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# Electromagnetic characterization of diamond-shaped metamaterial structures using a 4×4 array at ultra-wideband frequencies

**Defrianto, Erwin Kurnia, Saktioto*, Tengku Emrinaldi,**
**Feby Nur Sakinah, M. Ikhsan, Yan Soerbakti**
Department of Physics, Universitas Riau, Pekanbaru 28293, Indonesia

Corresponding author: saktioto@lecturer.unri.ac.id

## ABSTRACT

Metamaterials are artificially engineered media exhibiting electromagnetic properties not found in natural materials, such as negative permittivity, negative permeability, and negative refractive index. This study analyzes a diamond-shaped split ring resonator (SRR) metamaterial structure arranged in 1×1, 2×2, 3×3, and 4×4 arrays and characterized across the ultra-wideband (UWB) frequency range of 0.09 – 10 GHz. Numerical simulations were performed using CST Studio Suite 2019 to obtain S-parameters, followed by extraction of effective material parameters—permittivity, permeability, and refractive index—using the Nicolson–Ross–Weir (NRW) method. The results reveal strong multi-frequency resonances with clear epsilon-negative (ENG), mu-negative (MNG), double-negative (DNG), and epsilon-near-zero (ENZ) behaviors. The 4×4 array demonstrates the smoothest and most homogeneous effective response due to stronger inter-element coupling and medium homogenization. This work confirms that the diamond-shaped resonator can act as a versatile dispersive metamaterial suitable for wave manipulation and UWB electromagnetic engineering.

**Keywords:** Double-negative; epsilon-near-zero; metamaterial; split ring resonator; ultra-wideband

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## INTRODUCTION

Metamaterials have emerged as one of the most innovative classes of engineered media in modern electromagnetics, characterized by their ability to exhibit properties unattainable in naturally occurring materials. Unlike conventional materials whose electromagnetic responses are governed by intrinsic molecular composition, metamaterials derive their behavior from subwavelength structural design, enabling engineered responses such as negative permittivity, negative permeability, and negative refractive index [1-5]. These unconventional properties arise from the arrangement of periodically distributed “meta-atoms,” which interact with incident electromagnetic waves through tailored electric and magnetic resonances [6, 7]. As a result, metamaterials have played a transformative role in wave manipulation, artificial dispersion engineering, and high-precision field control across microwave to optical frequencies.

Among the numerous structures proposed in metamaterial research, the split ring resonator (SRR) remains one of the most widely adopted due to its ability to support strong induced magnetic resonances within compact geometries [8-12]. Various geometric modifications—including circular, square, spiral, and diamond-shaped SRR configurations—enable flexible tuning of resonance frequency, effective medium parameters, and quality factor [13, 14]. These structures exhibit hybrid electric–magnetic coupling that can be precisely controlled through geometric scaling, capacitive gaps, and inter-element spacing. Diamond-shaped SRR structures, in particular, offer enhanced capacitive discontinuities and distributed inductance, making them capable of supporting multi-band resonant behavior suitable for ultra-wideband electromagnetic applications [15-19].

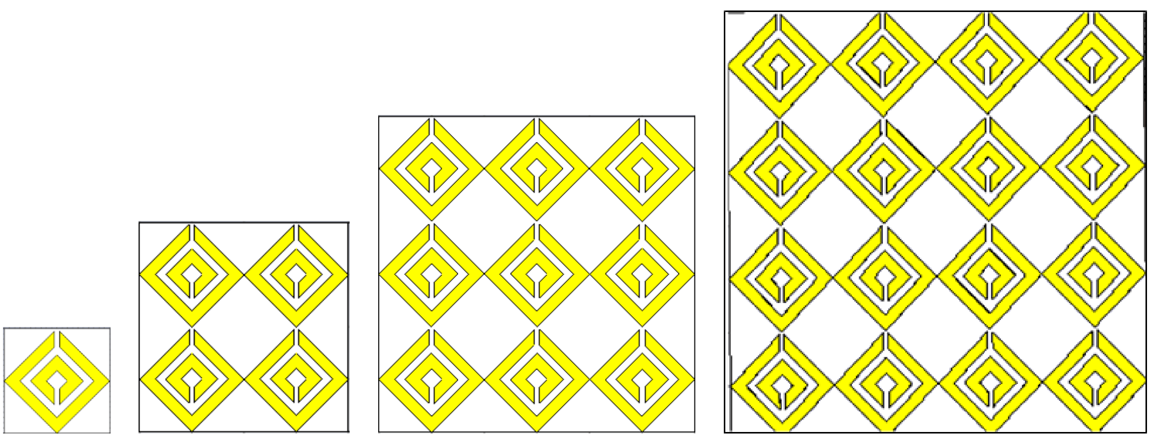
The characterization of metamaterials is typically performed through retrieval of effective medium parameters, including relative permittivity ($\varepsilon_r$), permeability ($\mu_r$), and refractive index (n), using methods such as the Nicolson–Ross–Weir (NRW) algorithm [20, 21]. These parameters determine whether the material behaves as an epsilon-negative (ENG), mu-negative (MNG), or double-negative (DNG) medium, each offering distinct electromagnetic phenomena such as phase reversal, backward-wave propagation, or extreme anisotropy [22-25]. By examining these effective parameters under different structural configurations—such as array arrangements of increasing complexity—it becomes possible to analyze the evolution of resonant behavior, inter-element coupling, and homogenization effects that govern the metamaterial's macroscopic electromagnetic performance.

