Dual-Polarized Phase-Gradient Reflecting Metasurface for 5G mmWave Coverage Improvement

Taran Anusorn[1], Panuwat Janpugdee, and Suwit Kiravittaya
Department of Electrical Engineering, Faculty of Engineering
Chulalongkorn University
Bangkok, Thailand
[1] anusorn.taran@gmail.com

Paramin Sangwongngam
National Electronics and Computer Technology Center (NECTEC), National Science and Technology Development Agency (NSTDA)
Pathum Thani, Thailand

***Abstract*—This paper proposes the design of a phase-gradient reflecting metasurface (MTS) to improve 5G mmWave coverage, following the principle of perfect anomalous reflection. The reflective responses of a simple structure with cross-shaped resonators have been investigated. The results from a full wave simulation show that the proposed MTS with a surface area of 23×23 cm^2 can anomalously reflect a linear dual-polarized plane wave at 25.8 GHz from an incident angle of 30° to a reflection angle of 54° with a more than 10 dB radiation power ratio between the main reflected beam and its sidelobe at a specular reflecting direction.**

Keywords—Metasurface, Anomalous Reflection, mmWave, Dual-Polarized Plane Wave.

I. Introduction

With enormously increasing data consumption, congestion in communication bandwidth causes the available sub-6 GHz spectrum to reach its limits. A millimeter wave (mmWave) frequency band is a prominent key solution to enabling faster data rates, greater channel capacity, and lower latency in 5G and beyond communication systems [1]. However, high-frequency electromagnetic waves naturally possess a high free space-path loss, resulting in limited coverage. Moreover, the propagation of mmWave is easily obstructed by typical materials such as walls and glass panels, causing non-line-of-sight (NLoS) link instability and coverage problems in crowded indoor scenarios, such as offices, department stores, and dense urban area deployments [1]-[3]. More base stations and access points can be installed to extend coverage in the NLoS region, but this measure also comes with high costs and increased network complexity.

Another possible way to overcome the NLoS limitation is to create a new propagation path that goes around the obstacle. By setting a flat metallic plate in the appropriate position, reflected signals will propagate in the specular direction, according to the law of reflection. To increase installation versatility, a periodic structure called a metasurface (MTS) can be designed to perform anomalous reflection, where incident waves are reflected in any desired direction, breaking the conventional law of reflection [4]. In past years, many configurations of reflecting MTSs have been proposed and analyzed [5]. Besides design complexity, which affects the cost of fabrication, the ability to manipulate two orthogonally polarized waves should be considered as well, since dual-polarized antennas are generally used in 5G base stations.

In this paper, an MTS has been designed to operate at 25.8 GHz and reflect the incident plane wave from an incident angle (θ_i) of 30° to a reflection angle (θ_r) of 54°. The proposed design incorporated a periodic arrangement of cross-shaped resonators that is able to provide the operation with a dual-polarized incident wave [6].

II. Design of Phase-Gradient Metasurface

To create a perfect anomalous reflection from the incident angle of θ_i to the reflection angle of θ_r at the operating wavelength of λ_0 (the projection of the wave vector to the reflector plane is aligned with the x-axis), the required reflection coefficient (R) of an MTS within the length of the diffraction period of $D = \lambda_0/|\sin\theta_i - \sin\theta_r|$ which is called a "supercell" [4] must be

$$R(x) = \frac{Z_s(x) - 120\pi}{Z_s(x) + 120\pi}, \qquad (1)$$

where the surface impedance of MTS (Z_s) is given by

$$Z_s(x) = \frac{120\pi}{\sqrt{\cos\theta_i \cos\theta_r}} \frac{\sqrt{\cos\theta_r} + \sqrt{\cos\theta_i}\, e^{j\Phi_r(x)}}{\sqrt{\cos\theta_r} - \sqrt{\cos\theta_i}\, e^{j\Phi_r(x)}}, \qquad (2)$$

and the phase of the reflected wave (Φ_r) is

$$\Phi_r(x) = k_0 x(\sin\theta_i - \sin\theta_r). \qquad (3)$$

Figure 1 shows the required reflection coefficient of the proposed MTS with a supercell length of 37.6 mm. The reflection phase gradually varies from −180° to 180° over the length of the supercell which is hard to achieve in practice. Then, the supercell is divided into eight sections so the unit cell length is 4.7 mm. The required phases of reflection for the individual unit cell are −16.37°, −51.26°, −93.29°, −148.10°, +148.10°, −93.29°, +51.26°, and −16.37° sorted from left to right along the x-axis, respectively.

