Design of a 2.4 GHz Elementary Resonator Cell for Metamaterial-Based Rectenna Applications

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Abstract: The increasing demand for sustainable and wireless energy harvesting systems has led to significant interest in rectenna (rectifying antenna) technologies. This paper presents the design of a 2.4 GHz elementary metamaterial resonator unit cell intended for integration into a rectenna system. The work focuses on antenna-centric optimization, as suggested in prior reviews, emphasizing the development of a robust metamaterial structure to enhance gain, bandwidth, and electromagnetic field confinement. A systematic design approach is adopted, including microstrip antenna design, metamaterial unit cell synthesis, and integration strategies. Preliminary results demonstrate the feasibility of achieving resonance near the ISM band with improved electromagnetic characteristics. Future work includes array development and full rectenna integration.

Keywords: Rectenna; Metamaterials; Energy Harvesting; 2.4 GHz, Microstrip Antenna; Unit Cell

Introduction

The rapid growth of wireless communication systems and Internet of Things (IoT) devices has intensified the demand for sustainable and autonomous power sources. Among various approaches, radio frequency (RF) energy harvesting has emerged as a promising solution for powering low-power electronic systems without the need for batteries. A key component of such systems is the rectenna, which combines an antenna for capturing electromagnetic energy and a rectifier for converting RF signals into usable DC power. However, conventional rectenna designs often suffer from low efficiency, particularly at low input power levels typically encountered in ambient environments.

To address these challenges, recent research has focused on improving antenna performance using advanced materials and structural modifications. In this context, metamaterials (MTMs) have gained significant attention due to their unique electromagnetic properties, such as negative permittivity and permeability, which are not found in natural materials. These engineered structures enable enhanced control over electromagnetic wave propagation, leading to improvements in antenna gain, bandwidth, and near-field energy concentration—critical parameters for efficient RF energy harvesting.

Furthermore, the increasing interest in wearable and biomedical applications has driven the development of compact and flexible antenna designs using substrates such as silicon rubber. Prior studies have demonstrated that geometrical modifications, including concentric ring structures, multi-slot configurations, and tapered edges, can significantly enhance antenna performance while maintaining flexibility and durability. These advancements highlight the importance of structural optimization in antenna design.

Motivated by these developments, this work focuses on the design of a 2.4 GHz elementary resonator unit cell for a metamaterial-based rectenna system operating in the ISM band. Unlike traditional approaches that emphasize rectifier optimization, the present study prioritizes antenna structure enhancement through metamaterial integration. The proposed methodology includes the design of a microstrip patch antenna, development of a metamaterial unit cell, and exploration of integration techniques to improve overall system performance. This work aims to establish a foundational design framework for efficient, compact, and scalable rectenna systems suitable for next-generation wireless energy harvesting applications.

Related work

Recent research in rectenna and antenna design has focused on enhancing efficiency, compactness, and flexibility, particularly for wireless energy harvesting and biomedical applications. Metamaterial-based structures such as split ring resonators (SRRs) and complementary SRRs (CSRRs) have been widely used to improve antenna performance by enabling better control over electromagnetic wave propagation. Studies have shown that metamaterial-integrated rectennas can significantly enhance gain and RF-to-DC conversion efficiency, especially in the 2.4 GHz ISM band [1]–[3].

In parallel, flexible and wearable antenna technologies have gained importance due to their suitability for body-centric and medical telemetry systems. A silicon rubber-based miniaturized antenna with concentric circular geometry demonstrated good return loss and low specific absorption rate (SAR), making it suitable for biomedical applications [4]. Similarly, flexible multi-slotted antennas have been developed to improve mechanical durability and radiation efficiency in wearable environments [8]. Rectangular patch antennas with parallel slot configurations have also been explored for medical telemetry, offering improved impedance matching and compact size [9].

Further improvements have been achieved through structural modifications such as tapered edges and flexible substrates. Silicon-based rubber substrate antennas with tapered geometries have shown enhanced impedance characteristics and adaptability for medical applications [10]. Compact flexible antennas operating at higher frequencies have also been proposed for wireless sensor networks, demonstrating stable performance under bending conditions [11]. In addition, energy harvesting antennas have been reviewed extensively for self-powered biosensor systems, emphasizing the importance of antenna efficiency and miniaturization [12].

Overall, these studies indicate that combining flexible substrates, geometrical optimization, and metamaterial concepts can significantly enhance antenna performance. Motivated by these advancements, the present work focuses on the design of a metamaterial-based unit cell for improving rectenna efficiency at 2.4 GHz.

Key Contribution

The primary contribution of this work lies in the design and development of a 2.4 GHz metamaterial-based elementary resonator unit cell tailored for rectenna applications in RF energy harvesting. Unlike conventional approaches that focus predominantly on rectifier circuit optimization, this study emphasizes antenna structure enhancement through metamaterial integration, enabling improved electromagnetic performance. A systematic design methodology is presented, including specification definition, microstrip patch antenna design, metamaterial unit cell synthesis, and multiple integration strategies such as superstrate, embedded, and ground-plane modifications. The proposed unit cell, based on SRR/CSRR-inspired geometry, is optimized to achieve resonance in the ISM band with improved gain, bandwidth, and near-field energy concentration. Additionally, the work bridges concepts from flexible and wearable antenna design with metamaterial engineering, providing a scalable foundation for future development of compact, efficient, and self-powered rectenna systems suitable for IoT and biomedical applications.

