Film-Type Transparent Passive Reconfigurable Intelligent Surface Design for Multi-Incidence-Reflection Relation on mmWave Communication

Yu-Da Chen*, Wei-Sheng Cheng*, Yu-Zhen Yang*, Chen-Kuan Kuo*
*BenQ Materials Corporation, Taoyuan, Taiwan

Abstract

We introduced a design of film-type transparent passive reconfigurable intelligent surface (RIS) to be functional for multi-incidence-reflection relation on mmWave communication. The metrology is based on the theory of diffraction equation and the phase distribution of meta-atoms in a phase array RIS for various angle of incidence. This design creates more flexibility for one single RIS to be deployed in sceneries to extend the coverage of mmWave network.

Author Keywords

reconfigurable-intelligent-surface; transparent; mmWave; film-type; passive; beam-steering; energy management.

1. Introduction

With the upcoming fifth generation (5G) and beyond 5G (B5G) millimeter wave (mmWave) network, it brings a low-latency [1] and high-speed data transmission for mobile communication. However, there is a significant path loss from atmospheric influence such as atmospheric fluctuations, temperature, and humidity [2]. To solve this problem, we may boost higher-power in each base station or increase the base station density.

Energy management is an emerging issue in recent years. Therefore, RIS is introduced to assist the data transmission and coverage extension with normal power consumption and normal density of base station. [2-3] Reflected-type RIS (R-RIS) is like an imaginary mirror to redirect the EM-wave signal to abnormal reflection, and transmitted-type RIS (T-RIS) is an imaginary lens to redirect the wireless signal to abnormal transmission. The theoretical physics of R-RIS and T-RIS are based on the generalized Snell's law equations, as below. [4]

$$\text{Reflection}: \sin\theta_r - \sin\theta_i = \frac{\lambda_0}{2\pi n_i}\frac{d\Phi}{dx} \quad (1)$$

$$\text{Refraction}: n_t \sin\theta_t - n_i \sin\theta_i = \frac{\lambda_0}{2\pi n_i}\frac{d\Phi}{dx} \quad (2)$$

Meta-atom [5] is a plasmonic particle with spherical wave in reflection and in transmission. With proper design and selection to form a periodical meta-atom distribution, a radio wave can be redirected to the designated direction in the far-field. Most passive phase array RIS were designed for one specific incidence-reflection condition [6-7] due to the wave-front distortion while the incidence-reflection relation changes, as shown in figure 1.

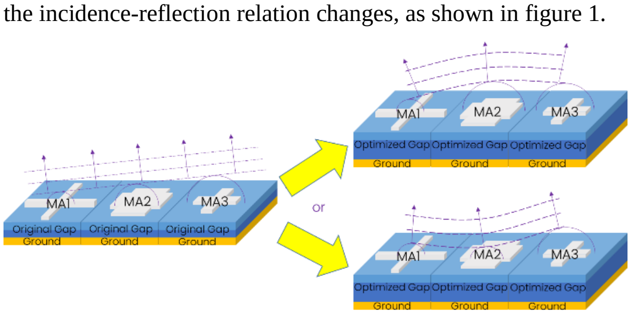


Figure 1. Scheme diagram of wave-front distortion.

In this study, we proposed a design of passive R-RIS to be functional for multi-incidence conditions. Two design cases were demonstrated. The film-type transparent RISs were fabricated and examined by measurement.

2. Design

An electromagnetic wave simulation algorithm was developed to calculate the theoretical near-field reflected phase for all meta-atom candidates. The grating period (d) were selected to meet the incidence-reflection requirements in figure 2. The incidence-reflection relation was calculated by the diffraction grating equation [4,8], as below.

$$\sin\theta_i + \sin\theta_m = \frac{m\lambda}{d} \quad (3)$$

Figure 2. Incidence-Reflection relation of 2 phase arrays.

In addition, a computer program was built to find out the less phase-sensitive meta-atoms to form the phase array in all required incidence-reflection relation (marked by dash circles in figure 2).

