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Multi-Band Circular Polarization Using Split Ring Resonators for X-Band Applications

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ABSTRACT

This paper presents the design, simulation, fabrication, and experimental validation of polarizers based on split ring resonator (SRR) structures for multi-band circular polarization in the X-band frequency range (8–12 GHz). Conventional polarization techniques suffer from narrow bandwidth, high transmission loss, and limited scalability. To address these limitations, optimized SRR configurations were developed in ANSYS HFSS, progressing from single-layer to multilayer architectures. The multilayer SRR configuration achieves an axial ratio below 3 dB across a 4 GHz bandwidth, a peak polarization conversion efficiency of 95%, and an average transmission loss below 1.6 dB. Reconfigurable varactor diode-integrated polarizers add dynamic tuning capability, allowing real-time adjustment of polarization states. The simulated and measured results are in close agreement, validating the proposed designs. The SRR-based polarizers are compact, efficient, and adaptable, making them suitable for satellite communication, radar systems, 5G networks, and Internet of Things (IoT) infrastructure.

Keywords: Split ring resonator (SRR); circular polarization; X-band; axial ratio; metamaterial; polarization conversion; reconfigurable polarizer; ANSYS HFSS

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1. Introduction

Electromagnetic wave polarization, which describes the orientation of the electric field vector, is fundamental to the design of modern communication systems, radar, and sensing technologies. Polarization is classified into linear (LP), circular (CP), and elliptical (EP) types according to the trajectory traced by the electric field vector at a fixed point in space.

Circular polarization is widely preferred for demanding applications because of its immunity to antenna orientation mismatch, multipath interference, and signal degradation. In the X-band frequency range (8–12 GHz), CP is used for radar target discrimination in cluttered environments, for reliable satellite communication links, and in emerging high-frequency wireless networks. In radar systems, circularly polarized waves interact differently with symmetric and asymmetric targets, which allows man-made objects to be distinguished from natural clutter such as raindrops, foliage, and sea surface reflections.

Despite these advantages, achieving high-quality circular polarization across a wide bandwidth remains difficult. Conventional polarization devices such as quarter-wave plates, meander-line polarizers, and waveguide-based polarizers are limited to narrow operating bandwidths and are prone to transmission losses and fabrication imperfections. These shortcomings have motivated extensive research into metamaterial- and metasurface-based designs, which use subwavelength-engineered electromagnetic properties to overcome the limitations of traditional approaches.

Split ring resonators (SRRs), a common metamaterial element, are well suited to polarization control because they generate artificial magnetic resonances at engineered frequencies. By tailoring the SRR geometry, in particular the ring radius, gap width, and orientation, the phase and amplitude of the orthogonal electric field components can be controlled to produce circular polarization states. Multilayer stacking extends the operating bandwidth by coupling resonances across layers, and reconfigurable designs that incorporate active elements such as varactor diodes allow dynamic polarization tuning.

This paper presents a systematic study of SRR-based circular polarizers spanning

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single-layer, double-layer, and multilayer configurations, all designed and validated for X-band operation. The key contributions are: (i) demonstration of a multilayer SRR polarizer achieving 4 GHz axial ratio bandwidth with ≤3 dB axial ratio; (ii) peak polarization conversion efficiency of 95%; (iii) average transmission loss below 1.6 dB; and (iv) dynamic polarization control via integrated varactor diodes. The organization of this paper follows: Section 2 reviews related work; Section 3 describes the design methodology and simulation framework; Section 4 covers fabrication and measurement; Section 5 presents results and discussion; Section 6 concludes the paper.

2. Related Work

The history of polarization control dates to the 19th century, when Étienne-Louis Malus discovered light polarization by reflection in 1808. The theoretical foundation was consolidated by Maxwell's electromagnetic theory, which unified the description of electric and magnetic field behavior. Early microwave-era polarizers, deployed in World War II radar systems, relied on waveguide structures and dielectric lenses, but suffered from narrow bandwidth and large physical dimensions.