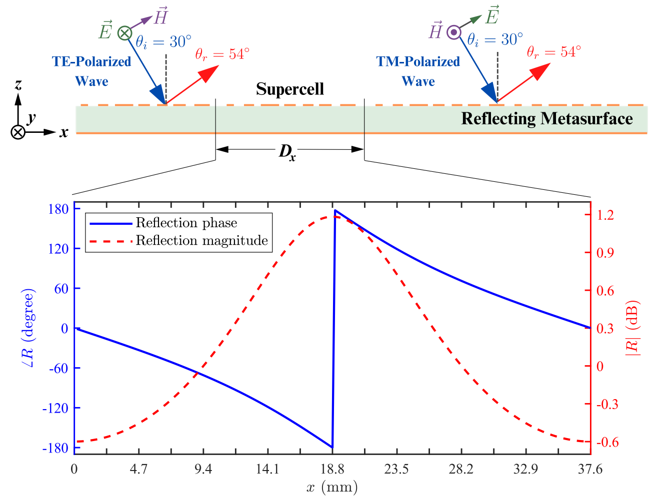

Fig. 1 Required reflection coefficient along the supercell length for the design of $\theta_i = 30°$ and $\theta_r = 54°$.

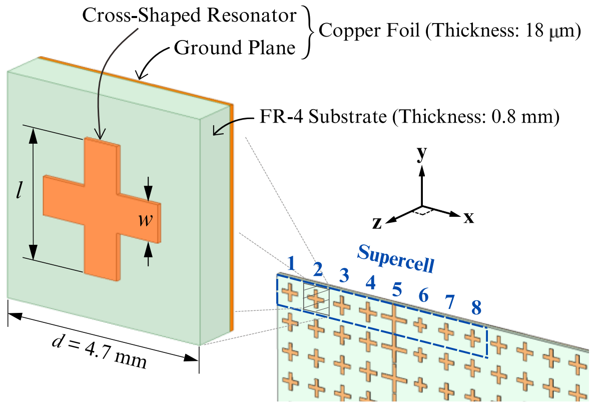

Fig. 2 Unit cell of the proposed metasurface.

III. METASURFACE CONFIGURATION

Each unit cell of the MTS (see Fig. 2) consists of a symmetrical cross-shaped resonator to support operation on both TE- and TM-polarized waves and reduce complexity. This resonator is printed on an inexpensive FR-4 substrate ($\varepsilon_r = 4.3$, $\tan\delta = 0.018$) with a thickness of 0.8 mm and a ground plane on the other face. Both the resonator and the ground plane are made of copper foil with a thickness of 18 μm.

The reflection response of the unit cell has been investigated in an electromagnetic simulation software (Ansys HFSS) by varying the length (l) and width (w) of the cross-shaped resonator under the infinite boundary condition and the Floquet excitation at 25.8 GHz. The results of this parametric analysis (not shown here) were determined for the appropriate dimensions for each unit cell. It was found that a cross-arm width of 0.4 mm could cover almost 360° of phase variation while altering the arm length. Therefore, each arm's length was determined to retrieve the required phase of reflection, while the width was fixed at w = 0.4 mm. The details of the chosen configuration are described in Table 1. From this table, the reflection phase retrieved from each unit cell is nearly equal to the requirement. However, the acquired magnitude of the reflection is not close to the magnitude condition at all. In fact, the positive magnitude of reflection, which means the magnitude of the reflected wave is greater than the incident one, is impossible to obtain from a passive element.

