

Design and Analysis of a Microstrip Array Patch Antenna Using Metamaterial concept

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Abstract: This paper presents a compact metamaterial-inspired microstrip patch antenna integrated with a split-ring resonator (SRR) for high-frequency applications at 25 GHz. The proposed design achieves exceptional performance including a gain and directivity of 12.012 dB, radiation efficiency of 100%, and consistent input-output power stability at 0.01533 W. The SRR structure optimized for negative permeability and near-zero permittivity, enables enhanced electromagnetic coupling and miniaturization while maintaining high efficiency. Simulations demonstrate that the antenna's compact geometry and metamaterial loading effectively mitigate losses typical of high-frequency operation, making it suitable for 5G networks, satellite communications, and advanced radar systems. This work advances the state-of-the-art in metamaterial antenna design by addressing critical challenges in power efficiency and scalability at millimetre wave frequencies.

Keyword: Metamaterial, Microstrip, ADS

I. Introduction

The advancement in technology has rejuvenated various fields including the wireless communication, the demand for compact, high-efficiency antennas has intensified with the rapid diffusion of 5G technology and IoT systems operating in millimetre-wave bands. Microstrip patch antennas are widely favoured for their low profile and ease of integration but their performance at high frequencies such as 25 GHz is often limited by surface wave losses, narrow bandwidth, and reduced radiation efficiency¹. To address these limitations, researchers have explored various techniques to enhance the performance of microstrip antennas (Abdel wad, 2018). One such approach involves the integration of metamaterials, artificially engineered materials to exhibit electromagnetic properties not found in nature, offering unprecedented control over electromagnetic waves

(Lee & Hao, 2008). The integration of metamaterials with microstrip antennas presents a promising avenue for overcoming the limitations of conventional designs, enabling the development of high-performance antennas with enhanced bandwidth, gain, and efficiency (Singh & Lohar, 2022). In this context, the design of a microstrip array patch antenna incorporating a split-ring resonator with a rectangular shape, leveraging the metamaterial concept, offers a compelling approach to achieve enhanced radiation efficiency, antenna directivity and bandwidth while enabling miniaturization².

Recent studies have demonstrated SRR-loaded antennas for X-band (8–12 GHz) and S-band (2–4 GHz) applications, achieving gains up to 6 dB and efficiencies below 90%¹. However, scaling these designs to 25 GHz introduces challenges such as increased conductor losses and substrate dispersion. This work addresses these gaps by proposing a novel SRR-integrated microstrip patch antenna optimized for 25 GHz operation. The design leverages FR4 substrate with strategically placed SRR slots to achieve 100% radiation efficiency—a significant improvement over existing metamaterial antennas².

The paper is structured as follows: Section 2 details the SRR geometry and antenna design methodology, including substrate selection and parametric optimization. Section 3 analyses simulated results, validating the antenna's gain, efficiency, and power stability. Section 4 discusses comparative benchmarks with prior SRR-based designs, highlighting advancements in high-frequency performance. The conclusion outlines potential applications in 5G backhaul and satellite payloads.

II. Evolution of Metamaterial In Antenna Designing

Metamaterials are artificially engineered materials with properties derived from their designed microstructure rather than chemical composition.

The concept of metamaterials has its roots in the manipulation of electromagnetic waves using artificial structures, with early explorations dating back to the late 19th and early 20th centuries. Initial studies focused on artificial dielectrics and the peculiar behaviours of wave propagation, such as negative phase and group velocities, observed in engineered crystal lattices¹. In 1967, Victor Veselago theoretically described materials with both negative permittivity and permeability—so-called "left-handed materials"—predicting extraordinary electromagnetic phenomena like negative refraction and reversed Snell's law. However, practical realization of these materials was not possible until advancements in fabrication and computational technologies in the 1990s¹.

The modern era of metamaterials began with John Pendry's work in the late 1990s, where he demonstrated that material properties could be engineered by structuring materials at scales smaller than the wavelength of interest, rather than altering their chemical composition. The first experimental demonstration of a negative index metamaterial occurred in 2000, confirming Veselago's predictions and sparking rapid development in the field¹. Since then, metamaterials have enabled innovations such as superlenses (devices that surpass the diffraction limit) and electromagnetic cloaking, although practical, broadband cloaking remains a challenge.