The advent of metamaterials in the early 2000s substantially changed polarization device design. SRRs, first characterized by Pendry et al. [1], were shown to exhibit negative effective permeability at resonance, enabling the design of compact anisotropic structures for polarization control. Smith et al. [2] demonstrated composite media with simultaneously negative permittivity and permeability, further expanding the design space. Quarter-wave plate analogs realized using SRR arrays provided an early demonstration of linear-to-circular polarization conversion at microwave frequencies.

Metasurfaces, which are planar arrays of subwavelength resonators, later became a more practical implementation platform because they provide polarization control with minimal thickness. Chen et al. [3] reviewed metasurface physics and applications and noted their potential for high-efficiency polarization manipulation. Liu and Cui [4] demonstrated dynamic electromagnetic wave control using active metasurfaces, while Wang and Zhai [5] proposed Z-shaped unit-cell metasurfaces for wide-angle circular polarization conversion.

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More recently, broadband operation has been a focus of intensive research. Geng et al. [6] demonstrated a broadband polarization conversion metasurface for X-band applications with high efficiency and low loss. Li et al. [7] realized multi-band circular polarization conversion using SRR-based designs, and Lee et al. [8] extended bandwidth through hybrid SRR configurations. In reconfigurable polarization, Pei et al. [9] demonstrated varactor-diode-tunable metamaterial polarizers, and Ma et al. [10] explored SRR integration for 5G and IoT networks. The present work builds on these advances by combining broadband multilayer design with experimental validation and dynamic tunability within a unified X-band design framework.

3. Design and Simulation Methodology

3.1 SRR Unit Cell Design

The unit cell design was guided by electromagnetic theory, specifically Maxwell's equations and polarization analysis using the Jones calculus formalism. Each SRR unit cell was engineered to generate the requisite phase shift between orthogonal electric field components (Ex and Ey) to achieve circular polarization. For ideal circular polarization, the amplitude ratio must equal unity ($|Txx/Txy| = 1$) and the phase difference between orthogonal components must equal 90°.

Three key geometric parameters were varied systematically: ring radius (r), gap width (g), and unit cell periodicity (p). Cell orientation angles were also optimized to couple energy between orthogonal polarization modes. Single-layer, double-layer, and multilayer (four-layer) configurations were examined. In multilayer designs, identical low-loss dielectric spacers separated adjacent SRR layers to control inter-layer coupling and uniformity.

3.2 Numerical Simulation

Full-wave electromagnetic simulations were performed using ANSYS HFSS, employing periodic boundary conditions (PBC) and Floquet port excitation to model the infinite array response. Adaptive mesh refinement ensured field convergence, with solution accuracy verified at each iteration. The finite element method (FEM) solver computed the complete scattering matrix, from which the axial ratio (AR), polarization conversion efficiency (PCE), and transmission (S21) and reflection (S11)

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coefficients were extracted.

The axial ratio was calculated from the co-polarized (Txx) and cross-polarized (Txy) transmission coefficients and the corresponding phase difference (Δφ) according to:

$$AR = 10\log_{10}\left[(|Txx| + |Txy|) / (|Txx| - |Txy|)\right] \quad (dB)$$

Optimal circular polarization (AR ≤ 3 dB) requires $|Txx| \approx |Txy|$ with $\Delta\varphi \approx 90°$. The polarization conversion efficiency is defined as $PCE = |Txy|^2 / (|Txx|^2 + |Txy|^2)$. Iterative optimization of design parameters refined the configurations until target performance metrics were satisfied.

4. Fabrication and Experimental Validation

4.1 Prototype Fabrication

Prototypes were fabricated on low-loss dielectric substrates using standard photolithography and wet-chemical etching processes. SRR patterns were etched on copper-clad laminate substrates selected for their low dielectric loss tangent. In multilayer configurations, precision alignment jigs ensured accurate inter-layer registration, and layers were bonded using a low-loss adhesive to maintain uniform spacing and structural integrity. Quality control procedures monitored etching uniformity and layer alignment to minimize fabrication-induced performance degradation.

For reconfigurable designs, varactor diodes were integrated into the SRR gaps. Bias networks were incorporated to deliver DC bias voltages while maintaining RF isolation. Multiple prototype samples of each configuration were fabricated to ensure measurement repeatability and allow statistical analysis of performance variability.

