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AI-Driven Metasurface-Based Printed Monopole Antenna for IoT-Enabled Wireless Applications

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Abstract

In the present context, IoT is vital for creating a wireless connectivity infrastructure, which leads to the engagement of IoT-enabled wireless applications. To address concerns about technological improvements as circular polarization & ambient field radiation, the Y-shaped printed monopole antenna with a SADEA-tuned smart metasurface (STSM) is being investigated. In this process, we will first analyze linearly polarized Y-shaped printed monopole antenna for the 3.5/5 GHz bands. To understand the transition from a linear-to-circular polarization (i.e., LP-CP), we connected one of parasitic conducting strip to a partial ground plane, by using a metallic strip. Furthermore the optimization for enhanced polarization bandwidth and gain to accomplish the performance trade-offs is pursued, with the placement of STSM under the radiator, as it offered measured 10-dB bandwidth > 45%, 3-dB bandwidth > 18%, antenna gain > 8.5 dBic, antenna efficiency > 75%, and improved front-to-back ratio (FBR) > -21.5 dBic with 3-dB beamwidth > 120° across the frequency bands, for targeting the ambient electromagnetic environment to RF energy harvesting and wireless power transmission applications.

1. Introduction

As on now, the development of energy sources that do not rely on batteries is currently a top priority [1]. With a low-power embedded systems being possibility, the RF energy harvesting through the electromagnetic spectrum bears the ability to reduce expenses with no need for periodic look out. So, it's a reference for the application of RF radiation in the realistic setting. These RF front-ends are vital to the process because it allows interacting with electromagnetic wave in ambient environment. By guaranteeing maximum reception of incoming signals irrespective of the direction, and utilizing their CP features to enhance signal matching displays their usefulness. It's being said that improved CP capabilities are required from application perspective [1]. The via [2] and metasurfaces (MTS) [3-7] are some of the methods used to design the CP monopole antenna [8]. The acquisition of expanded CP properties, however, is a need for effective polarization system. These features are quite crucial for IoT-enabled wireless applications including the 5G, RF energy harvesting, & wireless power transmission applications [8].

To satisfy the need from applications perspectives, always remains a challenge for researchers in this field, especially when it comes to implementing well-defined and efficient metasurfaces using AI-based techniques [9, 10], because a specific type of analogy was not previously described for that, even though it is considered to be quite required. In a general way, SADEA stands for surrogate model assisted differential evolution for antenna synthesis that have been documented for optimizing antenna parameters for getting improved performances [1], no reporting of its application for the design of engineered MTS have been made so far. Thus, work needs to be done to investigate the techniques potential operational aspects, particularly relation towards the 3.5/5 GHz bands, for broadening bandwidth and gain. It demonstrates the broader set of CP features and directed pattern, by the means of a metallic short and the STSM of symmetrically positioned unit cells. So, good performance for IoT-enabled wireless applications is offered by printed monopole antenna with the STSM as a reflector layer that is investigated in this present work.

2. Circularly Polarized Y-Monopole Antenna

The YSMA antenna on FR-4 substrate is seen in Figure 1. So, the effectiveness of an Y-shaped monopole radiator in this instance depends on a crucial element. It is typical for the input impedance of a $\lambda_o/4$ monopole antenna to exhibit resistive quality measuring 50-Ω at an resonant frequency located in the midpoint. So, this is because, the impedance attributes are modified to achieve improved performance. As a result of it, the antenna's length at this point is made = $\lambda_o/4$. It is seen that, when the frequency is lower than its resonance frequency, it exhibits capacitive traits & when these frequency is higher than its resonance frequency, its input impedance turns into inductive. With the addition of twin parasitic conducting strips (PCS), as measuring 21.6 mm (length) and 1.84 mm (width), we have extended the partial ground plane. So, there is a 1.16 mm separating the strips from the uppermost half of the partial ground plane. To achieve CP traits, a communication between one of the parasitic conducting strips (PCS_L) and the partial ground plane is crucial. By using a metallic strip, the components are shorted to achieve CP. Thereby, the simplified method for achieving on the transition from linear (LP)-to-circular polarization (CP) is offered in the research paper, reported for the very first time in the literature.