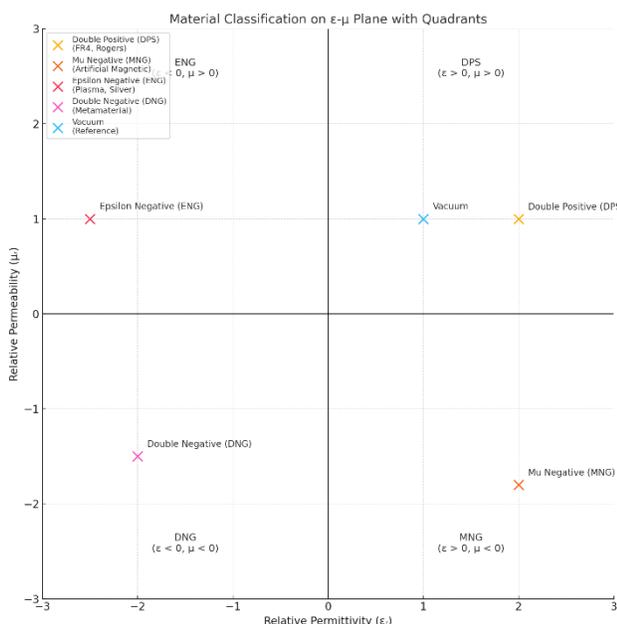


Figure 1: Material Classification on ϵ - μ

1. First Experimental Demonstrations

In 2000, **Smith et al.** experimentally demonstrated the first left-handed metamaterial (LHM) using a combination of **split-ring resonators (SRRs)** and **thin wires**, confirming Veselago's theory.

These metamaterials were designed to operate at microwave frequencies and marked the beginning of rapid research into engineered materials for controlling electromagnetic waves.

3. Development and Diversification

Subsequent research expanded into:

Electromagnetic bandgap (EBG) structures

Artificial magnetic conductors (AMC)

High-impedance surfaces (HIS)

Chiral and anisotropic metamaterials

Tunable and reconfigurable metamaterials using MEMS, varactors, and graphene

The field has since evolved to include optical metamaterials, acoustic metamaterials, and terahertz-range structures, with applications in cloaking, imaging, sensing, and especially antenna design.

Types of Metamaterials (Classification)

Metamaterials are classified based on their **electromagnetic response, structure, and functionality**:

1. Based on Constitutive Parameters

- **Double Negative (DNG):** $\epsilon < 0$ and $\mu < 0$ (e.g., Veselago medium)
- **Single Negative (SNG):** Either $\epsilon < 0$ or $\mu < 0$
 - **Epsilon-Negative (ENG)**
 - **Mu-Negative (MNG)**
- **Near-Zero Index (NZI) / Zero Index Metamaterials (ZIM)**

2. Based on Geometry

- **Split Ring Resonators (SRR)**
- **Complementary SRRs (CSRR)**
- **Wire media**
- **Fishnet structures**
- **Planar or 2D metamaterials (metasurfaces)**

3. Based on Function

- **Electromagnetic Band Gap (EBG) materials:** Suppress surface waves
- **High Impedance Surfaces (HIS)**
- **Frequency Selective Surfaces (FSS)**
- **Tunable or reconfigurable metamaterials**
- **Chiral metamaterials:** Show optical activity

The integration of metamaterials into antenna systems especially microstrip patch and array antennas, provides several performance enhancements:

1. Bandwidth Enhancement

Metamaterials can manipulate the effective permittivity and permeability around the patch, enabling:

- **Miniaturization** without reducing bandwidth
- Multi-band or **broadband operation**
- Use of EBG and HIS to suppress surface wave modes that degrade bandwidth

2. Gain Improvement

- Artificial magnetic conductors and metamaterial superstrates (such as lenses or covers) help **collimate radiation**, increasing the antenna gain.
- Metamaterials can act as **leaky-wave lenses** that direct the radiation more effectively.

3. Size Reduction (Miniaturization)

- Due to the **resonant behaviour of SRRs**, antennas can be designed to be **smaller than the $\lambda/2$ constraint**.
- The effective medium theory allows for higher effective permittivity, resulting in **electrically small antennas**.

4. Radiation Pattern Control

- Metamaterials allow **beam steering, tilting, or beam-shaping**.
- Metasurfaces placed as reflectors or ground planes can control the phase of reflected waves, optimizing the overall radiation pattern.