4.2 Measurement Setup

Experimental characterization employed a vector network analyzer (VNA) in a calibrated waveguide measurement setup. The fabricated polarizer samples were placed between a pair of orthogonally oriented linearly polarized horn antennas, which served as transmitter and receiver. Transmission (S21) and reflection (S11) parameters were recorded across the 7–13 GHz range at 10 MHz frequency intervals. The co-polarized and cross-polarized transmission coefficients were extracted by rotating the receive antenna by 90°. Axial ratio bandwidth was

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determined as the frequency range over which the measured AR remained below 3 dB.

5. Results and Discussion

5.1 Axial Ratio Bandwidth

Table 1 summarizes the axial ratio performance for all three SRR configurations. The single-layer design achieves an AR bandwidth of 0.9 GHz (8.2–9.1 GHz), demonstrating functional but narrowband circular polarization. The double-layer configuration expands bandwidth to 2.5 GHz (8.0–10.5 GHz) through inter-layer resonance coupling, while the multilayer design spans the full X-band (8.0–12.0 GHz) with a 4.0 GHz AR bandwidth, more than four times the single-layer result.

Table 1: ***Axial ratio bandwidth comparison across SRR configurations***

Configuration	Frequency Range (GHz)	AR (dB)	Bandwidth (GHz)
Single-layer SRR	8.2–9.1	≤3.0	0.9
Double-layer SRR	8.0–10.5	≤3.0	2.5
Multilayer SRR	8.0–12.0	≤3.0	4.0

5.2 Transmission Characteristics and Phase Response

Figure 1 shows the simulated transmission coefficients Txx and Txy as a function of frequency for the multilayer configuration under normal incidence of a linearly polarized wave. At f_1 = 10.12 GHz, Txx = −15.34 dB and Txy = −10.19 dB, corresponding to a cross-polarization dominance that indicates strong polarization mode conversion. At f_2 = 10.81 GHz, Txx = −7.22 dB and Txy = −6.99 dB, showing near-equal amplitude components favorable for circular polarization generation.

Figure 2 presents the phase difference ($\Delta\varphi$) between the orthogonal transmission components. At 10.12 GHz, $\Delta\varphi$ = 120.28°, which is within an acceptable margin for near-circular polarization, while at 10.81 GHz, $\Delta\varphi$ = 75.28°. The variation of phase difference across the bandwidth accounts for the slight deviation from the ideal 90° condition and is reflected in the measured axial ratio values. The corresponding axial ratios are AR = 1.8 dB at 10.12 GHz and AR = 1.0 dB at 10.81 GHz (Fig. 3), both well below the 3 dB threshold defining effective

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circular polarization.

5.3 Polarization Conversion Efficiency

Table 2 reports the peak polarization conversion efficiency for each configuration. The single-layer design achieves a PCE of 85% at 8.5 GHz. The double-layer configuration improves to 92% at 9.2 GHz. The multilayer design reaches a peak PCE of 95% at 10.0 GHz, attributable to the optimized multi-resonance interaction between layers. This value exceeds that of several recently reported SRR and metasurface designs and shows that the added multilayer complexity produces a real efficiency gain.

Table 2: ***Peak polarization conversion efficiency***

Configuration	Peak PCE (%)	Frequency at Peak (GHz)
Single-layer SRR	85	8.5
Double-layer SRR	92	9.2
Multilayer SRR	95	10.0

5.4 Transmission and Reflection Coefficients

Table 3 presents the experimentally measured S21 and S11 coefficients for the multilayer SRR configuration across the X-band. Transmission loss remains low across the entire band, ranging from −1.5 dB at 10.0 GHz to −2.5 dB at 8.0 GHz. Return loss (S11) values are consistently below −25 dB, confirming good impedance matching and indicating that the device operates with high radiative efficiency. These results confirm that the design supports energy-efficient polarization conversion.

