leveraged to overcome some of the challenges in reconfigurability. In [4], the authors proposed a Rotman Lens-based rectenna to achieve high gain throughout a wide angular coverage at $28\,\mathrm{GHz}$, but this design system did not enable any communications. In another work, [5] demonstrated an energy-autonomous Rotman Lens-based co-polarized backscattering RFID tag operating at $28\,\mathrm{GHz}$ with wide angular coverage, but the system does not harvest from the incident signals nor allows angular reconfigurability of the backscattering signal. Building upon previous efforts, the authors, for the first time, propose a low power Rotman lens-based RIS mmID design operating at $28\,\mathrm{GHz}$. The proof-of-concept prototype provides two operational modes namely: harvesting of electromagnetic energy incident on the mmID and re-direction of a backscattering response to set the foundation for a highly dynamic system with a potential for a fully energy-autonomous system.

II. Low Power Rotman Lens-based RIS mmID System

The signal blockages in a complex urban environment are illustrated in Fig. 1, where the receivers in the range of ports 1, 3, 4, and 6 have lost their access to their transmitters in ports 2 and 5, respectively. The system here provides a solution to this major communication challenge observed at mm-Waves and proposes to efficiently re-direct signals

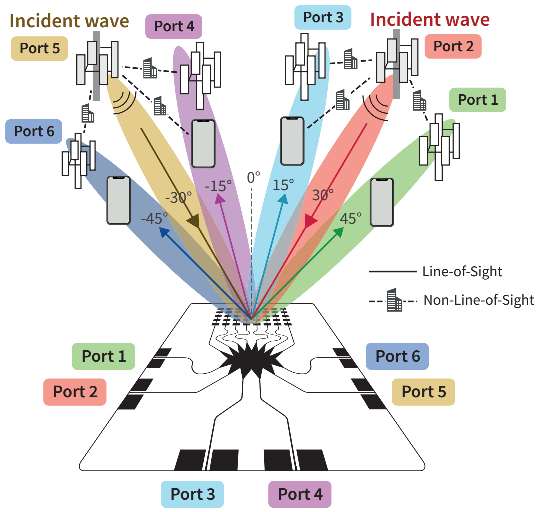


Fig. 1. Rotman lens antenna array beaming diagram in a complex urban environment.

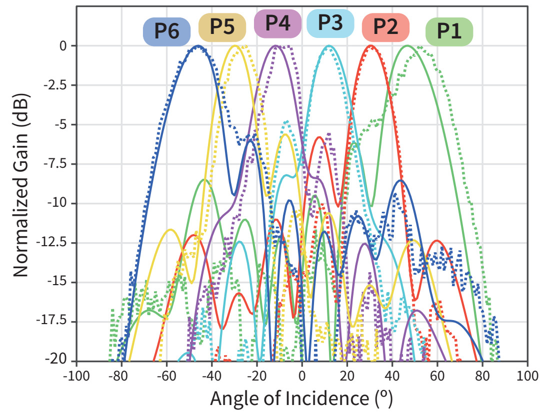
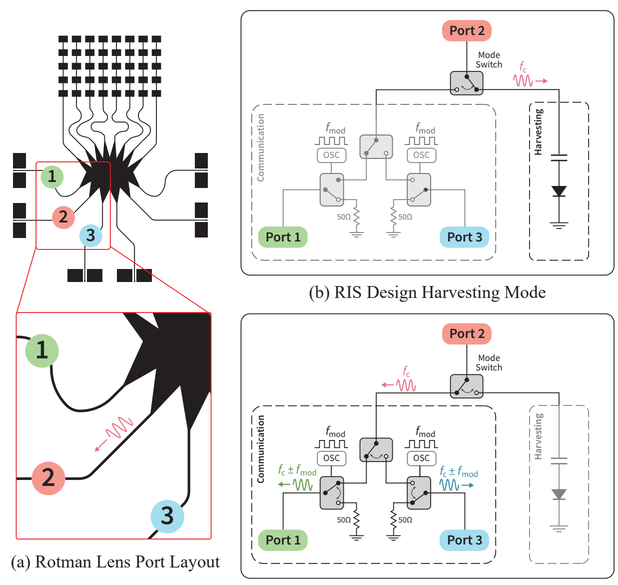


Fig. 2. Rotman lens simulated and measured normalized gain at 28 GHz.



