URSI-RCRS 2024, ARIES/GEHU, Bhimtal, India, 22 - 25 October, 2024

Leaky-wave Beam Scanning Antenna based Retrodirective Coded Metasurface

Komal Kumari*, Ravi Anand, Rakesh Prasad, and Anirban Sarkar*
School of Computing and Electrical Engineering Indian Institute of Technology Mandi, Mandi, India
s23050@students.iitmandi.ac.in, D22142@students.iitmandi.ac.in, D23137@students.iitmandi.ac.in, anirban@iitmandi.ac.in

Abstract

This paper presents an advanced leaky-wave beam scanning antenna integrated digital coded MS for high-end communication applications. The system operates within the X-band frequency range (8.19-10.38 GHz), achieving a notable 16° retrodirective beam scanning and multi-beam generation. The digital metasurface (MS), optimized for 10 GHz center frequency, significantly enhances electromagnetic wave manipulation and retro-direction. Simulations demonstrate high directivity, consistent gain, and efficient phase control over the five frequency points. The integration showcases robust performance through detailed 2-D and 3-D radiation patterns in both the *x-z* and *y-z* plane, highlighting strong coupling and precise wave reflection paving the way for next-generation wireless systems.

1. Introduction

The current advancement of metamaterials and MSs has revolutionized the manipulation of electromagnetic waves, offering unparalleled control over their propagation properties in various frequency bands and applications [1], [2]. Among these, retrodirective MS has emerged as a promising technology for achieving efficient and adaptive wave control, particularly in telecommunications, radar systems, and sensor networks [3], [4]. These MSs enable the autonomous re-transmission of incident signals back towards their source directionally, thus enhancing communication reliability and sensor efficiency [5]. Retrodirective MS operates on the principle of phase conjugation, which allows them to reflect incoming waves back towards their origin regardless of the angle of incidence [6]. This unique capability has significant implications for various applications, such as in wireless power transfer, where maintaining alignment between the transmitter and receiver is crucial [7]. Additionally, in radar systems, retrodirective MSs can improve target detection and tracking by ensuring that the reflected signals are precisely directed back to the radar source, thereby enhancing signal strength and accuracy [8].

Several novel approaches have been explored to enhance the performance and bandwidth of retrodirective MSs (RMS). For instance, a broadband two-dimensional (2-D) RMS was developed using crossed arrays of striplines mounted on both sides of a substrate, achieving high power efficiency and independent control of retrodirective angles for incident waves along x- and y-directions [9]. Another approach introduced dual-polarized RMS designs following the generalized phase law (Snell's law) of reflection, demonstrating high retro-directivity at oblique incident angles for both TM and TE polarizations [10]. Further advancements include the use of reciprocal multiple angle retro-reflective MSs based on surface impedance concepts and numerical optimization. These designs have shown significant performance improvements, particularly in terms of maintaining reciprocity and reducing losses at higher periodicities [11]. Moreover, MSs designed to operate at multiple incident angles have been proposed, highlighting their potential for RCS enhancement over a wide angular range [12]. Phase-gradient MSs have also been employed to demonstrate 2-D retrodirective characteristics at specific angles by precisely tuning the supercell dimensions. This approach allows for independent control of retrodirective angles along different directions, thereby enhancing the flexibility and applicability of RMS designs [13]. Non-reciprocal MSs have also been explored, demonstrating the capability to achieve retro-directivity at multiple desired angles of incidence [14].

Keeping the above discussions in our mind, we proposed a single layered reflective coded digital MS integrated with frequency beam-scanning antenna for retro-directive application in X-band. By going through various literatures, we have found that this idea of beam-scanning antenna integrated coded MS for this application is limited and needs attention. In this proposed model, we have used the LWA as a source feed, which changes the direction of beam with change in frequency.