Phase Array 1	MA1	MA2	MA3
Reflected Phase	155.37	255.65	354.19

Phase Array 2	MA1	MA2	MA3	MA4	MA5	MA6	MA7	MA8	MA9	MA10
Reflected Phase	151.57	182.87	214.33	244.09	276.38	305.94	333.85	370.69	402.62	433.59

Figure 3. Scheme diagram of meta-atoms deployment, phase distribution, incidence-reflection for 2 RIS (phase array1 and phase array2).

The designed phase array 1 consists of 3 individual meta-atoms (MA1-MA3) with equal pitch (less than the wavelength of the

ISSN 0097-996X/25/5603-1901-$1.00 © 2025

working frequency), and the designed phase array 2 consists of 10 individual meta-atoms with equal pitch (MA1-MA10). A spherical wave array with gradually increased near-field phase were arranged in order. An electromagnetic wave simulation with Fraunhofer approximation was then conducted to ensure the main-lobe direction and to predict the theoretical intensity of beam-forming wave-front in the far-field distance. The wave-front in the far field of each RIS acts like an imaginary mirror for guiding the incident EM-wave to the assigned direction, as shown in figure 3. The positive (+) sign stands for the angle in right-handed side, and the negative (-) sign represents the angle in left-handed side.

3. Fabrication and Result

A passive RIS design was conventionally based on the Print Circuit Board (PCB) manufacturing process. [6] For the purpose of boosting up the transmission of a RIS in the visual (VIS) wavelength region, we innovated a film-type RIS with layers of polymer films. As shown in figure 4, a semi-transparent RIS and a transparent RIS were developed with transmittance over 65% and over 75%.

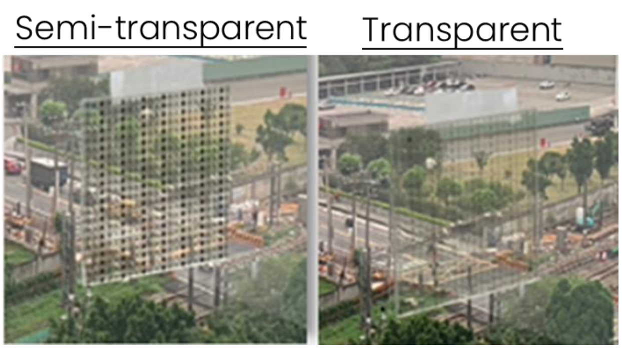
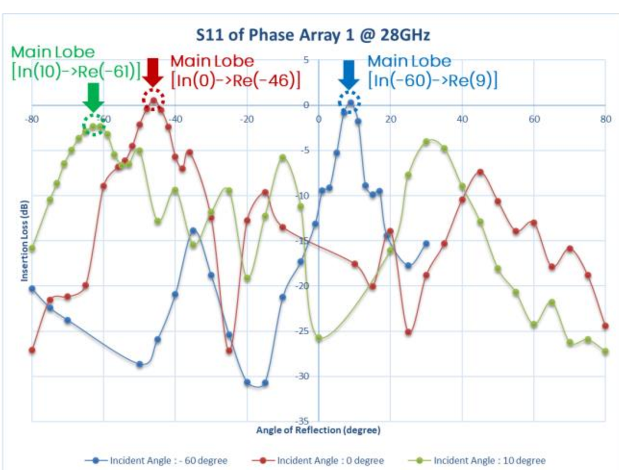


Figure 4. Semi-transparent and transparent RIS

A transmit(TX)-RIS-receive(RX) measurement was conducted to examine the actual performance of two RIS (phase array 1, phase array 2). The TX antenna provides a mmWave radioactive signal (25.5GHz-30.5GHz). The RX antenna was assigned to capture the reflective signal scattered from the RIS. Both TX and RX were controlled and monitored by a network analyzer.



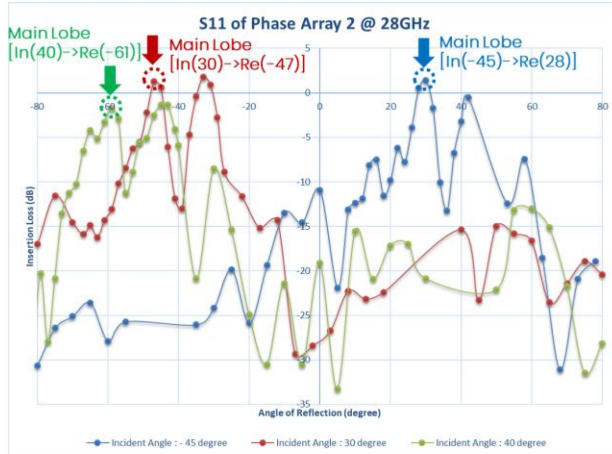


Figure 5. Experimental results of angular Insertion Loss for (phase array1) and (phase array2) at various incidence conditions.