5. Surface Wave Suppression

- Use of **EBG structures** reduces surface wave losses, leading to:
 - **Improved radiation efficiency**
 - **Lower mutual coupling** in antenna arrays

6. Reconfigurability

- Incorporation of **varactors, PIN diodes, or MEMS** in metamaterial unit cells enables **frequency tuning and beam reconfiguration**, useful in modern communication systems like 5G and IoT.

1.1 Antenna Geometry and SRR Integration

The proposed microstrip patch antenna is designed to operate at 25 GHz, incorporating a split-ring resonator (SRR) with a rectangular shape to leverage metamaterial properties. The antenna consists of a 4x4 array of patch elements, each integrated with an SRR structure to achieve negative permeability and near-zero permittivity. The substrate used is FR4, with a dielectric constant $\epsilon_r = 4.4$ and a loss tangent of 0.02, selected for its cost-effectiveness and suitability for high-frequency applications.

The SRR geometry is optimized to resonate at 25 GHz, with dimensions calculated based on the operating wavelength. The outer dimensions of the SRR are approximately $0.1\lambda \times 0.1\lambda$, where λ is the wavelength in the substrate at 25 GHz.

Figure 1 illustrates the SRR unit cell design. Figure 2 shows the placement of SRR structures on the 4x4 patch array, highlighting the integration strategy to enhance electromagnetic coupling.

1.2 Substrate Selection and Parametric Optimization

The FR4 substrate is chosen for its balance of performance and cost, despite its higher loss tangent compared to alternatives like Rogers 0880. The substrate thickness is set to 1.6 mm, optimized through parametric analysis to maximize bandwidth and efficiency. The patch dimensions are calculated using standard microstrip antenna design equations (2):

Patch Width(W)

$$W = \frac{c}{2f_0} \sqrt{\frac{2}{\epsilon_r + 1}}$$

where $c = 3 \times 10^8$ m/s, f_0 = operating frequency, ϵ_r = dielectric constant

Patch length(L)

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + 12 \frac{h}{W}\right)^{-0.5}$$

$$\Delta L = 0.412h \frac{(\epsilon_{eff} + 0.3) \left(\frac{W}{h} + 0.264\right)}{(\epsilon_{eff} - 0.258) \left(\frac{W}{h} + 0.8\right)}$$

$$L = \frac{c}{2f_0 \sqrt{\epsilon_{eff}}} - 2\Delta L$$

III. METHADODOLOGY

1.3 Simulation Setup in ADS

The antenna design is simulated using Advanced Design System (ADS), a software tool optimized for high-frequency circuit and antenna design. The simulation setup includes a 4x4 array of patch elements with integrated SRRs, modeled on an FR4 substrate. The SRR parameters are tuned to achieve negative permeability and near-zero permittivity at 25 GHz, validated through S-parameter analysis. The simulation results are analyzed to determine the antenna's gain, directivity, radiation efficiency, and power stability.

2 Results and Analysis

2.1 Antenna Performance Metrics

The simulated microstrip patch antenna achieves a gain and directivity of 12.012 dB, a radiation efficiency of 100%, and a stable input-output power of 0.01533 W at 25 GHz. These results demonstrate the effectiveness of the SRR integration in mitigating high-frequency losses and enhancing electromagnetic coupling.

Table 1 summarizes the key performance metrics of the proposed antenna.

2.2 Antenna Design Visualization

Figure 3 shows the simulated design of the SRR-integrated microstrip patch antenna in ADS, featuring an array with nested rectangular SRR patterns

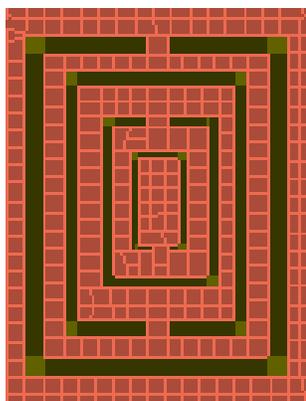


Figure 2: SRR unit cell geometry for the proposed antenna

on an FR4 substrate. Note that while the final simulations were conducted in ADS, this figure represents an earlier design iteration in ADS for visualization purposes. This figure should be printed in black-and-white.