2. Digital Coded Reflective Metasurface Design and Analysis

2.1 Unit-cell Design and Simulation

A low loss dielectric substrate (Rogers RT/duroid 5880) having $\varepsilon_r = 2.2$, and $tan\delta = 0.001$, backed by solid ground plane is used to realize the unit cell design for TM-polarized electromagnetic (EM) wave. Unit-cell loaded with two symmetrical metallic pattern and PIN diode is used to control the binary pattern of 1-bit digital coded MS depicted in Figure 1(a) and (b), in which the geometrical parameters are used as follows: $p = 6, l_s = 6, w = 0.5, l = 3.5, d = 0.6, l_d = 1.4, and\ w_d = 0.46\ (all\ in\ mm)$. In this study, our focus is on evaluating the retrodirective capabilities of the MS without actively controlling the PIN diodes. Among the two symmetrical metallic pattern one is shorted using metallic via with ground to realize the -ve direct current (DC) voltage, whereas the other is used for +ve DC voltage bias. The overall dimension of the meta-atom (unit-cell) is $6\times 6 \times 1.6mm^3$, making the unit cell as $0.2\times 0.2 \times 0.05\lambda_0^3$ at the centre frequency of 10GHz. The complete analysis and optimization of the design unit cell is carried out using full-wave commercial EM-simulator ANSYS HFSS 2023 R2. The equivalent circuit model of the pin diode is used in simulator to realize the ON (1) and OFF (0) states of the diode. The reflection phase and amplitude of the designed unit-cell is depicted in Figure 2(a) and (b) respectively. The difference between the simulated phase response of 1 and 0-states of the unit cell shows 180^o phase variation in the frequency range of 9.6-10.4 GHz, whereas exactly 180^o phase is at 10 GHz.

2.2 Digital Metasurface Design

A digital coded MS is an artificial structure composed of an array of sub-wavelength unit-cells integrated with active elements, each designed to manipulate electromagnetic waves in a controlled manner. Therefore, each unit cell of our proposed digital coded MS as depicted in Figure 1(c), is designed to realize the retro-directive beam incident from different angles at different operational frequency points. Here, 6x6 unit-cell comprises one macro-cell and 6x6 array of macro-cells constitute the complete MS. Our proposed digital coded MS design, forming a large planar structure capable of dynamically controlling the retro-reflection of incident waves, specifically to achieve retro-directivity of single beam. Based on the principle of MS particle design, we have developed a 1-bit digital coded MS sample. Organized into six Macro cells, each comprising six rows, this configuration allows for six distinct states (2^6 combinations) across the MS, which can be controlled using FPGA model.

3. Antenna Integrated Digital Coded MS

3.1 Leaky-wave Antenna

The idea of modulated slots in planar leaky-wave antenna using substrate integrated waveguide (SIW) technology is used to design a feed source for MS, providing single main beam at different angle with frequency variation as depicted in Figure 3. The designed antenna can be used for uninterrupted to first quadrant of visible free space through the broadside. The complete antenna comprises of two tapered microstrip line for feed and sinusoidally modulated slots as radiators. The proposed antenna has an application in X-band (8-12 GHz) with an extensive beam scanning

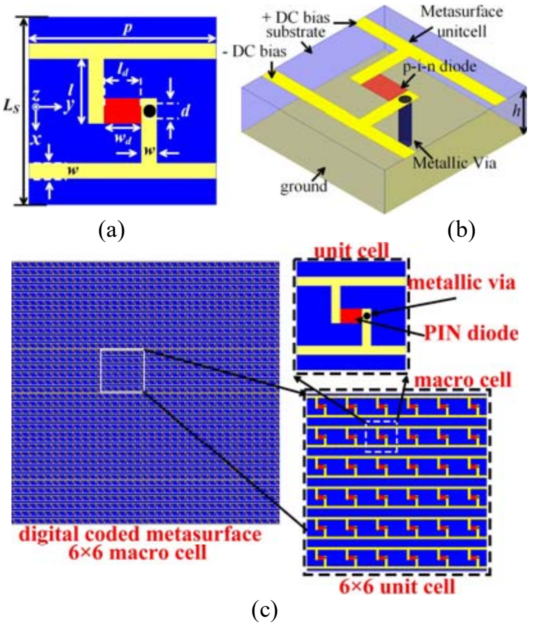


Figure 1. Schematic of the proposed digital retrodirective MS (a) and (b) top and isometric view of unitcell (c) complete MS.

