SPLIT RING RESONATOR-BASED METAMATERIAL PERFECT ABSORBERS FOR MULTIBAND APPLICATION

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Abstract

The increasing reliance on IoT devices highlights the necessity for autonomous operation, driving the demand for self-sustaining power solutions. To address this challenge, energy-harvesting technologies are being explored to enable devices to function independently of traditional power sources. These systems utilize ambient energy from solar, thermal, vibrational, or electromagnetic waves, contributing to sustainability efforts and facilitating the development of energy-efficient IoT networks in resource-constrained settings. Among these advancements, Split Ring Resonator- based Metamaterial Perfect Absorbers (MPAs) have emerged as a promising solution for achieving nearly complete electromagnetic wave absorption in subwavelength structures. This paper explores recent progress in the design, theoretical modeling, and characterization of metamaterial absorbers, emphasizing their potential for applications in energy harvesting and electromagnetic shielding. This study introduces a novel metamaterial absorber with optimized absorption characteristics for frequency-selective applications. The proposed unit cell is engineered to enhance impedance matching and maximize absorption efficiency. Simulation results across the 2–16 GHz frequency range reveal distinct absorption peaks at 4 GHz, 10 GHz, and 14 GHz, confirming its multiband performance. These findings validate the absorber's effectiveness in manipulating electromagnetic waves, making it well-suited for applications in wireless energy harvesting, reconfigurable antennas, EMI shielding, and radar systems.

Introduction

Metamaterials are engineered materials designed to exhibit unique electromagnetic (EM) properties not found in nature, enabling unprecedented control over EM waves. The term metamaterial, derived from the Greek meta (beyond), refers to materials with properties extending beyond those of conventional substances. First theorized in 1968 by physicist Victor Vassalage, metamaterials were predicted to exhibit negative dielectric permittivity (ε) and magnetic permeability (μ), forming a left-handed orthogonal set of electric field (E), magnetic field (H), and wave vector (k). Typically composed of electrically small resonators, these materials achieve negative refractive indices, enabling applications like superlenses and invisibility cloaks. Despite their potential, practical use is limited by fabrication challenges and losses in dispersive materials. The EM properties of metamaterials are characterized by their permittivity (ε) and permeability (μ), which define the refractive index (n) of the material. Depending on the signs of ε and μ, four types of metamaterials can be defined: double-positive (DPS), epsilon-negative (ENG), mu-negative (MNG), and double-negative (DNG). In materials with negative ε and μ, the propagation direction of EM waves is reversed, resulting in unusual wave behaviors. These interactions between incident EM waves and the UCs cause changes in transmission and reflection characteristics, making metamaterials a powerful tool for controlling EM waves in novel ways. Absorbers are essential in modern wireless communication systems and IoT devices, reducing interference and enhancing communication reliability by improving antenna performance and minimizing reflections for clearer signals. They also play a critical role in electromagnetic compatibility

(EMC) by protecting sensitive electronics from interference, while contributing to efficient energy harvesting and precise RF sensing, which support sustainable energy and accurate data collection. Metamaterials as Perfect Absorbers (MPAs) further enhance the efficiency, accuracy, and cost-effectiveness of devices operating in the THz spectrum, making them ideal for future IoT technologies. By integrating periodic or nonperiodic metal structures on dielectric substrates, MPAs offer a compact, eco-friendly solution with matched impedance, which depends on the material permittivity and permeability, aligning with the free space impedance to achieve near- zero return loss. The negative values of permittivity and permeability result in a negative refractive index, enabling close to 100% absorption efficiency. MPAs minimize reflection and transmission of electromagnetic waves, guided by impedance matching with free space, and typically consist of dielectric layers and metallic resonators, with elements like split-ring resonators (SRRs) controlling the electromagnetic response. Substrate materials further enhance absorption, while tuning permittivity and permeability optimizes the impedance to match the characteristic free space impedance of 377 Ω, ensuring high absorption efficiency and supporting sustainable and advanced technological applications. Split Ring Resonator (SRR) Structures for Absorption Yufei Zhang et al. [5] propose a broadband metamaterial absorber for the S, C, and X bands. It consists of an FR-4 substrate, resonant metal structure, lumped resistance, and a metal backplate. The absorber achieves over 90% absorption with a 130% relative bandwidth from 2.7 to 12.7 GHz. Its absorption mechanism is analyzed through equivalent medium theory and parametric research. The design ensures polarization and incidence angle insensitivity, with over 80% absorption at angles under 40°. Experimental results align with simulations, confirming its potential for EMC, radar, and protection applications.
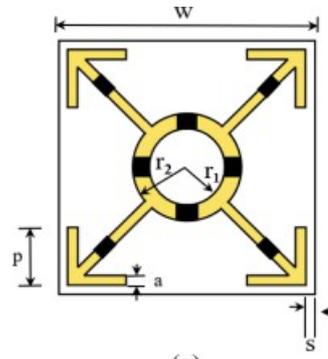

Fig 1. Unit cell proposed by Yufei Zhang et al [5].