(a) Rotman Lens Port Layout

(b) RIS Design Harvesting Mode

(c) RIS Design Communication Mode

Fig. 3. Rotman lens-based RIS mmID system schematic

from the transmitting base station to mobile users or another base station. Rotman Lens has a feature to map the incident angle with its corresponding beam port as shown in Fig. 1. Incident waves from different incident angles will be focalized passively to different beam ports and vice versa [6]. With this feature, the device is able to receive signals from one direction, focalize them to one of the beam ports, then redirect them to another direction by exciting other ports on the Rotman lens without consuming any external energy.

The system control is enabled by 8 non-reflective MASW-011102 SPDT switches from Macom that can be controlled by mechanical switches composed on a breadboard. The proof-of-concept prototype includes a Rotman lens and 8 antenna arrays each with 5 serially fed patches that are designed, simulated, and optimized in CST Studio Suite, similar to the design proposed in [4]. The simulated and measured normalized gain pattern of the Rotman Lens is shown in Fig. 2, showing symmetry and agreement between simulation and measurements. The total proposed system is symmetric, so only half of the system will be explained in the following sections. The other half of the system is deemed to perform identically.

A. *Design of Mode Switch and Energy Harvesting Feature*

In order to allow an energy-autonomous operation, an energy harvesting feature is integrated along with the communication beam re-direction ability. Therefore, the system can be configured to operate either in harvesting or communication mode. The aforementioned SPDT switch is used to control energy harvesting/communication modes ("Mode Switch"), shown in Fig. 3. This SPDT switch requires a voltage of $-1.5\,\mathrm{V}$ and therefore a solar cell is used to provide an initial voltage biasing to toggle the switch to harvesting mode to start the system operation. The mode switch is controlled by mechanical switches on a breadboard for simplicity and on-demand control.

When starting the system with harvesting mode, the incident signal is focalized to port 2 and fed into a $28\,\mathrm{GHz}$ rectifier. The half-wave rectifier is made of a MA4E1317 Schottky diode with a $100\,\mathrm{nF}$ capacitor as a DC block to prevent the harvested voltage from flowing back to the mode switch and causing damage to the component. The layout and performance of the rectifier are shown in Fig. 4, characterized at $28\,\mathrm{GHz}$ with input power from $-3\,\mathrm{dBm}$ to $10\,\mathrm{dBm}$ for its harvested power and harvesting efficiency. Since the Rotman Lens antenna array allows beamforming passively, the only components that consume power in this system are the SPDT switches and oscillators that will be later described in Section II-B. The system is tested with a solar cell for proof of concept, but Fig. 4 shows that the rectifier is able to harvest the needed power at the lowest input power at $2.5\,\mathrm{dBm}$, denoted with the black dotted line. Therefore, this system is able to harvest power from the transmitter to provide fully-passive operation. In order to get enough input power into the rectifier for the harvesting mode, the system can be operated at up to

11 m away with 75 dBm EIRP while still providing sufficient power, 159.6 µW, to the oscillators and SPDT switches used in communication mode.

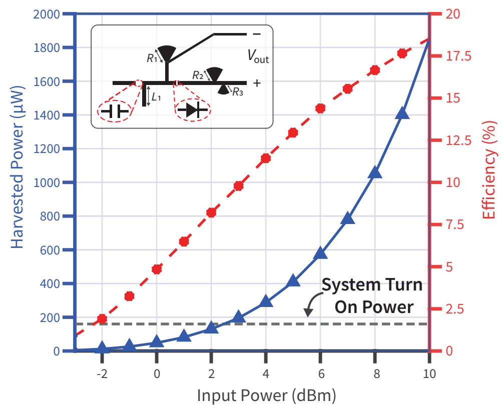


Fig. 4. Harvested power and efficiency versus input power into the 28 GHz rectifier with an inset of the circuit layout with dimensions labeled $L_1 = 2.18$ mm, $R_1 = 1.61$ mm, $R_2 = 1.43$ mm, and $R_3 = 0.95$ mm.

B. *Design of RF Re-direction Capabilities*

When the system harvests enough energy to turn on, it will toggle the SPDT switch into communication mode for beam selection and signal modulation, achieved by the same SPDT switch ("Function Switch"). The function switch is also controlled by mechanical switches on a breadboard for simplicity. When in communication mode, the signal can be re-directed to either 45° or 15°, port 1 or port 3. The other non-excited ports, including the ones on the other half-plane (port 4 and port 6), will be terminated with 50Ω loads to properly operate the Rotman lens for the reduction of signal reflections and leakages between ports. The function switch, controlled by a TS3006 Semi Oscillator, provides amplitude-shift keying (ASK) modulation at 250 kHz to the re-directed signals, showing as f_{mod} in Fig. 3. Due to the designed controlling scheme, the device is able to re-direct and backscatter signals simultaneously.