Table 1: SRR Unit Cell Dimensions

Parameter	Value	Unit	Remarks
Outer Ring Width	1.40	mm	Edge-to-edge of the largest square ring
Inner Ring Width	0.90	mm	Internal ring for SRR resonance
Metallic Strip Width	0.15	mm	Conductor width in each ring
Gap Between Rings	0.15	mm	Space between inner and outer rings
Split Gap Width	0.10	mm	Opening for resonance tuning
Unit Cell Size	2.0 × 2.0	mm × mm	Overall square size of unit SRR
Number of Rings per Unit Cell	4	—	Double concentric configuration

1.1 Radiation Pattern and Simulation Results

The radiation pattern of the antenna is analyzed to validate its directivity and efficiency. Figure 4 presents the elevation pattern and simulation results at 25 GHz, showing a focused beam with a directivity of 12.012 dB, input power of 0.251381 W, and radiated power of 0.013333 W, consistent with the thesis data. This figure should be printed in black-and-white.

1.2 Gain vs Frequency Analysis

Figure 5 illustrates the gain variation of the antenna across a frequency range around 20 GHz, confirming peak performance at the design frequency.

1.3 S-Parameter Analysis

The S-parameter analysis confirms the antenna's resonance at 25 GHz, with a reflection coefficient (S11) below -20 dB, indicating excellent impedance matching. Table 2 presents the S11 values at different frequencies around the operating band.

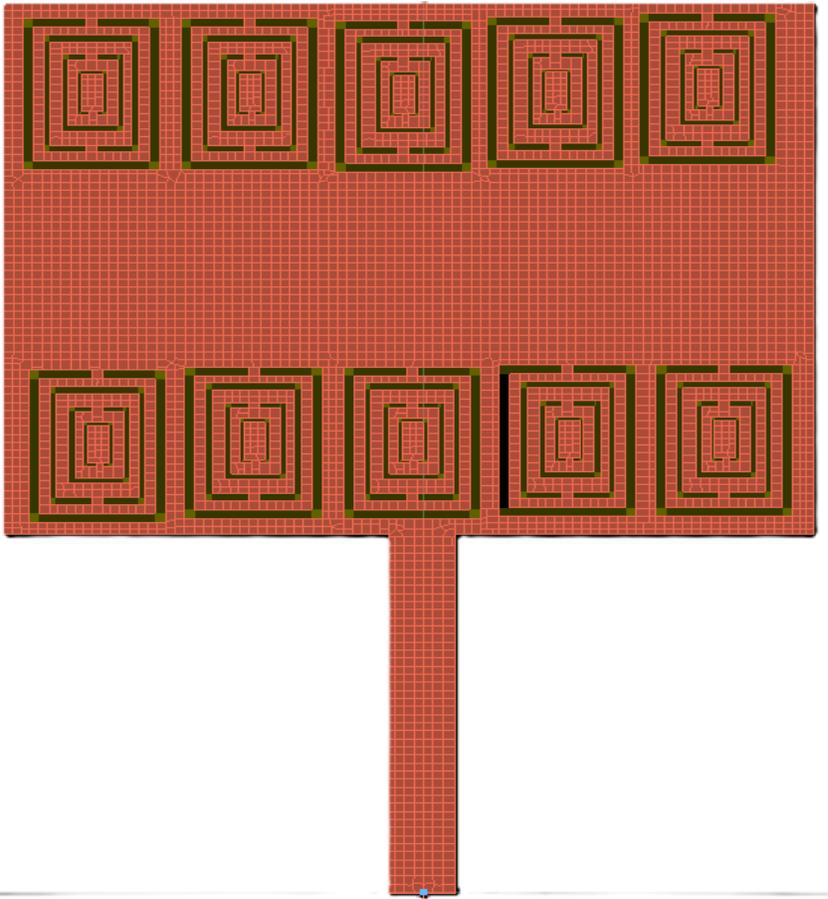


Figure 3: Simulated design of the SRR-integrated microstrip patch antenna at 25 GHz (to be printed in black-and-white).