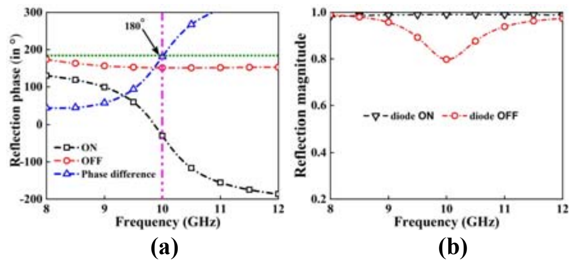


Figure 2. (a) and (b) Reflection phase and amplitude profile of the active unit-cell with frequency.

range of 92^o (from -46^o to +46^o). The designed antenna generates a fan-shaped beam that is stable over a large bandwidth. At center frequency of 10.07 GHz the 10 dB return loss bandwidth or impedance bandwidth in the leaky region is recorded at 30.37 % (8.31-11.39GHz). The maximum gain of 14.43 dB is achieved.

3.2 Retrodirective Metasurface and Antenna Integration

In our setup, the leaky-wave antenna is positioned 100mm above the MS in the +Z-direction as depicted in Figure 5, a distance significantly greater than the operating wavelength at 10 GHz. Given that the wavelength λ_o at 10 GHz is 30mm, this placement distance corresponds to over $3\lambda_o$. This spacing ensures optimal interaction between the leaky wave antenna and the MS, facilitating effective retrodirective reflection. By maintaining this specific distance, we achieve precise control over the wave propagation and reflection characteristics, essential for the desired retrodirective performance.

4. Results and Discussions

The radiation and gain pattern of the designed leaky-wave beam scanning antenna integrated with the retrodirective coded MS was simulated using 3-D EM full-wave simulator (ANSYS HFSS) to observe the beam steering capabilities across the X-band frequency range. Figure 4 shows the normalized and realized gain patterns of the antenna at various frequencies from 8.1 GHz to 11.4 GHz. It reveals the actual gain achieved by the antenna, considering all system losses. The main lobe for each frequency can be seen prominently, with the highest gain occurring around the broadside direction. The gain patterns indicate that as the frequency increases, the main lobe shifts slightly, demonstrating the antenna's frequency-dependent beam scanning capability. The side lobes are relatively low compared to the main lobe, indicating good directionality and minimal interference.

Figure 6(a) represents the normalized gain patterns of the frequency beam-scanning antenna integrated MS, at six different frequencies, such as 8.19, 9.65, 9.84, 10.07, 10.25, and 10.38GHz. One can clearly observe that for frequency 8.19, 9.65, 9.84, 10.07, 10.25, and 10.38 GHz the antenna main beam was directed at -46°, -8°, -2°, 0°, 2°, and 8° respectively, whereas after reflection from MS it points at -16°, -8°, -2°, 0°, 2°, and 8° respectively. The 2-D reflected far-field pattern for 36× 36 unit-cell is depicted in Figure 6. Both the normalized and gain pattern in the H-plane $\Phi = 0^{o}$ is shown in Fig. 6(a) and (b) respectively.

For better illustration of the retro-reflected beam under five different angles of incidence at five different frequencies are simulated and depicted in Figure 7. This illustrates the multi-beam manipulation and beam scanning capabilities of a programmable reflective MS integrated with an antenna, designed for retrodirective applications. One can clearly observe that the reflected beam from MS split into multiple beams due to the phase variation along the *x*-axis. In Fig 7(a) and (b), the *y-z* plane and the *x-z* plane of the simulated model is shown, where five different angles of incidence at five different frequencies point is used as the feed source. The MS reflects main beams at different frequencies, scanning from -8° at 9.6 GHz to 8° at 10.38 GHz, demonstrating a wide scanning range essential for retrodirective functionality. The reflected beams and their angles emphasizing precise beam direction control through frequency adjustments, crucial for future wireless communication. Figure 7(c) provides an isometric view of the MS structure and the corresponding reflected beam patterns, showcasing the ability to dynamically steer beams with varying frequencies. The complete simulated model along with the radiation field is shown in Figure 8 for five different frequencies. These results can be used