III. Evaluation of Low Power Rotman Lens-Based RIS mmID System

The proof-of-concept prototype includes a Rotman lens and 8 antenna arrays, the energy harvester, and the SPDT switches at 28 GHz is fabricated on a Rogers RO4350B substrate ($\epsilon_r = 3.66$ and $h = 170$ µm) with an inkjet-printed masking technique followed by etching, shown in Fig.5 and is 12 cm × 11 cm in size. The measurements are performed indoors with the device placed 1.54 m away from two 28 GHz horn antennas with 20 dBi gains in a bistatic configuration, one as a transmitter and one as a receiver. For the wireless interrogation, a 83640L Signal Generator from Agilent is used to generate a continuous wave (CW) at 28 GHz to the transmitting antenna. With the transmitting antenna placed at a 30° incident angle (port 2), the power level of the 250 kHz subcarrier from the RIS mmID is monitored on the 8565E spectrum analyzer from Agilent while sweeping the receiver antenna from −70° to 70° in steps of 5° in both re-direction configurations of 15° (port 3) and 45° (port 1). This bistatic measurement is repeated with the transmitting antenna at a −30° incident angle (port 5) to achieve the complete characterization of the re-direction capabilities. The normalized received power from this re-direction characterization is displayed in Fig. 6. These results demonstrate the re-direction capabilities of the RIS mmID with a low power consumption of 159.6 µW. It can be seen that the re-directed signal directions at ports 1, 3, 4, and 6 can be activated on-demand when the proper toggling configuration is applied with low leakage and reflection at other ports, validating the redirecting concept utilizing the fully-passive Rotman Lens.

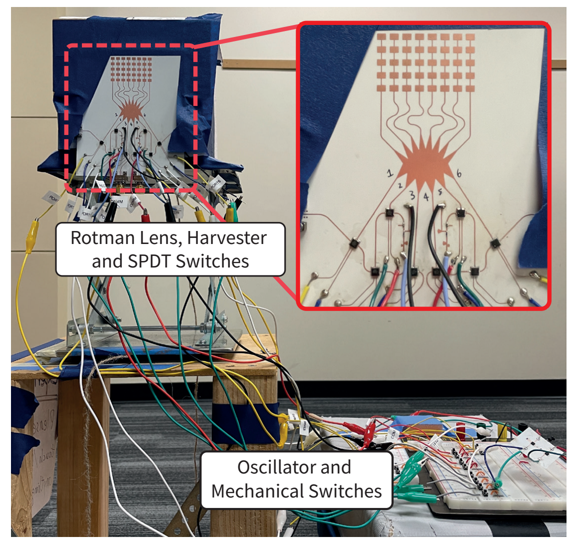


Fig. 5. Rotman Lens-Based RIS mmID.

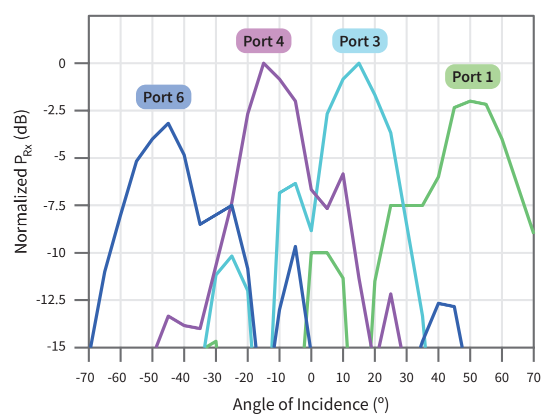


Fig. 6. Rotman Lens-Based RIS mmID Radiation Pattern in Communication Mode.

The system is also tested at medium range indoors from 2 m to 10 m away with the same bistatic configuration to validate the long-range possibility with the setup shown in Fig. 7. The transmitting antenna is placed at an angle of incidence of 30°, port 2, with 41 dBm EIRP and the power level of the 250 kHz subcarrier is monitored at port 1 and port 3, 45° and 15° respectively. Fig. 8 displayed the received power at port 1 (blue) and port 3 (red) with proper re-direction configuration and its phase noise level (black). It shows that the power level and the phase noise decrease as the distance increases. It is calculated that the proposed system can operate up to $125\,\mathrm{m}$ away with $75\,\mathrm{dBm}$ EIRP. Since self-interference between the transmitter and receiver decreases when the distance increases, the sensitivity increases. It is expected that further increasing the spatial isolation between the transmitting and receiving antennae can improve sensitivity to the thermal noise level of $-91.9\,\mathrm{dBm}$, calculated by $S_{Rx} = -174 + G_{LNA} + NF + 10\log_{10}(F_{Samp})$, where G_{LNA}, NF, and F_{Samp} are the gain of the LNA in dB, noise figure of the LNA in dB, and sample rate in Hz, respectively.