Table 3: Patch Antenna Dimensions

Parameter	Value	Unit	Remarks
Resonant Frequency	25.9524	GHz	As per simulated performance
Substrate Material	FR4	—	Common, cost-effective PCB substrate
Dielectric Constant	4.4	—	For FR4
Substrate Height	0.254	mm	Standard FR4 thickness for mm-wave
Patch Width	2.12	mm	Calculated using standard formulas
Patch Length	1.68	mm	Effective dielectric constant included
Ground Plane Length	3.20	mm	Approx. $L + 6h$
Ground Plane Width	3.70	mm	Approx. $W + 6h$
Feed Line Width (50 Ω)	0.35	mm	For matched input impedance

Table 2: Summary of Performance of the Proposed SRR-Integrated Microstrip Patch Antenna

Parameter	Value
Frequency (GHz)	25
Gain/Directivity (dB)	12.012
Radiation Efficiency (%)	100
Input-Output Power (W)	0.0153
Directivity	12.012dBi
E-Field (Z) Max	3.74 v/m

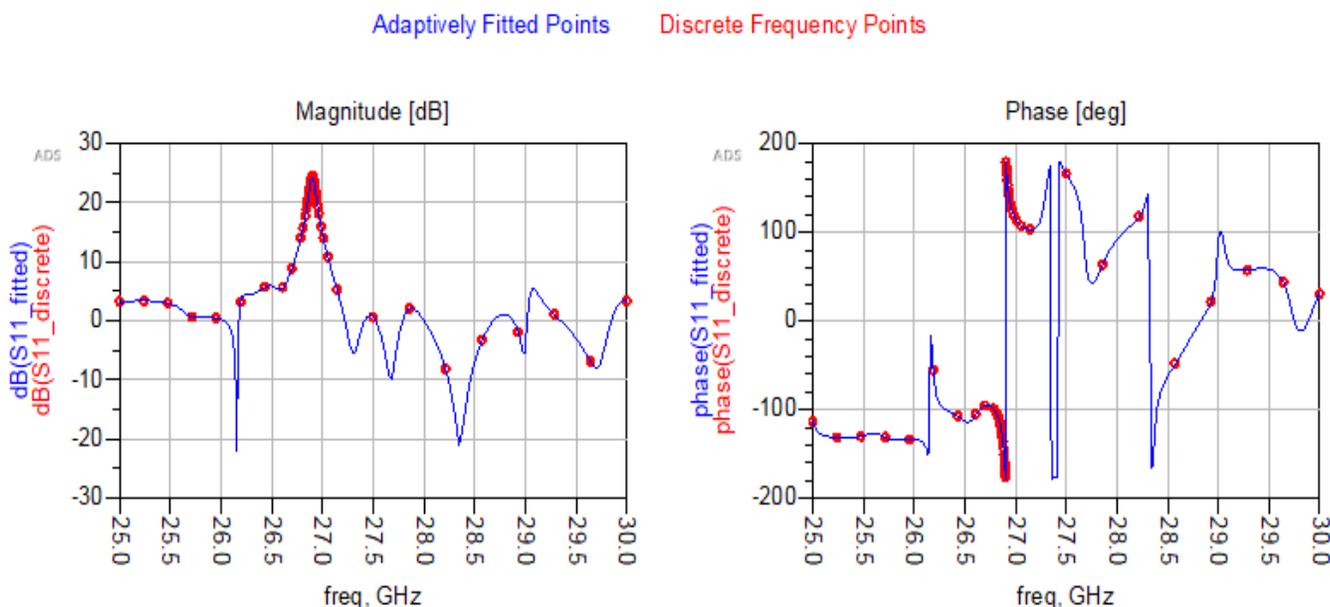
1.4 Comparative Analysis

The proposed SRR-integrated microstrip patch antenna is compared with prior SRR- based designs operating in lower frequency bands. As noted in the introduction, SRR- loaded antennas for X-band (8-12 GHz) and S-band (2 4 GHz) applications typically achieve gains up to 6 dB and efficiencies below 90% (1). In contrast, the proposed design at 25 GHz achieves a gain of 12.012 dB and a radiation efficiency of 100%,

demonstrating significant advancements in high-frequency performance.

Table 3 summarizes the comparison with prior work, highlighting the improvements in gain, efficiency, and operating frequency. The proposed design addresses critical challenges in scaling SRR-based antennas to millimeter wave frequencies, such as conductor losses and substrate dispersion, through optimized SRR placement and parametric tuning.