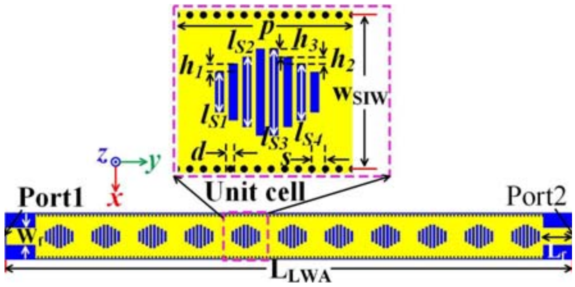
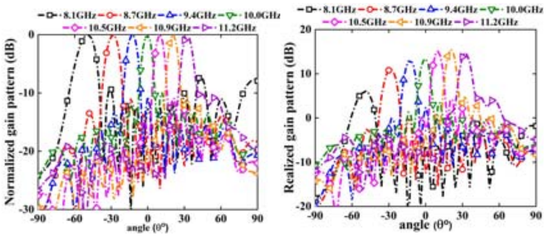


Figure 3. Frequency-beam scanning leaky-wave antenna ntenna integrated digital coded MS.



(a) (b)

Figure 4. Simulated radiation pattern of leaky-wave antenna (a) normalized pattern (b) realized gain pattern.

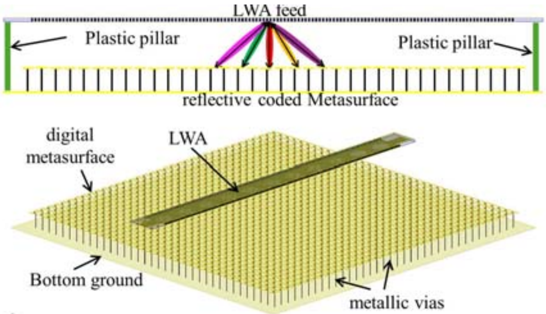
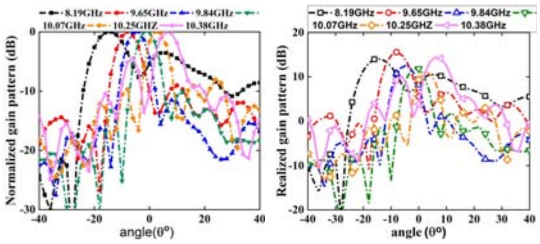


Figure 5. Antenna integrated digital coded MS.



(a) (b)

Figure 6. Simulated radiation pattern of retrodirective metasurfcae (a) normalized pattern (b) realized gain pattern.

for highlighting the MS's potential for advanced communication systems requiring adaptive and automatic beam steering

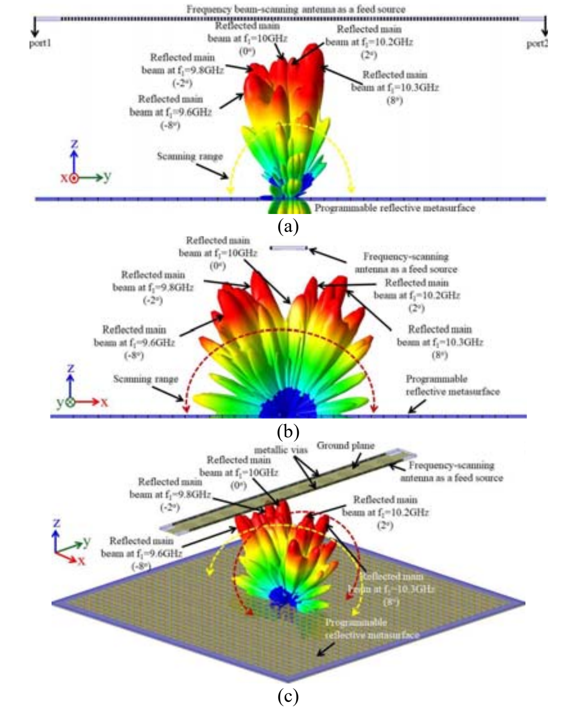


Figure 7. 3-D radiation pattern different incidence angle (a) in y-z plane (b) in x-z plane (c) overall view.