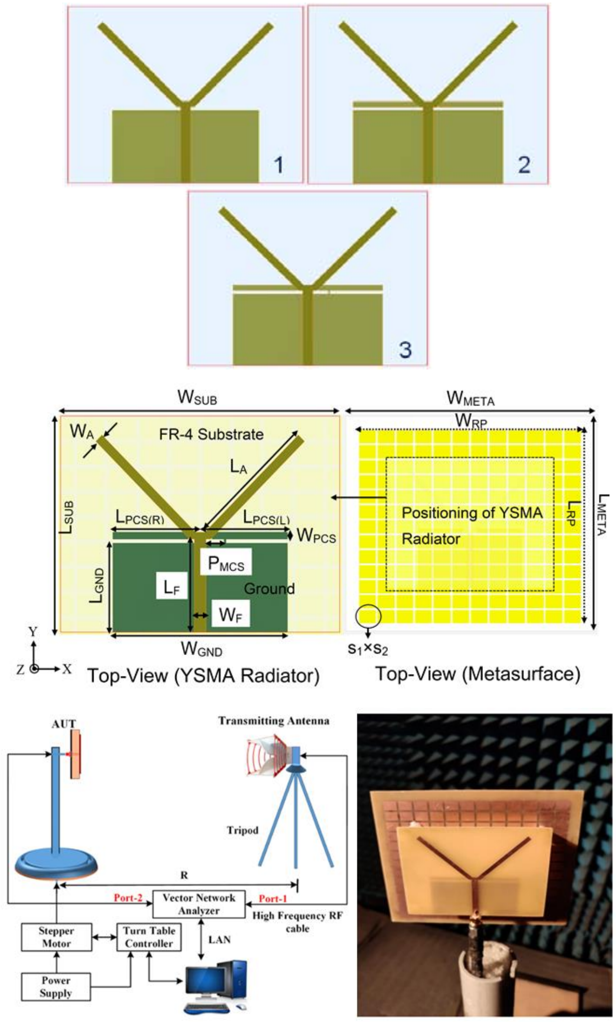

Figure 1. Proposed design: Schematic and Prototype with the measurement setup for evaluating far-field properties.

3. CP Mechanism through CEM Approach

The CP analysis responses are depicted in Figure 2(a)-(d). Herewith, most fundamental and significant methodology for finding CP, the surface current distribution analysis is performed. The stage-2 lacks PCS, preventing a link with the partial ground plane as a result of; the surface currents on the horizontal spaces cancel each other. The monopole arms have just upward and downward surface currents, as resulting in LP waves. By using metallic strip, we connect one of the parasitic conducting strips (PCS_L) to the partial ground plane in the next stage. So, this alters the surface current organization on both PCS_L & partial ground plane. For horizontal surface current, currents on the top edge of the PCS_L & bottom edge of the partial ground plane flows in a same direction. The horizontal & vertical components are needed for the generation of CP. In stage-3, horizontal and vertical currents are seen, confirming presence of CP.

Now, the second way is to examine CP with electric field distribution. By connecting the PCS_L to the partial ground plane with the metallic strip, enables proposed antenna to perform a left-handed circular polarization (LHCP) in the +*z*-direction., phase of electric field vectors changes from 0° to 90° (counterclockwise rotation). LHCP is confirmed by orthogonal electric field pattern change. A normalized radiation pattern is the third and last CP analysis method. It analyzes stage-3 radiation pattern, shows a fundamental correlation between relative powers, levels of LHCP and RHCP are in checked to the maximum limit. Thereby, '3' methodologies have been used to interpret the CP [8].