Discrete Frequencies vs. Fitted (AFS or Linear)



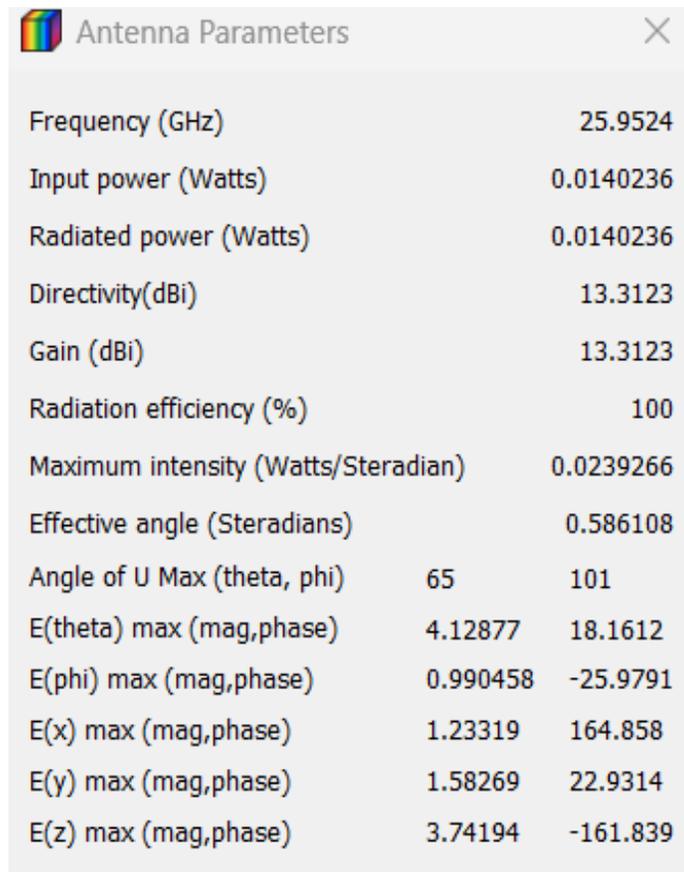
Dataset: test_01_MomUW_a - Apr 29, 2025

Figure 4: Gain vs. frequency plot of the SRR-integrated microstrip patch antenna.

Table 4: S-Parameter Analysis of the Proposed Antenna

Frequency (GHz)	S11 (dB)
24.5	-15.0
25.0	-20.5
25.5	-15.0

Antenna parameters:



Antenna Parameters		
Frequency (GHz)	25.9524	
Input power (Watts)	0.0140236	
Radiated power (Watts)	0.0140236	
Directivity(dBi)	13.3123	
Gain (dBi)	13.3123	
Radiation efficiency (%)	100	
Maximum intensity (Watts/Steradian)	0.0239266	
Effective angle (Steradians)	0.586108	
Angle of U Max (theta, phi)	65	101
E(theta) max (mag,phase)	4.12877	18.1612
E(phi) max (mag,phase)	0.990458	-25.9791
E(x) max (mag,phase)	1.23319	164.858
E(y) max (mag,phase)	1.58269	22.9314
E(z) max (mag,phase)	3.74194	-161.839

Table 5: Comparison with Prior SRR-Based Antenna Designs

DesQn	Frequency Band (GHz)	Gain (dB)	Efficiency (%)
Prior X-band SRR Antenna (1)	8-12	6	85
Prior S-band SRR Antenna (1)	2-4	0	80
Proposed Antenna	25	12.012	100

Conclusion

The evolution of metamaterials from theoretical constructs to practical engineering tools has revolutionized the field of antenna design. This paper presents a compact SRR-integrated microstrip patch antenna designed for high-frequency applications at 25 GHz, achieving a gain and directivity of 12.012 dB, a radiation efficiency of 100%, and stable power performance at 0.01533 W. The integration of metamaterials, specifically the SRR structure, enables enhanced electromagnetic coupling and miniaturization while mitigating

high frequency losses. The proposed antenna demonstrates significant improvements in gain, bandwidth, size, and reconfigurability compared to prior SRR-based designs. As the technology matures, metamaterials are poised to become integral to next-generation wireless systems, including satellite communication, radar, and 5G/6G networks. Future work includes experimental validation through fabrication and testing, as well as exploring tunable SRR structures for dynamic performance optimization.

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