Elkorany et al. [6] design metallic metamaterial absorbers for terahertz applications, covering narrowband, wideband, and ultrawideband ranges. Their approach optimizes impedance matching and minimizes reflection to reduce computational complexity. The absorbers maintain wide-angle and polarization independence, with CST simulations confirming their performance. A perfect absorber with 100% efficiency at 1.6 THz was demonstrated. Bandwidth tuning is achieved by adjusting physical parameters while ensuring stability across periodicities and permittivities. Manh Cuong Tran et al. [7] introduce a broadband metamaterial microwave absorber verified through simulations and experiments. Their design departs from traditional unit cell boundary conditions, using four coding metamaterial blocks to form 12×12 topologies. The absorber covers 16–33 GHz, with experimental results matching theoretical predictions. Two optimization strategies—random unit cell removal and meta-block combination—enhance performance. Achieving up to 98% absorption, the design is promising for radar anti-detection, energy harvesting, and satellite communications.
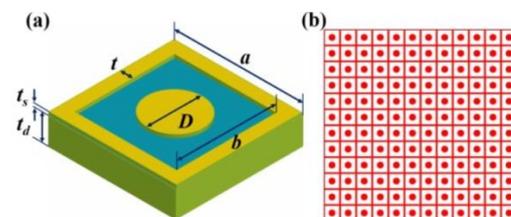

Fig. 2 Structure proposed by [7]

John Bosco John Paul et al. [8] present a circular ring-shaped metamaterial (CRM) absorber for RF energy harvesting in the UWB spectrum. The design features a circular ring with rectangular strip lines and a central square

slot on an FR4 substrate. With unit cell dimensions of 15×15×1.6 mm, configurations of 2×2, 3×3, and 4×4 are analyzed using Ansys HFSS simulations.

The absorber exhibits negative refractive index properties across 4–13 GHz, achieving over 80% absorption efficiency with polarization insensitivity. Field analysis highlights strong current concentration on conductive rings, enhancing RF energy harvesting. Its high efficiency, broad frequency range, and low-cost fabrication make it ideal for IoT sensors and RF energy applications.
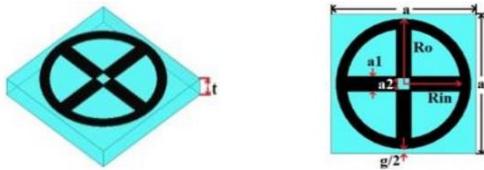

Fig 3. Structure proposed by [8]

Furkan Dincer et al. [9] propose a metamaterial absorber (MA) for electromagnetic energy harvesting at 2.40 GHz in the ISM band. The design features a square ring resonator with two gaps, integrating chip resistors for power delivery. Transmission and reflection analyses confirm its effectiveness for energy harvesting. Numerical results show an 83.6% efficiency at 2.40 GHz. This study demonstrates the potential of MA-based structures as efficient ISM band energy harvesters.
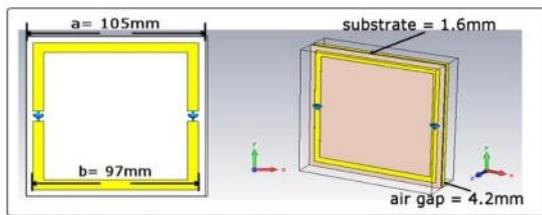

Fig.4 Structure proposed by [9]

C. Fowler et al. [10] propose an RF energy harvesting rectenna using a metamaterial perfect absorber (MPA). Schottky diodes efficiently convert RF waves into DC power, aided by Fabry-Perot cavity resonance for enhanced energy capture. This design boosts RF- to-DC conversion efficiency 16-fold at ambient power levels. A reflecting ground plane improves efficiency by reducing diode resistance but limits omni directional harvesting. Despite this, the compact and

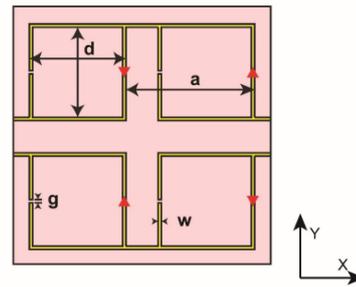tunable rectenna shows strong potential for low-power RF energy harvesting.