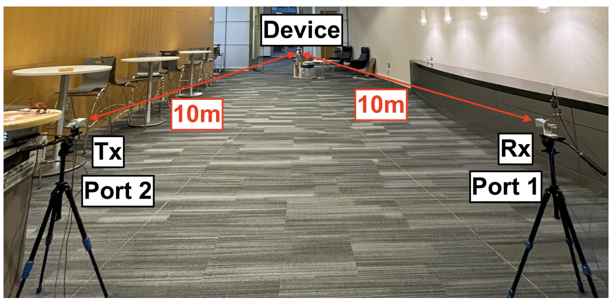


Fig. 7. Medium range experimental setup.

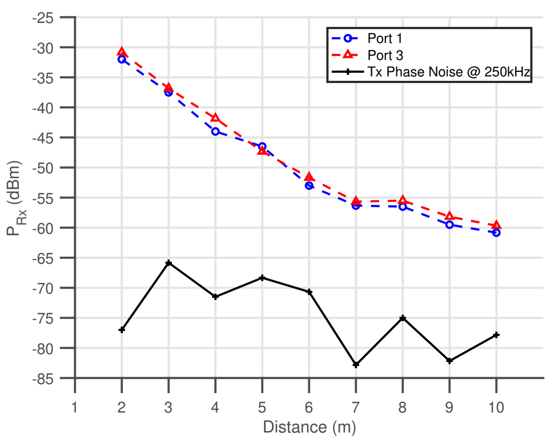


Fig. 8. Medium range received power and phase noise measurements.

IV. Conclusion

This paper demonstrates a low-power Rotman Lens-based RIS mmID with an energy harvesting feature in addition to the capability to achieve signal re-direction with modulation at 5G mm-Wave frequency band. This proof-of-concept system is supplied by a solar cell, but the implemented rectifier is able to harvest the amount of power needed for re-directing at the lowest of $2.5\,\mathrm{dBm}$ input power. Therefore, this result suggests a potential for a fully energy-autonomous RIS system. Even though the harvester can only operate up to $11\,\mathrm{m}$ away from the transmitting base station, it can communicate to mobile users and base stations up to $125\,\mathrm{m}$ away, realizing a powerful efficient long-range communication network with the ability to control the signal redirection. This harvesting feature also addresses the path optimization challenge mentioned in [1] by sensing the incoming signal with the harvester. Further implementation of nano power boost converter can be connected to the rectifier to supply low-power timer, and therefore developing the current system into a fully energy-autonomous signal re-directing mmID tag.

Meanwhile, since the transmitting and receiving antennas are spatially separated in the bistatic configuration, this system is able to achieve high sensitivity up to the thermal noise level even though it is a co-polarized design. Furthermore, this system can be improved by implementing more RF switches to achieve more dynamic beamforming. It is important to note that this current design is a static proof of concept in which the re-directing path is restricted. In order to increase the re-direction complexity, a multi-layer board with an increased number of switching paths is needed and a trade-off in total power consumption.

Table 1 shows the comparison of the proposed system with other existing RIS prototypes. It can be seen that these existing prototypes achieve better re-direction coverage and turnability with bulky metasurfaces or N × N structures but do not operate at the mm-Wave frequency band while consuming a lot more power than the proposed system in this work. Noted that since this work proposes a system, the power consumption is compared on a system level with other work.

Table 1. Current RIS Design Comparison

Ref.	[2]	[2]	[3]	This work
Freq.	10.5 GHz	4.25 GHz	2.3 GHz	28 GHz
Footprint (cm^2)	1703	363	20794	132
Power Consumption	10 W	0.72 W	153 W	159.6 µW
Re-direction Coverage	Elevation Azimuth	Elevation Azimuth	Elevation	Azimuth
Energy Harvesting	N/A	N/A	N/A	Enabled

Acknowledgement

The authors would like to thank the National Science Foundation (NSF) for supporting this work.

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