Recent studies have demonstrated that expanding unit cells into larger arrays can significantly influence metamaterial behavior by smoothing resonance peaks, stabilizing frequency dispersion, and enhancing medium homogeneity [26, 27]. These array-induced interactions form collective resonant modes that differ from those observed in isolated unit cells, enabling more predictable and tunable electromagnetic responses. Understanding these phenomena is essential for the development of advanced electromagnetic devices that require precise material control at ultra-wideband frequencies.

In this context, the diamond-shaped SRR metamaterial examined in this study provides a compelling platform for exploring array-driven homogenization and multi-resonant behavior across the 0.09–10 GHz band. By systematically analyzing 1×1, 2×2, 3×3, and 4×4 array configurations, this work aims to elucidate how geometric periodicity influences electric and magnetic resonances, thereby shaping the metamaterial's effective medium properties. The insights gained are expected to support the development of next-generation engineered electromagnetic materials for diverse scientific and technological applications.

## RESEARCH METHODOLOGY

The research methodology consists of three main stages: (1) structural design of the diamond-shaped metamaterial, (2) electromagnetic simulation using CST Studio Suite, and (3) extraction of effective medium parameters using the Nicolson–Ross–Weir (NRW) method. All procedures were designed to comprehensively characterize the metamaterial's electric and magnetic responses within the 0.09 – 10 GHz ultra-wideband range.



(a) (b) (c) (d)

**Figure 1.** Array configurations of the diamond-shaped metamaterial structure: (a) 1×1 unit cell, (b) 2×2 array, (c) 3×3 array, and (d) 4×4 array.

The metamaterial structure was designed based on a modified Split Ring Resonator (SRR) geometry arranged into a diamond-shaped layout (see Figure 1). This design incorporates a conductive copper pattern deposited on an FR-4 dielectric substrate with a relative permittivity of approximately $\varepsilon_r = 4.3 – 4.6$ and a thickness of 1.6 mm. The metallic pattern had a thickness of 0.035 mm, consistent with common PCB fabrication standards. The SRR geometry includes a closed loop with a capacitive gap, providing the necessary inductive–capacitive interplay required to generate magnetic and electric resonances. Structural parameters such as radius, gap width, trace width, and periodic spacing were carefully optimized to ensure strong resonance within the target frequency band. Four array configurations—1×1, 2×2, 3×3, and 4×4—were constructed to investigate the influence of inter-cell coupling and periodic arrangement on metamaterial homogenization.

Electromagnetic simulations were performed using CST Studio Suite 2019, applying a waveguide-port excitation under transverse electromagnetic (TEM) illumination. perfect electric conductor (PEC) and perfect magnetic conductor (PMC) boundaries were used to enforce symmetry and reduce computational load, following standard metamaterial simulation practices [3]. Each model was simulated across the full UWB frequency range to obtain S-parameters, including reflection (S11) and transmission (S21). Since the metamaterial incorporates a metallic ground plane, transmission is effectively suppressed ($S21 \approx 0$), simplifying the analysis to reflection-driven retrieval. The resulting S-parameter data were exported for further processing in MATLAB.

