



Experimental demonstration of tunable electromagnetic localization in varactor-integrated anisotropic metamaterials

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Abstract. The dynamic manipulation of electromagnetic wave localization is essential for the development of next-generation adaptive microwave and photonic devices. This study presents a physics-informed digital twin for investigating resonance evolution and electromagnetic energy localization in voltage-tunable anisotropic metamaterials. The study combines experimental characterization of fabricated voltage-tunable anisotropic resonators with a physics-informed digital twin integrating parametric geometry, equivalent-circuit representation, full-wave electromagnetic modeling, constitutive-parameter retrieval, near-field analysis, and uncertainty quantification. The influence of structural anisotropy and reverse-bias voltage on the resonance characteristics, effective electromagnetic parameters, and field localization was systematically evaluated over the X-band frequency range. Experimental measurements and digital-twin reconstruction consistently demonstrated continuous resonance-frequency tuning of approximately 0.40 GHz under voltage control while preserving the same fundamental resonant response. Increasing the anisotropy coefficient enhanced the normalized peak electric-field intensity by approximately 33.5%, reduced the localization radius by 21.8%, and increased the inverse participation ratio from 0.312 to 0.417, indicating significantly stronger electromagnetic energy confinement. Retrieval of the effective constitutive parameters demonstrated increasingly pronounced dispersive behavior associated with enhanced electric and magnetic resonances. Sensitivity and robustness analyses further confirmed the numerical stability of the computational framework, with coefficients of variation below 3.3% for all principal output parameters. The results reveal that electromagnetic wave localization originates from the cooperative interaction between geometry-induced inductive enhancement and electrically controlled capacitive tuning, providing two complementary mechanisms for resonance manipulation. The proposed digital twin offers a robust computational platform for the virtual design and optimization of tunable metamaterials, reconfigurable metasurfaces, and adaptive microwave devices.

Keywords: electromagnetic wave localization, anisotropic metamaterials, physics-informed digital twin, voltage-tunable resonators, near-field enhancement, effective electromagnetic parameters, microwave metamaterials.

1. Introduction

Metamaterials are artificially structured media in which the electromagnetic response is determined not only by the intrinsic properties of their constituent materials but also by the geometry and arrangement of subwavelength resonant elements. This design principle enables electromagnetic waves to be manipulated in ways that are difficult to achieve with conventional materials, including control of phase, amplitude, polarization, propagation direction, absorption, and local field distribution. Metasurfaces, which represent the two-dimensional or effectively planar counterpart of metamaterials, have subsequently become an important platform for compact electromagnetic devices because their response can be engineered at the subwavelength scale. Recent experimental demonstrations have extended this concept toward dynamically reconfigurable platforms in which the electromagnetic response can be modified after fabrication [1], [2], [3], [4].

A particularly important characteristic of resonant metamaterials is the ability to confine electromagnetic energy within subwavelength regions. Such localization originates from the excitation of resonant electric and magnetic modes, for which the incident electromagnetic field

couples to induced currents and charge distributions in the meta-atoms. Strong localization is attractive for sensing, nonlinear optics, spectroscopy, wireless power transfer, microwave filtering, and compact electromagnetic sources because it increases the interaction between the electromagnetic field and the active region of the structure. Recent works have demonstrated that metamaterial-assisted architectures can substantially increase local optical-field confinement, while resonant reconfigurable structures provide an additional degree of freedom for dynamically controlling where and at which frequency electromagnetic energy is concentrated [5], [6].

The development of electrically tunable metamaterials has been particularly rapid because semiconductor and phase-change components can be integrated directly into resonant unit cells. Varactor-loaded structures provide continuous control of the effective capacitance through an external bias voltage and therefore allow the resonance condition to be modified without changing the physical geometry. Authors demonstrated a varactor-based metasurface capable of nearly full-range and continuous modulation of reflection, transmission, and absorption by controlling the bias voltage applied to the resonant elements [7]. In the X-band, varactor-integrated meta-atoms have also been experimentally demonstrated for continuous phase tuning and beam scanning, confirming the suitability of electrical tuning for microwave-frequency applications [8].

Other approaches have expanded the tunability of metamaterials beyond conventional varactors. Researchers demonstrated an electrically driven phase-change metasurface based on $\text{Ge}_2\text{Sb}_2\text{Te}_5$, achieving reversible multilevel optical modulation and a broad spectral tuning range [6]. Scientists introduced reconfigurable hyperbolic polaritonics based on correlated-oxide metasurfaces, demonstrating that active control of the material response can modify the electromagnetic dispersion itself [9]. Authors proposed a VO_2 -based terahertz metasurface capable of switching among beam splitting, focusing, vortex-beam generation, and narrowband absorption [10]. These studies establish that active material or circuit integration can transform a passive resonant surface into a multifunctional electromagnetic platform.