The angular insertion loss (S11) of (phase array1) and (phase array 2) at 28GHz was illustrated in figure 5. The main lobes of reflected fields for all incidence cases are notably occurred at the same angles predicted in the figure 2. Furthermore, the 28GHz radio wave from incidence $(-60°, 0°, 10°)$ were respectively redirected to reflection $(9°, -46°, -61°)$ via phase array 1, and the 28GHz radio wave from incidence $(-45°, 30°, 40°)$ were respectively redirected to reflection $(28°, -47°, -61°)$ via phase array 2.

4. Conclusion

Two passive RIS design were demonstrated by the theory of grating diffraction and the plasmonic property of metasurface. The reflected phase of each meta-atom was calculated via a near-filed electromagnetic algorithm, and the theoretical performance of the phase array was predicted via a far-field wave simulation. These two film-type RIS with high transparency in VIS were fabricated and proved to be functional for multi-incidence-reflection conditions. After all, we may take the advantage of the multi-incidence-reflection relation of a single RIS to extend the coverage of mmWave network in scenario, as shown in figure 6.

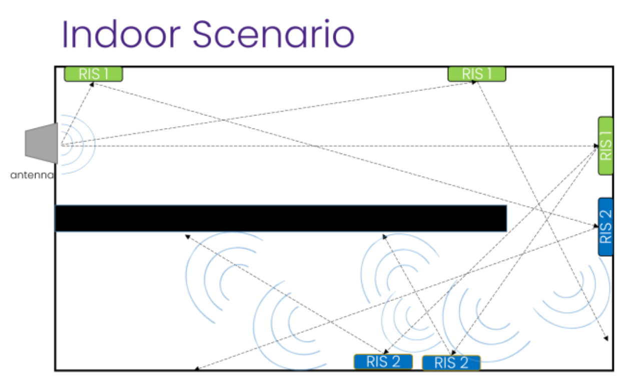


Figure 6. Indoor Scenario of RIS deployment to extend coverage of mmWave network.

5. References

1. Sharma T, Chehri A, Fortier P. Reconfigurable intelligent surfaces for 5G and beyond wireless communications: A comprehensive survey. Energies, 2021; 14(24), 8219.
2. Ratul RH, Zaman SM, Chowdhury HA, Sagor MZH, Kawser MT, Nishat MM. Atmospheric influence on the path loss at high frequencies for deployment of 5g cellular communication networks. 14th International Conference on Computing Communication and Networking Technologies (ICCCNT), IEEE, 2023; pp. 1-6.
3. Zhang S, Zhang H, Di B, Tan Y, Di Renzo M, Han Z, et al. Intelligent omni-surfaces: Ubiquitous wireless transmission by reflective-refractive metasurfaces. IEEE Transactions on Wireless Communications, 2021; 21(1), 219-233.
4. Yu N, Genevet P, Kats MA, Aieta F, Tetienne JP, Capasso F, et al. Light propagation with phase discontinuities: generalized laws of reflection and refraction. Science, 2011; 334(6054), 333-337.
5. Meinzer N, Barnes WL, Hooper IR. Plasmonic meta-atoms and metasurfaces. Nature photonics, 2014; 8(12), 889-898.
6. Rana B, Cho SS, Hong IP. Passive Type Reconfigurable Intelligent Surface: Measurement of Radiation Patterns. Micromachines, 2023; 14(4), 818.
7. Li X, You JW, Gu Z, Ma Q, Chen L, Zhang J, et al. Passive human sensing enhanced by reconfigurable intelligent surface: Opportunities and challenges. IEEE Communications Magazine, 2024.
8. Bonod N, Neauport J. Diffraction gratings: from principles to applications in high-intensity lasers. Advances in Optics and Photonics, 2016; 8(1), 156-199.