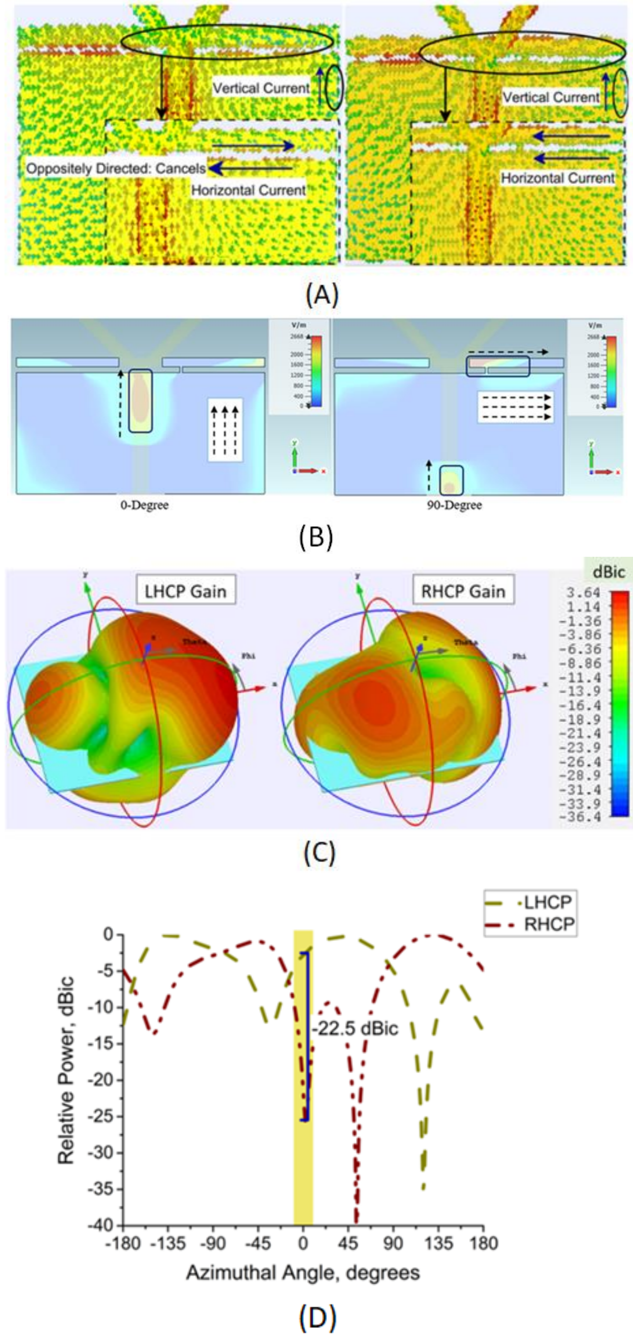

Figure 2. CP analysis: (A) method-I, (B) method-II, and (C), (D) method-III.

4. STSM Using AI-Tuned SADEA Method

In general, surrogate model-assisted differential evolution for antenna synthesis, or SADEA is the novel approach to