TABLE I. DETAIL OF THE CHOSEN CONFIGURATION

Unit cell no.	Length l (mm)	Reflection coefficient			
		Phase $\angle R$ (Degree)		Magnitude $\|R\|$ (dB)	
		Retrieved	Required	Retrieved	Required
1	2.79	−15.11	−16.37	−2.13	−0.56
2	2.86	−52.07	−51.26	−2.52	−0.27
3	2.94	−92.75	−93.29	−2.18	+0.34
4	3.11	−147.93	−148.10	−1.08	+1.05
5	4.50	+148.17	+148.10	−0.06	+1.05
6	2.22	+93.39	+93.29	−0.28	+0.34
7	2.60	+51.63	+51.26	−1.04	−0.27
8	2.72	+16.74	+16.37	−1.79	−0.56

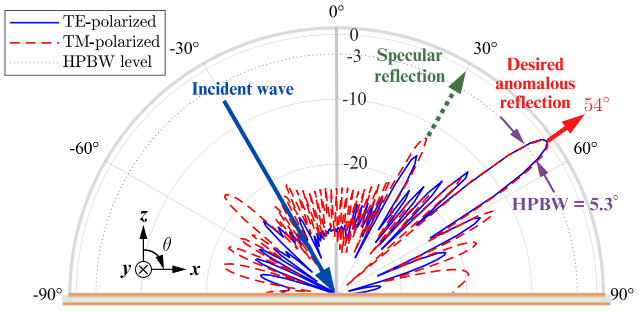

Fig. 3 Normalized radar cross section patterns of the proposed MTS at 25.8 GHz.

IV. RESULT AND DISCUSSION

The proposed MTS configuration with a surface area of 23×23 cm^2 was illuminated with both TE- and TM-polarized waves in the simulation software to investigate the anomalous reflection by considering the radar cross section (RCS) patterns on the xz plane. The obtained patterns are normalized with their maxima and plotted in Fig. 3. The simulation result shows that our MTS can mainly reflect both polarized waves with an incident angle of $\theta = -30°$ to the expected direction of $\theta = 54°$ with a 4.25° half-power beamwidth. Moreover, the specular reflection appeared to be a sidelobe with less than −10 dB compared to the main beam. This means that if the required phase variation could be achieved, the phase-gradient structure would perform a good enough anomalous reflection without meeting the reflection magnitude requirement.

V. CONCLUSION

In this work, a phase-gradient reflecting metasurface has been designed to perform an anomalous reflection of a dual-polarized wave at 25.8 GHz. With a proper selection of dimension parameters, a simple cross-shaped resonator can give the reflection phase needed for a periodic arrangement of the metasurface. The results endorse the concept that the reflecting metasurface is suitable for low-complexity and low-cost 5G coverage improvement in the mmWave frequency bands.

REFERENCES

[1] W. Hong *et al*., "The Role of Millimeter-Wave Technologies in 5G/6G Wireless Communications," in *IEEE Journal of Microwaves*, vol. 1, no. 1, pp. 101-122, Jan. 2021.

[2] K. Zheng, D. Wang, Y. Han, X. Zhao and D. Wang, "Performance and Measurement Analysis of a Commercial 5G Millimeter-Wave Network," in *IEEE Access*, vol. 8, pp. 163996-164011, 2020.

[3] G. R. Maccartney, T. S. Rappaport, S. Sun and S. Deng, "Indoor Office Wideband Millimeter-Wave Propagation Measurements and Channel Models at 28 and 73 GHz for Ultra-Dense 5G Wireless Networks," in *IEEE Access*, vol. 3, pp. 2388-2424, 2015.

[4] A. Díaz-Rubio, V. S. Asadchy, A. Elsakka, and S. A. Tretyakov, "From the Generalized Reflection Law to the Realization of Perfect Anomalous Reflectors," *Science Advances*, vol. 3, No. 8, Aug. 2017.

[5] M. H. Dahri, M. H. Jamaluddin, M. I. Abbasi and M. R. Kamarudin, "A Review of Wideband Reflectarray Antennas for 5G Communication Systems," in *IEEE Access*, vol. 5, pp. 17803-17815, 2017.

[6] T. Hongnara *et al*., "Dual-Polarized Reflective Metasurface Based on Cross-Shaped Resonator for 5G Wireless Communication Systems at 28 GHz," *2019 International Symposium on Antennas and Propagation (ISAP)*, Xi'an, China, 2019, pp. 1-2.