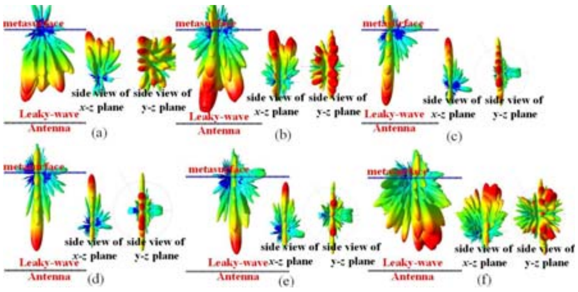


Figure 8. Simulated 3-D retrodirective radiation pattern with proposed model in *xz* and *yz* plane at (a) 8.19 (b) 9.65 (c) 9.84 (d) 10.07 (e) 10.25 (f) 10.38 GHz.

5. Conclusion

Frequency beam-scanning leaky-wave antenna integrated retrodirective reflective active metasurface for distinct incidence angle is proposed in this paper. Reflection phase of digital MS is controlled by inclusion of six Macro-cells, where every microcell is designed using generalized Snell's law of reflection. Further MS is integrated with leaky-wave antenna which act as a feed source. The antenna main beam changes its direction by changing the frequency. Numerical simulation validates the proposed idea of retro-reflection of spherical plane wave for five different angles of incidence (-8°, -2°, 0°, 2°, and 8°) at five different frequency point (9.6, 9.8, 10, 10.2, and 10.3GHz). The integration of the leaky-wave antenna with the MS has demonstrated significant improvements in directional gain and retrodirective performance.

6. References

1. D. R. Smith, J. B. Pendry, and M. C. K. Wiltshire, "Metamaterials and negative refractive index," *Science*, vol. 305, no. 5685, pp. 788-792, Aug. 2004.

2. N. Yu and F. Capasso, "Flat optics with designer Metasurfaces," *Nature Materials*, vol. 13, no. 2, pp. 139-150, Feb. 2014.

3. M. Kalaagi and D. Seetharamdoo, "Retrodirective Metasurfaces from non-reciprocal to reciprocal using impedance modulation for high-super-cell-periodicity designs," *Appl. Phys. A* vol. 126, no. 300, 2020.

4. L. Li, H. Zhao, C. Liu, et al., "Intelligent Metasurfaces: control, communication and computing," *eLight*, vol. 2, no. 7, 2022.

5. S. V. Hum and J. Perruisseau-Carrier, "Reconfigurable reflectarrays and array lenses for dynamic antenna beam control: A review," *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 1, pp. 183-198, Jan. 2013.

6. D. L. Sounas and A. Alù, "Non-reciprocal photonics based on time modulation," *Nature Photonics*, vol. 11, pp. 774-783, Nov. 2017.

7. D. Shrekenhamer, W.-C. Chen, and W. J. Padilla, "Liquid crystal tunable metamaterial absorber," *Physical Review Letters*, vol. 110, no. 17, 2013.

8. B. A. Munk, Frequency Selective Surfaces: Theory and Design, *New York: John Wiley & Sons*, 2005.

9. T. V. Hoang, C.-H. Lee, and J.-H. Lee, "Two-dimensional efficient broadband retrodirective Metasurface," *IEEE Transactions on Antennas and Propagation*, vol. 68, no. 3, pp. 2451-2456, Mar. 2019.

10. M. Kalaagi and D. Seetharamdoo, "Design of dual polarized retrodirective Metasurfaces," *2018 IEEE Radio and Antenna Days of the Indian Ocean (RADIO)*, 2018.

11. M. Kalaagi and D. Seetharamdoo, "Reciprocal Optimized Surface Impedance Multiple Angle Retro-Reflective Metasurfaces," *2018 IEEE Radio and Antenna Days of the Indian Ocean (RADIO)*, 2018.

12. M. Kalaagi and D. Seetharamdoo, "Retrodirective metasurface operating simultaneously at multiple incident angles," *12th European Conference on Antennas and Propagation (EuCAP 2018)*, London, UK, 2018, pp. 1-5.

13. T. V. Hoang and J.-H. Lee, "Two-Dimensional Retrodirective Metasurface using Generalized Snell's law," *2018 International Symposium on Antennas and Propagation (ISAP). IEEE*, 2018.

14. M. Kalaagi and D. Seetharamdoo, "Eleven Channel Retrodirective Metasurface Based on the Combination of the Generalized Phase Law and Impedance Modulation," *2019 13th European Conference on Antennas and Propagation (EuCAP). IEEE*, 2019.