To evaluate the metamaterial's effective electromagnetic characteristics, the Nicolson–Ross–Weir (NRW) retrieval method was applied. This method estimates the relative permittivity $\varepsilon_r$ (ω), relative permeability $\mu_r$ (ω), and refractive index n(ω) from S11 and S21 measurements [4, 5]. The reflection coefficient Γ and transmission coefficient T were first expressed as complex quantities:

$$S11 = |S11|e^{i\theta 11} \tag{1}$$

$$S21 = |S21|e^{i\theta 21} \tag{2}$$

where, |S11| and |S21| are the magnitudes, θ11 and θ21 are the corresponding phase components. The effective refractive index n was obtained from:

$$\varepsilon_r = \frac{2c}{j2\pi f t_m} \frac{1-(S21+S11)}{1+(S21+S11)} \tag{3}$$

$$\mu_r = \frac{2c}{j2\pi f t_m} \frac{1-(S21-S11)}{1+(S21-S11)} \tag{4}$$

$$n = \sqrt{\varepsilon_r \mu_r} \tag{5}$$

where $\varepsilon_r$ denotes the relative permittivity, $\mu_r$ represents the relative permeability, c is the speed of light, f is the source frequency, and tm corresponds to the waveport separation distance.

These formulas allow identification of epsilon-negative (ENG), mu-negative (MNG), and double-negative (DNG) frequency bands where $\varepsilon_r < 0$, $\mu_r < 0$, or both simultaneously become negative [6]. The extracted parameters were analyzed for each array configuration to determine the influence of periodicity and coupling on resonant strength, dispersion characteristics, and medium homogenization.

Finally, the simulation results—including permittivity, permeability, and refractive index curves—were compared across all structural configurations. This multi-stage methodological approach enables a systematic understanding of how geometric design and periodic arrangement govern the overall electromagnetic behavior of the diamond-shaped metamaterial.

## RESULTS AND DISCUSSION

The simulated electromagnetic response of the diamond-shaped metamaterial was analyzed through the retrieval of effective permittivity, permeability, and refractive index across the frequency range of 0.09 – 10 GHz. The results reveal distinct resonant behaviors governed by the inductive–capacitive interaction inherent to the split ring resonator (SRR) geometry. These phenomena appear consistently across all array configurations, although the amplitude, bandwidth, and stability of each resonance exhibit clear dependence on the periodicity and size of the array. The presence of strong electric and magnetic resonances confirms that the structure behaves as an engineered dispersive medium, capable of supporting negative-index behavior under specific spectral conditions.