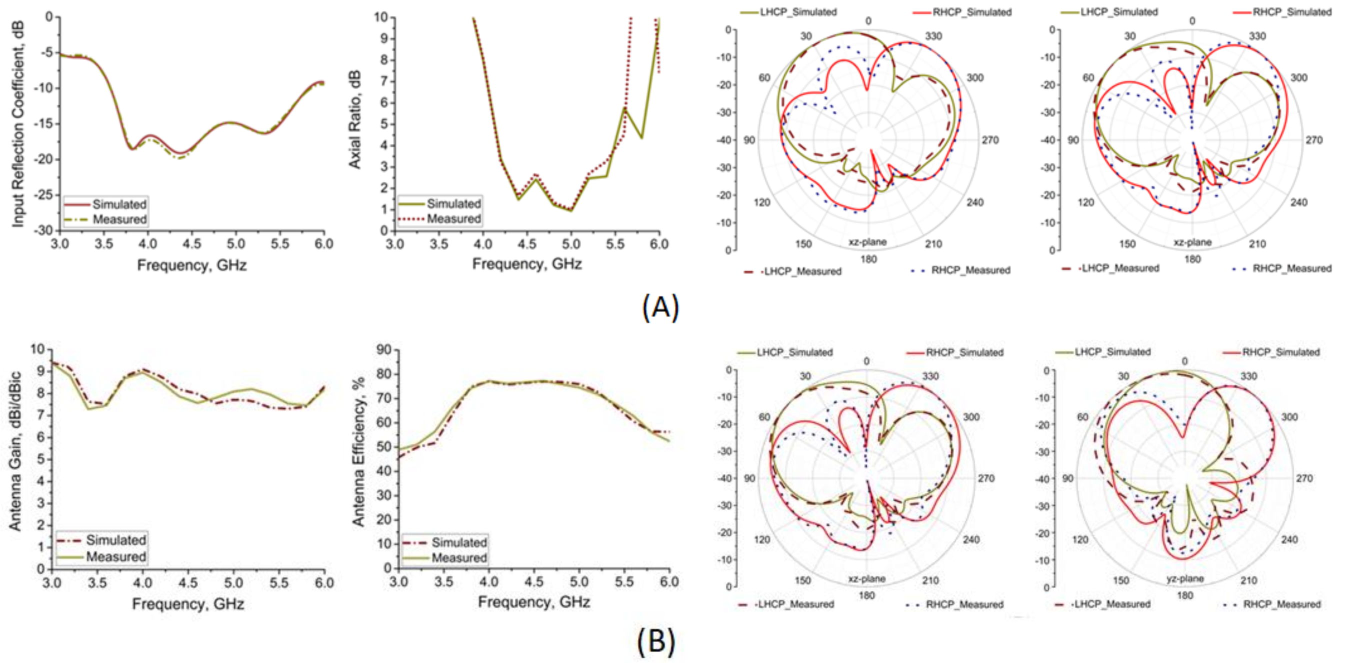

Figure 3. Validation: (A) Bandwidth & Radiation pattern at 4.5 GHz and (B) Gain, Efficiency & Radiation pattern at 5 GHz.

antenna design grounded on artificial intelligence (AI). It takes into account of the fundamental periodic boundaries for computational electromagnetism (CEM) associated for the metasurfaces (MTS), in particularly with evaluation of its unit cells using the notions of evolutionary computing and machine learning to get rid of the needless complexity affecting the performance trade-offs from the applications perspective [10-12].

When using AI-driven SADEA approach, the objective is to achieve optimized outcomes for improving a bandwidth and reduction in the area of occupation. So, the goals are intended to be accomplished through the SADEA method. A STSM ($S_1 \times S_2 = 0.01\lambda_o \times 0.06\lambda_o$, $W_{RP} = 1.78\lambda_o$, $L_{RP} = 1.48\lambda_o$, $W_{META} = 2\lambda_o$, and $L_{META} = 1.65\lambda_o$ at $\lambda_o = 5$ GHz, are taken for dimensions of grid-slotted sub-patches cells, intermediate gap, & overall size of the MTS layer), is put at $0.33\lambda_o$, just below the CP monopole antenna to attain better outcomes. Since, reflector layer is made in the form of STSM (has a surface area of $1.78\lambda_o \times 1.48\lambda_o$), as shown in the Figure 1. It consists of grid-slotted sub-patches of 12×12 cells, as of each cell is $0.1\lambda_o \times 0.06\lambda_o$, intermediate gap of $0.016\lambda_o$. So, sub-patches are positioned on the rectangular-shaped PEC body having an overall dimension of $2\lambda_o \times 1.65\lambda_o \times 0.02\lambda_o$.

$$h_{air-gap} = 0.42\lambda_0 - h_{sub}\sqrt{\varepsilon_r} \quad (1)$$

Considering further, there are factors in equation-(1) that affect the effective gap ($h_{air-gap}$) between RF front-end and STSM, includes the thickness (h_{sub}), relative permittivity of substrate, and λ_o. The $h_{air-gap}$ in theory is 21.85 mm, but $h_{air-gap}$ in simulation is 20 mm. A conclusive mathematical approach is implemented out, operationalize the reflectors & determine their optimal positioning with relation to the monopole radiator. By utilizing analytical methodology, it is possible to find $h_{air-gap}$ with relative ease. Gain^{avg} of 8.55 dBic is achieved by STSM antenna, represents an increase of > 3.5 times of the non-MTS case (stage-1 and 2). The 10-dB bandwidth undergoes 1.12-fold improvement, that is increasing from 2.11 GHz to 2.37 GHz and with the 3-dB bandwidth was increased from 460 MHz to 1.06 GHz, resulted an increase of > 2.3 times compared to previous.