Table 3: ***Measured S-parameters for multilayer SRR configuration***

Frequency (GHz)	S21 (dB)	S11 (dB)
8.0	−2.5	−25.0
9.0	−1.8	−30.0
10.0	−1.5	−35.0

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11.0	−1.6	−33.0
12.0	−2.0	−28.0

5.5 Simulation–Experiment Agreement

Table 4 compares simulated and experimentally measured AR bandwidths. The differences are small, 0.1 GHz for the single-layer and 0.2 GHz for the multilayer configuration, and can be attributed to minor fabrication tolerances such as etching depth variation and uncertainty in the adhesive layer permittivity. The close agreement validates the ANSYS HFSS models and confirms the reliability of the proposed design methodology.

Table 4: ***Simulated vs. measured axial ratio bandwidth***

Configuration	Simulated BW (GHz)	Measured BW (GHz)
Single-layer SRR	0.9	0.8
Double-layer SRR	2.5	2.4
Multilayer SRR	4.0	3.8

5.6 Reconfigurable Polarizer Performance

The reconfigurable SRR design with integrated varactor diodes was tested under three bias voltage conditions. As summarized in Table 5, the resonance frequency shifts from 9.5 GHz at 0 V to 10.5 GHz at 2 V, demonstrating a continuous tuning range of 1.0 GHz with a bias step of 1 V. The AR remains below 3 dB (between 2.9 dB and 2.5 dB) across all bias states, which shows that dynamic frequency tuning does not degrade polarization quality. This allows the polarizer to adapt in real time to changing spectral conditions, which is useful for cognitive radar and adaptive satellite communication systems.

Table 5: ***Reconfigurable polarizer tunability results***

Bias Voltage (V)	Resonance Frequency (GHz)	AR (dB)
0.0	9.5	2.9
1.0	10.0	2.7

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2.0	10.5	2.5

5.7 Comparative Analysis and Trade-Offs

Table 6 consolidates all key performance metrics across configurations, providing a direct comparison for engineering design selection. The multilayer design provides the widest AR bandwidth, the highest peak PCE, and the lowest transmission loss, but at the cost of higher fabrication complexity. The single-layer design, while limited in bandwidth (0.9 GHz) and efficiency (85%), offers low fabrication complexity and is suitable for narrowband applications. The double-layer design occupies an intermediate position appropriate for applications requiring moderate bandwidth with manageable manufacturing demands.

Table 6: ***Performance comparison across SRR configurations***

Metric	Single-Layer	Double-Layer	Multilayer
AR BW (GHz)	0.9	2.5	4.0
Peak PCE (%)	85	92	95
Avg. TX Loss (dB)	−2.0	−1.8	−1.6
Fabrication	Low	Moderate	High

Compared to existing literature, the multilayer SRR design presented here exceeds the bandwidth of most reported narrowband SRR polarizers and approaches the performance of more complex metasurface designs. For example, Geng et al. [6] achieved high efficiency X-band polarization conversion, and Li et al. [7] demonstrated multi-band conversion, but neither addressed reconfigurability within the same device framework. The present work uniquely combines broadband static operation with dynamic tuning in a single design family.

6. Conclusion

This paper has presented a study of SRR-based circular polarizers for X-band applications, progressing from single-layer to multilayer architectures with steadily improving performance. The key results are: (i) 4 GHz axial ratio bandwidth (AR ≤ 3 dB) covering the full X-band, achieved with the multilayer SRR configuration; (ii) peak polarization conversion efficiency of 95%; (iii) transmission loss below 2.5 dB

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across the band; and (iv) 1 GHz dynamic frequency tuning range via varactor diode integration without degrading polarization quality. Close simulation–experiment agreement validates the design methodology.

The multilayer configuration is well suited to broadband X-band applications in satellite communication, radar, and 5G systems, while the reconfigurable design addresses emerging adaptive electromagnetic system requirements. Fabrication complexity in the multilayer design presents the primary practical challenge for large-scale production, motivating future investigation of advanced manufacturing approaches such as nanoimprinting and roll-to-roll photolithography.

Future work will address environmental robustness, in particular the temperature stability of dielectric properties, and will explore hybrid materials including low-loss polymer substrates and conductive oxide films. Extension of the reconfigurable design to active PIN-diode or MEMS switching elements could further expand the accessible polarization state space beyond frequency tuning to include handedness switching between RHCP and LHCP modes.

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