Review of Metasurface-Integrated Circularly Polarized Antennas: Design Techniques and Machine Learning Approaches

Alka Verma[1], Ashish Dixit[2], Sai Kiran Oruganti[3]
[1,2,3]Lincoln University college, Malaysia

Email: pdf.alka@lincoln.edu.my, ashishdixit1984@gmail.com, saisharma@lincoln.edu.my

Abstract: A lot of advancements has been done on Circularly Polarized antenna which encompasses benefits of no polarization mismatch and reduction in multipath but limited by characteristics such as limited Bandwidth, low-gain level, and very poor radiation efficiency. To solve this issue, Researchers have begun to integrate Metasurfaces on CP antenna. Metasurfaces allow antennas to change the properties of the electromagnetic wave via their own sub-wavelength engineered, with the goal of having an antenna with a very high level & ability to provide CP transmission without the limitations. In this paper, a review of the current development of CP antennas with Metasurface and machine learning assisted is also provided. This review will also provide the latest applications for these types of antennas in different areas of telecommunications.

Keyword: Circularly Polarized Antenna, Metasurface, Gain, bandwidth. Machine learning

Introduction

Circularly polarized (CP) antennas have become popular due to their ability to minimize problems associated with polarization mismatch between transmitting and receiving antennas. Circularly polarized waves have continuously rotating electric fields as they propagate, which gives rise to much more stable communications links as the antennas move out of alignment with each other. Because of these advantages, CP antennas are widely utilized in many industries, including satellite navigation, remote sensing, RFID systems, aerospace platforms, and wireless sensor networks.Typical CP antennas have reached a large level of use, while at the same time, CP antennas[1] have been subject to narrow impedance and axial ratio bandwidth limitations. Larger antennas are usually required to improve gain, which is typically not advantageous for portable and compact wireless communication devices. To simultaneously develop high gain, large relative bandwidth, and stability for circular polarization is one of the most significant challenges of designing antennas today.

Recently, metasurfaces have become a viable solution to these limitations. Metasurfaces consist of planar configurations of electrically small elements, which interact with electromagnetic waves in a controlled manner. By appropriately designing the unit cells, metasurfaces can modify the phase, amplitude, and polarisation of the incident electric field [2]. This opens new design possibilities for antenna designers, thereby allowing them to customize electromagnetic characteristics of the antenna without increasing its dimensionality. The combination of metasurfaces with CP antennas has resulted in numerous research breakthroughs. Various metasurface structures have been tested to enhance antenna performance, including artificial magnetic conductors (AMCs), frequency selective surfaces (FSSs), polarisation conversion layers and partially reflective surfaces. These configurations have all shown improvements in antenna performance, such as increased antenna gain, increased impedance and axial ratio bandwidths, reduction of unwanted surface-wave effects, and improved overall efficiency. In addition, in some cases, the incorporation of metasurfaces allows for the implementation of new developments in fabrication processes and computer simulation of electromagnetic effects have also greatly contributed to the fast-paced development of this area. Due to many studies, researchers have shown many different types of metasurface-enabled CP Antennas that function either at dual-band, multi-band or wideband with low profile characteristics. More recently, researchers have become interested in using programmable and re-configurable metasurfaces because they allow the antenna characteristics (such as gain and polarization) to be dynamically controlled. Therefore, metasurface antennas are an appropriate implementation for adaptive wireless systems since they allow for dynamic changes in the communication environment.

This paper is organised as follows: Section provides a brief overview of how metasurfaces are used to enhance performance of CP antennas. Section 3 shows the machine learning assisted with metasurface based CP antenna. Section 4 consists of the conclusions of the entire study.

Metasurface based CP antenna

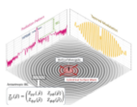
In comparison with Linearly Polarized antennas, CP antennas have the following advantages: Lower polarization mismatch loss; Reduced effects of multipath fading; Greater flexibility for orientation between the transmitter and receiver. Because of these advantages.Circularly polarized antennas have attracted much interest in wireless communication, satellite navigation, RFID and IoT applications because of their resistance to polarization mismatch and multipath fading. To achieve CP radiation many methods have been proposed. One method that has been popular is to use a dual-fed patch antenna and a quadrature hybrid coupler to feed two modes that are orthogonal to each other and are 90° out of phase [3]. This results in better polarization purity and larger axial-ratio bandwidths. Stacked patch configurations have been used extensively to improve impedance and AR bandwidth [4]. Dielectric resonator antennas are also a good option because of their high radiation efficiencies and large bandwidths and various methods can be used to create circularly polarized radiation either through perturbation elements or exciting the two orthogonal modes [5]. Crossed-dipole antennas have provided exceptional performance for broadband CP antennas because of their inherently large impedance characteristics and simple feeding structures [6]. The above reported work still faces the issue of surfaces wave which degrades CP antenna ‘s performance. Researchers are looking for new methods to enhance the performance of circularly polarized antennas to meet the growing need for performance from modern wireless communication systems. Metasurfaces allow precise creation of structures that can control electromagnetism and cause improve performance of antennas.