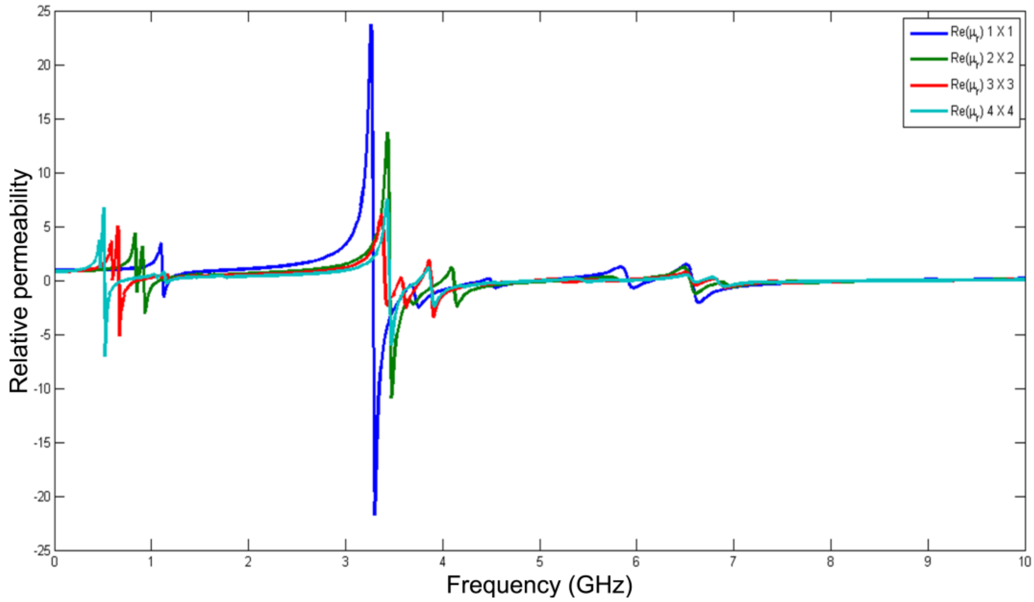


**Figure 2.** Relative permeability versus frequency graph for diamond-shaped metamaterial.

The relative permeability exhibits a prominent resonance characteristic of SRR-induced magnetic coupling (see Figure 2). In the 1×1 configuration, the permeability spectrum demonstrates a sharp resonant peak followed by a rapid transition into negative values, indicating strong magnetic oscillation within a narrow band. As the array size increases, the resonance peak becomes broader and its amplitude diminishes, particularly in the 3×3 and 4×4 configurations. This trend suggests that inter-element coupling contributes to the redistribution of magnetic field energy, thereby yielding a more homogenized effective medium response. The muted resonance observed in the 4×4 array indicates that the structure begins to approach the behavior of a bulk artificial magnetic material rather than a collection of discrete resonant elements, suggesting that increasing the lattice density enhances effective-medium homogenization and reduces localized resonant contrast.

The retrieved permittivity profile reveals multiple electric resonances, especially in the lower frequency region between 0.5 and 1.5 GHz (see Figure 3). These resonances result in extreme fluctuations in $\varepsilon_r$, with values ranging from highly positive to highly negative within narrow intervals. The large oscillations observed in the single-cell configuration arise from the strong capacitive concentration at the split gap of the resonator. With increasing array size, these oscillations become progressively moderated, reflecting enhanced spatial averaging of the electric field. Notably, for frequencies above approximately 2 GHz, all configurations show a gradual convergence toward $\varepsilon_r \approx 0$, indicating epsilon-near-zero (ENZ) behavior. This transition is particularly well-defined in the 4×4 array, suggesting that larger periodic structures can support effective electrical homogenization and controlled phase progression.

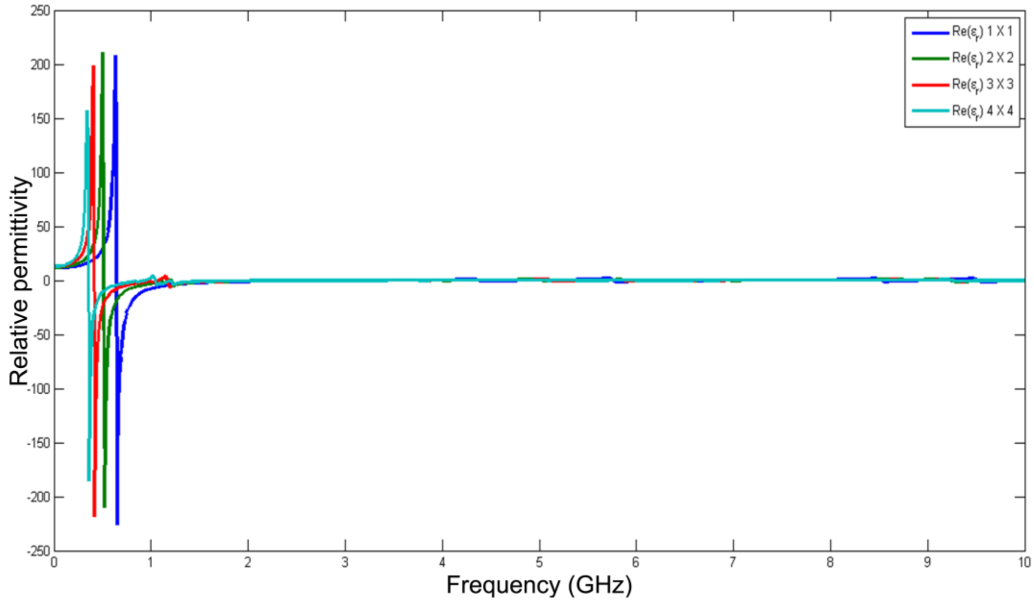



**Figure 3.** Relative permittivity versus frequency graph for diamond-shaped metamaterial.

The effective refractive index, derived from the combined permittivity and permeability spectra, further elucidates the metamaterial's dispersive properties (see Figure 4). Negative-index behavior is observed across multiple resonant bands, especially where both $\varepsilon_r$ and $\mu_r$ assume negative values simultaneously. In the 1×1 configuration, the refractive index exhibits steep transitions and narrow negative bands, reflecting the strong local resonance of an isolated SRR. As the structure evolves into larger arrays, the negative-index bands widen, their magnitude becomes less extreme, and the overall spectral response smoothens. The 4×4 configuration demonstrates the most balanced negative-index region, indicating that periodic interactions among resonator elements contribute to more stable and extended backward-wave propagation characteristics. Such behavior aligns with established theoretical expectations for periodic metamaterials, where array effects facilitate effective medium formation and minimize abrupt spectral discontinuities.