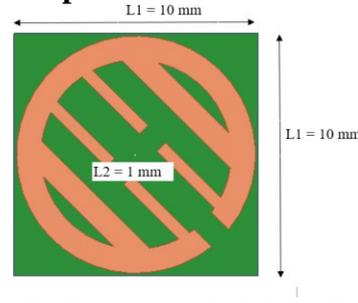Fig.6 Structure Proposed by [10]

Proposed Unit Cell

Fig 7. Proposed Unit Cell

The proposed unit cell features a square patch with a circular resonator and slotted elements to enhance electromagnetic interactions. Its compact 10 mm × 10 mm design enables periodic array arrangements for improved absorption performance. The structure incorporates a split-ring resonator (SRR), strip lines, and split-strip lines to control permittivity (ε) and permeability (μ). These components facilitate precise impedance matching, optimizing energy absorption. The substrate used is RT 5880, which has a low loss tangent of 0.0009, reducing reflection losses. With a dielectric constant (ε_r) of 2.2, the material supports efficient electromagnetic wave manipulation. Copper is used for construction due to its high conductivity, ensuring minimal energy dissipation. The combination of these materials enables broadband and multiband absorption properties. The integration of multiple resonating elements enhances performance across a wide frequency range.

This design makes the unit cell highly effective for various electromagnetic

applications. The unit cell is optimized for efficient absorption by matching the free-space impedance (377 Ω) while slotted metallic traces introduce capacitance and inductance effects.

These slots enhance localized electric and magnetic fields, improving absorption performance. Full-wave electromagnetic simulations evaluate the reflection coefficient(S_{11}) and transmission characteristics. The results confirm its multiband absorption capabilities. Additionally, the design exhibits negative permittivity (ε) and permeability (μ)
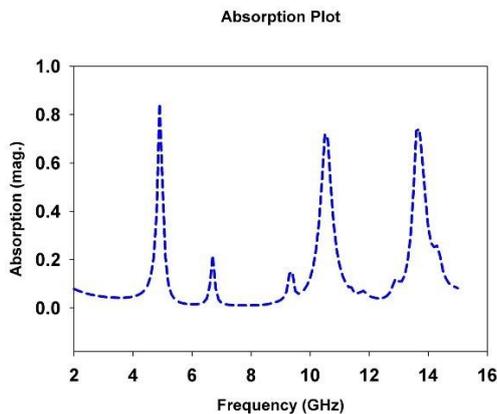at specific frequencies.

Fig 8. Absorption Plot

The graph illustrates the absorption spectrum of a metamaterial absorber, showing absorption as a function of frequency in GHz. It features multiple sharp absorption peaks, with the highest reaching approximately 88% at around 5 GHz. Additional strong resonances appear near 10 GHz and 12.5 GHz, while absorption drops significantly between these peaks. This variation indicates frequency ranges where the structure reflects or transmits more electromagnetic waves instead of absorbing them efficiently. The sharp peaks demonstrate the narrowband nature of the absorber, driven by electromagnetic resonance. Impedance matching minimizes reflection, while transmission suppression enhances absorption at resonant frequencies. These peaks result from electric and magnetic dipole interactions within the metamaterial. For specific applications like radar absorption, sensors, or energy harvesting, aligning these peaks with target frequencies is crucial, while broadband absorption can be achieved by structural modifications such as stacking layers or integrating diverse resonators.

Conclusion:

Metamaterials have revolutionized electromagnetic wave manipulation, enabling applications ranging from energy harvesting to radar absorption and sensing. The studies reviewed highlight advancements in metamaterial absorbers, demonstrating their ability to achieve high absorption efficiencies across various frequency bands. The proposed structure features a square patch with a circular resonator and slotted elements, designed to enhance electromagnetic interactions and optimize absorption performance. By incorporating split-ring resonators, strip lines, and split-strip lines, the structure effectively controls permittivity (ε) and permeability (μ) for precise impedance matching. Full-wave simulations confirm its multiband absorption capabilities, polarization insensitivity, and wide- angle performance. With a compact design and high conductivity materials, the proposed unit cell ensures minimal energy dissipation, making it a strong candidate for RF energy harvesting and electromagnetic shielding. Experimental and simulation results validate its performance, achieving near-total absorption efficiency. Despite fabrication challenges, metamaterials continue to evolve, offering compact, cost- effective solutions for modern wireless communication and energy applications. Future research will focus on optimizing broadband absorption and exploring novel metamaterial configurations to enhance efficiency and scalability for real-world use.

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