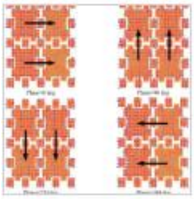
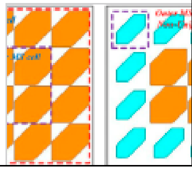
Metasurfaces are made up of periodically placed subwavelength structures that allow for manipulation either amplitude, phase or polarization of electromagnetic fields by designing the geometry of the structures themselves. The association of CP antennas with metasurfaces is a very active area of study due to the ability of metasurface technology to provide an effective method of overcoming limitations related to conventional CP antenna designs. Metasurfaces have been shown to significantly improve several antenna characteristics including impedance bandwidth, axial ratio bandwidth, gain, and efficiency of radiation. Metasurface-loaded slot antennas , patch antennas and monopole antennas have all shown improvements in circularly polarized performance, while being compact in size. Furthermore, metasurface-loaded reflectors and superstrates have been used to create higher concentrations of radiated energy and to improve directivity of antennas. Recent studies have also examined the use of tunable and reconfigurable metasurfaces, allowing for modification of antenna characteristics in accordance with operational needs. These types of structures could provide the opportunity for dynamic control of polarization states, operating frequency and radiation pattern, making them appealing candidates for adaptive communications systems and future wireless networks. The versatility of metasurfaces and their ability to simultaneously improve multiple performance characteristics have made them a significant design resource in developing modern circularly polarized antennas.

Machine learning assisted CP Antenna

ML approaches are gaining popularity as an alternative approach to antenna design and optimization. Instead of depending solely upon the repeated execution of full-wave EM simulations to optimize CP antenna designs by developing an ML model that characterizes the relationships between CP antenna design parameters and CP antenna electromagnetic performance characteristics, an engineer can develop the model, characterize the design variable and performance characteristic pairs, and apply it to perform the CP antenna design. This will allow the engineer to use the ML model developed for the CP antenna design in place of performing the full-wave EM simulation to determine CP antenna design characteristics, resulting in significant savings of both time and computational resources in executing the full-wave EM simulations for CP antenna design. Machine learning applications in CP antenna design are mainly focused on predicting the resonant frequencies, estimating the bandwidth characteristics, optimizing the axial ratio, and improving the radiation performance.Most antennas use learning algorithms to model and optimize the performance of the antenna, including the use of ANNs, SVMs, GPRs, RFs, and deep learning models, for antenna modeling and optimization[7-10]. These techniques are extremely useful because they can model the nonlinear interactions between the geometrical parameters of an antenna and the antenna's performance; therefore, allow designers to explore their design space more efficiently than traditional trial-and-error methods. Table 1 gives a summary of few ML assisted CP antennas and identifies its outcome and limitation.

Table 1. Representative Studies on Machine Learning-Assisted Metasurface-Based Circularly Polarized Antennas

Ref. No	Antenna Type	Metasurface Configuration	ML Technique	Objective	Key Outcome	Limitations
[7]	Modulated Metasurface Antenna	Leaky-Wave Metasurface 	MLP + SHAP	Antenna design interpretation and optimization	Improved design transparency and reduced optimization effort	Requires large training datasets; limited validation on practical fabricated antennas
[8]	Broadband CP Metasurface Antenna	Triple-Mode Excited Metasurface 	Characteristic Mode-Based Optimization	Gain and AR bandwidth enhancement	Wideband CP operation and improved radiation characteristics	No machine learning implementation; increased design complexity
[9]	Single-Layer CP Metasurface Antenna	Hybrid Metasurface	Surrogate-Assisted Design	Miniaturization and bandwidth improvement	Reduced antenna size while maintaining CP	Surrogate model accuracy decreases for highly

					performance	nonlinear designs
[10]	Non-Uniform CP Metasurface Antenna	CPW-Fed Metasurface 	Characteristic Mode Optimization	Wideband circular polarization	Improved AR bandwidth and polarization purity	Fabrication tolerances may affect performance; lacks adaptive optimization