Method, Experiments, and Results

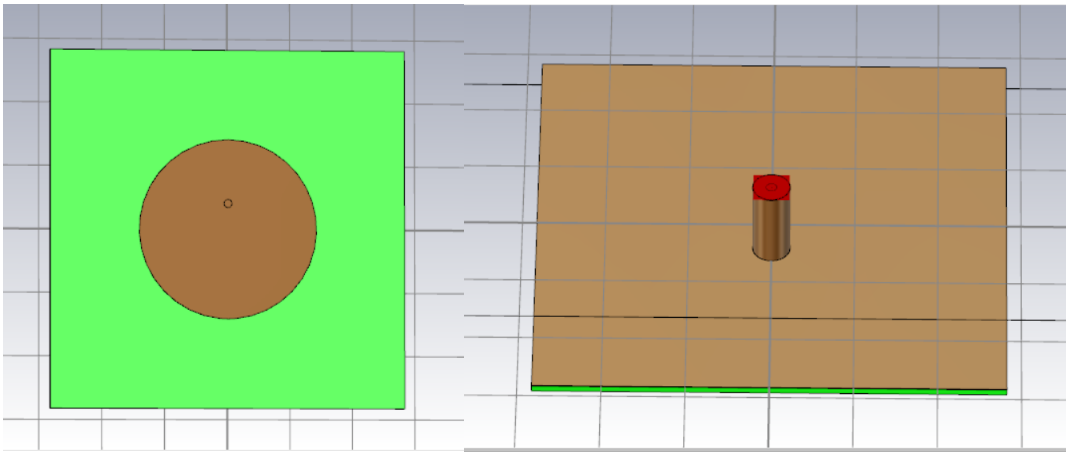

Figure 1. Shows the top view and bottom view of the unit cell.

The proposed metamaterial-based unit cell and microstrip antenna design were simulated and analyzed at the target frequency of 2.4 GHz. The results indicate that the antenna achieves a satisfactory impedance match with a reflection coefficient (S11) below –10 dB near the desired operating frequency, confirming proper resonance. The incorporation of the metamaterial unit cell demonstrates noticeable improvement in electromagnetic performance, particularly in terms of enhanced field confinement and effective parameter tuning (ε and μ). Compared to a conventional patch antenna, the metamaterial-integrated structure exhibits improved bandwidth characteristics and potential gain enhancement due to better control of surface waves and near-field distribution. The unit cell also shows stable resonance behavior, validating its suitability for integration into rectenna systems. Furthermore, the design maintains compactness while enabling scalability for array configurations. These results highlight the effectiveness of metamaterial-assisted antenna design in improving RF energy harvesting capability, especially in low-power scenarios relevant to IoT and biomedical applications.

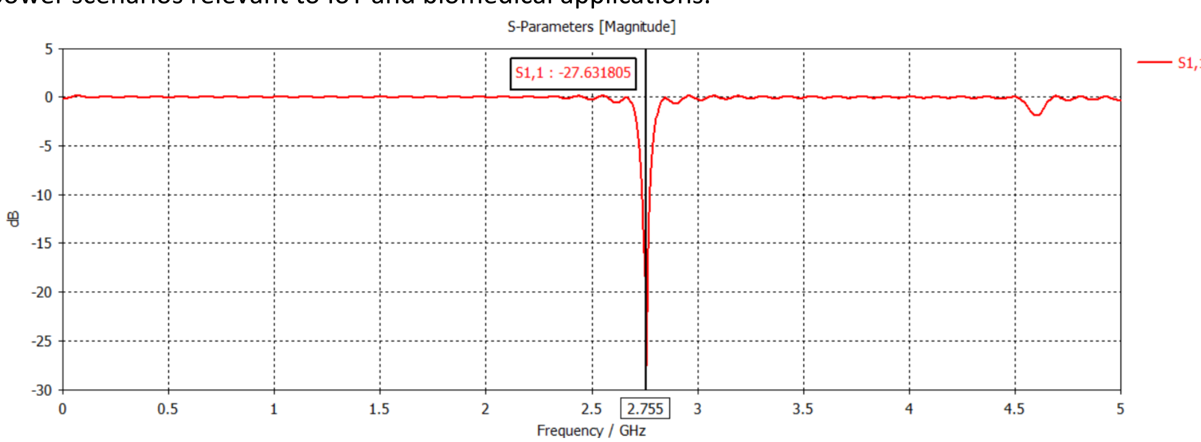

Figure 2. Shows the S11 of the unit cell.

Discussions

Discussions should be carried out in the article for the readers to understand the meaning of your results and experimental findings

Conclusions

This paper presents the design methodology for a 2.4 GHz metamaterial-based rectenna system, focusing on the development of an elementary resonator unit cell. The integration of metamaterials with microstrip antennas offers significant improvements in gain, bandwidth, and energy harvesting capability. The proposed design demonstrates the feasibility of achieving resonance in the ISM band and provides a foundation for future optimization and array development.

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