Implementation of the efficient STSM layer is responsible for these improvements. The development of these kinds of structure's capacity is dependent upon its geometry. As a result, the unit cells will concentrate the radiation fields on quasi-TM_{30} modes. This technique not only encourages the further dispersion of the electric field, but it improves impedance performance. The appearance of higher modes is caused by the existence of STSM unit cells due to these grid-slotted sub-patches. Also, adoption of SADEA brings improvement of impedance matching in STSM design by analyzing the spaces that exist between these sub-patches.

5. Experimental Validation

The model of proposed STSM antenna is shown in Figure 1. Figure 3(a), depicts 10-dB bandwidth for measured and simulated cases: 46.41% at 3.59-5.76 GHz and 2.17 GHz, and 48.45% at 3.57-5.84 GHz and 2.27 GHz, respectively. Similarly, the measured & simulated 3-dB bandwidths are given by: 4.19-5.41 GHz, 1.22 GHz, 25.42% & 4.22-5.28 GHz, 1.06 GHz, 23.31%. Figure 3(b) shows that in bands the antenna has an efficiency > 75% and CP gain of 7.5 to 9.35 dBic. With an FBR > 21.5 dBic, Figure 3 shows the strong directional radiation patterns at the 4.5 and 5 GHz.

6. Conclusion

This research paper in deep explores about the potential of IoT-enabled wireless applications by using the broadband circularly polarized printed monopole antenna based on a

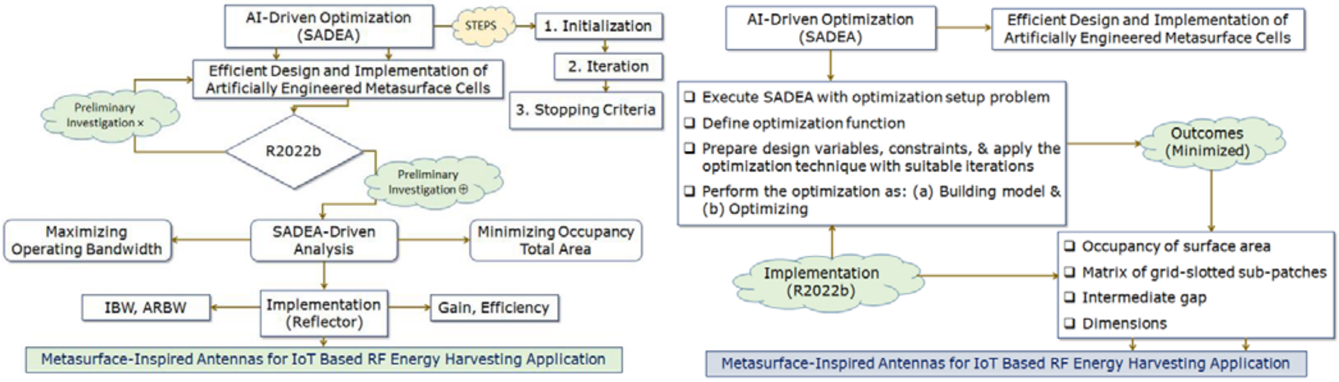

Figure 4. Block diagram of SADEA: Methodology and its MATLAB 2022b platform implementation for the proposed case.

metasurface (STSM) reflector. In the operating frequency ranges, it offers a broadened 10-dB and 3-dB bandwidths, average CP gain > 8.5 dBic, & antenna efficiency > 75%. Based on these outcomes, the AI-tuned smart metasurface antenna is better fit for IoT-enabled wireless applications, uses in areas like wireless power transmission, RF energy harvesting [11], RIS, UAV, 5G communications [12], and depicts a better performance than the reported designs in [2-7]. Complete workflow that is followed in this research work is shown in Figure 4 for quite better understanding.

6. Acknowledgements

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