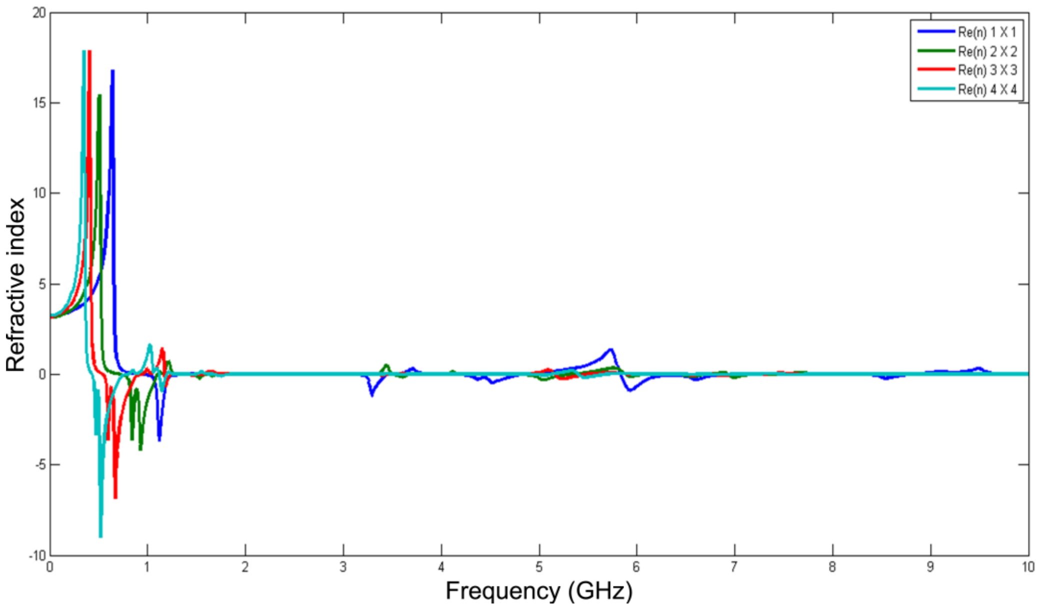



**Figure 4.** Refractive index versus frequency graph for diamond-shaped metamaterial.

Overall, the comparative analysis of the four array configurations demonstrates a clear evolution from highly localized resonant behavior toward homogenized medium characteristics as the array size increases. While single-cell structures exhibit intense and sharply defined resonances, their responses are highly sensitive to local field variations and therefore less suitable for broadband applications. Conversely, larger arrays—particularly the 4×4 configuration—exhibit broadened resonances, smoother dispersion, and more consistent effective parameter trends. These observations confirm that structural periodicity plays a pivotal role in governing the electromagnetic performance of metamaterials. The findings highlight the capability of the diamond-shaped SRR design to support multi-resonant, ENZ, and negative-index phenomena, demonstrating its potential applicability for advanced electromagnetic manipulation across the UWB spectrum.

## CONCLUSION

The results of this study demonstrate that the diamond-shaped split-ring resonator metamaterial exhibits strong and tunable electromagnetic behavior across the ultra-wideband spectrum, characterized by distinct electric and magnetic resonances, epsilon-near-zero transitions, and the emergence of negative-index regions. Systematic comparison of the 1×1, 2×2, 3×3, and 4×4 array configurations reveals a clear progression from highly localized resonant responses toward increasingly homogenized effective-medium characteristics as the array size increases, with the 4×4 arrangement providing the most stable and broadband dispersion profile. These findings confirm that the geometric periodicity and inter-element coupling inherent in larger arrays play a decisive role in shaping the metamaterial's dielectric and magnetic properties, thereby establishing the diamond-shaped configuration as a promising platform for engineered electromagnetic materials suitable for advanced UWB wave manipulation and dispersive device applications.

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