Conclusion

The use of metasurfaces has expanded the design possibilities of circularly polarized (CP) antennas by improving key performance parameters such as gain, bandwidth, axial-ratio bandwidth, and radiation efficiency without substantially increasing antenna size. Structures such as artificial magnetic conductors (AMCs), frequency-selective surfaces (FSSs), polarization-conversion metasurfaces, and reconfigurable metasurfaces have been successfully employed in a wide range of applications, including satellite communication, radar, IoT devices, and emerging 5G/6G systems. Although notable progress has been achieved, issues related to fabrication accuracy, bandwidth limitations, and system integration continue to require further investigation. In parallel, machine learning methods are increasingly being explored to simplify antenna design and reduce the dependence on extensive electromagnetic simulations. The combination of data-driven optimization techniques and metasurface-based antenna designs is likely to support the development of more efficient and adaptable CP antennas for future wireless communication technologies.

References

[1] Shilpee Patil, Alka Verma , Anil Kumar Singh and Binod Kumar Kanaujia,"A low –profile circularly polarized microstrip antenna using elliptical electromagnetic bandgap structures." International Journal of Microwave and Wireless Technologies, pp1-10 , 2021. (SCI journal-impact factor-0.93).

[2] Alka Verma, Anil Kumar Singh, Neelam Srivastava, Shilpee Patil and Binod Kumar Kanaujia," Performance enhancement of circularly polarized patch antenna using slotted circular EBG-based metasurface." *Frequenz*, (2020), 75(1-2), 35–47. (SCI journal-impact factor-0.726).

[3] H. Nawaz, A. U. Niazi, M. Ahmad, and M. A. Khan, "Dual Circularly Polarized Patch Antenna with Improved Interport Isolation for S-Band Satellite Communication," *International Journal of Antennas and Propagation*, vol. 2021, Art. no. 8022207, 2021.

[4] H. Liu, C. Mu, T. Yan, S. Fang, G. Wang, and Z. Wang, "Dielectric Lens with Stacked Cone-Shaped Cavity for Broadside Radiation Enhancement of Circularly Polarized Patch Antenna," *IET Microwaves, Antennas & Propagation*, vol. 14, no. 13, pp. 1610–1618, 2020.

[5] U. Patri and A. Kumar, “A Novel Ultra-Wideband Circularly Polarized Stacked Cylindrical Dielectric Resonator Antenna with Modified Ground Plane,” *International Journal of RF and Microwave Computer-Aided Engineering*, vol. 32, no. 8, e23221, 2022.

[6] X. Song, A. Dong, X. Li, Y. Zhang, H. Yang, and Y. Li, “Gain-enhanced and Mechanical Reconfigurable Slot Antenna with Metasurface,” *Applied Computational Electromagnetics Society Journal*, vol. 38, no. 8, pp. 1–10, 2023

[7] A. Amini, A. Moshiri, M. A. C. Zadeh, and V. Nayyeri, “Interpretable Artificial Intelligence for Modulated Metasurface Antenna Design Using SHAP and MLP,” *Scientific Reports*, vol. 15, Art. no. 24029, Jul. 2025.

[8] D. K. Naik, D. C. Panda, R. Swain, A. Muduli, and A. Pal, “Characteristic Mode Inspired Broadband Circularly Polarized Metasurface Antenna With Triple-Mode Excitation for Sub-6 GHz Applications,” *Scientific Reports*, vol. 15, Art. no. 33965, 2025.

[9] Q. Chen, J. Yang, C. He, D. Zhang, S. Huang, M. Huang, L. Zhang, and M. Wang, “A CPW-Fed Non-Uniform Metasurface Antenna With Low-Profile and Wideband Circular Polarization Property,” *AIP Advances*, vol. 15, no. 7, Art. no. 075334, 2025.

[10] D. K. Naik, D. C. Panda, R. Swain, A. Muduli, and A. Pal, “Characteristic Mode Inspired Compact Broadband Circularly Polarized Non-Uniform Metasurface Antenna for Sub-7 GHz Applications,” *AEU – International Journal of Electronics and Communications*, vol. 200, Art. no. 155939, 2025.