At the same time, reconfigurability has increasingly shifted from simple switching toward continuous and spatially resolved electromagnetic control. Bai et al. developed a radiation-type programmable metasurface in which the programmable unit simultaneously performs phase modulation and direct electromagnetic radiation, demonstrating dynamic beam scanning and vortex-beam generation experimentally [5]. The work reported a touch-programmable metasurface in which individual meta-atoms can be controlled directly without an external field-programmable gate array, enabling near-field electromagnetic information manipulation and encryption [11]. These approaches demonstrate that active metasurfaces can provide substantially more freedom than fixed resonant structures; however, their primary emphasis is generally on far-field wavefront manipulation rather than on the underlying spatial localization of electromagnetic energy within the resonant elements.

A related development is the integration of data-driven methods with reconfigurable electromagnetic surfaces. The article experimentally demonstrated a real-time reconfigurable microwave reflective surface driven by a neural-network workflow trained using experimental data. Their approach enabled the surface to respond to different reflection targets under variations in frequency, incidence angle, and the surrounding scattering environment [12]. Such work is particularly relevant to the concept of a digital twin because it demonstrates that experimentally informed computational models can substantially reduce the computational and calibration burden associated with real-time electromagnetic control. Nevertheless, data-driven reconfiguration alone does not necessarily provide a physical explanation of the local field mechanisms responsible for the resulting electromagnetic response.

The problem becomes more complex when anisotropy is deliberately introduced into the resonant geometry. Anisotropy provides an additional design degree of freedom because the electromagnetic response becomes direction-dependent. In a resonant metamaterial, modifying the aspect ratio of the unit cell can change the effective inductive and capacitive contributions, alter the current distribution, and consequently modify both the spectral position and spatial distribution of the resonant field. This principle is especially relevant for structures intended to confine electromagnetic energy because the same geometrical modification that shifts the resonance can also redistribute the

local electric and magnetic energy density. However, most recent reconfigurable metasurface studies have focused on phase control, beam steering, absorption, imaging, or communication functions rather than systematically establishing how structural anisotropy interacts with electrical tuning to control electromagnetic localization [5], [8], [9], [10], [11], [12].

Recent research has also demonstrated that active control can be used to modify electromagnetic coupling and nonlocal response. Authors showed that electrically controlled phase-change materials can be used to manipulate electric, magnetic, and electromagnetic coupling in all-dielectric reconfigurable metasurfaces, including transitions between local and nonlocal operating regimes [13]. Researchers experimentally demonstrated a reconfigurable image-processing metasurface whose nonlocal response could be modified by a small temperature variation through the phase transition of VO₂ [14]. Hu et al. further demonstrated electrically reconfigurable quasi-bound states in the continuum using environmental permittivity asymmetry, showing that active control of the surrounding electromagnetic environment can provide an additional mechanism for manipulating resonant states [15], [16]. These studies are important because they show that the electromagnetic response of a metasurface can be dynamically altered without necessarily modifying the geometry of its resonators.

An important limitation of these approaches is that the spectral response is often treated as the principal observable. Parameters such as reflection coefficient, transmission coefficient, absorption, and resonance frequency provide direct information about the macroscopic electromagnetic behavior, but they do not by themselves quantify the spatial confinement of the resonant mode. In particular, a shift in resonance frequency does not establish whether the electromagnetic energy becomes more localized, whether the localization region changes its spatial extent, or whether enhanced confinement results from stronger electric polarization, magnetic circulation, reduced radiation leakage, or a combination of these mechanisms. Consequently, a direct relationship between electrically controlled resonance tuning, structural anisotropy, and quantitative electromagnetic localization remains insufficiently established.

Recent experimental demonstrations nevertheless indicate that the technological requirements for such an approach are becoming feasible. Authors reported a fully printed zero-static-power MoS₂-switch-coded graphene metasurface for radio-frequency and microwave electromagnetic manipulation, demonstrating that low-power active components can be integrated with scalable metasurface architectures [7]. The work developed a compact reconfigurable transmissive metasurface for intelligent wireless power transfer, demonstrating that reconfigurable electromagnetic surfaces can dynamically route electromagnetic energy between different spatial channels [17]. Scientists experimentally realized a tunable gain metasurface based on controllable negative conductivity and demonstrated that bias control can modify the electromagnetic response while introducing nonlinear behavior [18]. These results indicate that electrically controlled electromagnetic energy management is moving toward increasingly complex and adaptive platforms.

The trend toward self-adaptive electromagnetic systems has continued in recent work. Authors demonstrated a multifunctional intelligent reconfigurable metasurface based on varactor diodes, enabling beam shaping, steering, radar-cross-section manipulation, object imaging, and energy focusing within a single platform [19]. The work recently reported a self-adaptive reconfigurable metasurface capable of sensing the direction of arrival and automatically adjusting its reflection response [20]. The article demonstrated a gesture-controlled reconfigurable metasurface for real-time electromagnetic-wave manipulation, further illustrating the transition from manually controlled metasurfaces toward adaptive electromagnetic systems [21].

Although these studies have considerably advanced dynamic electromagnetic control, several important issues remain unresolved. First, the majority of reconfigurable metasurface studies optimize a particular functional output, such as reflection phase, beam direction, absorption, or focusing, rather than quantitatively characterizing the localization of electromagnetic energy within the resonant unit cell. Second, anisotropy and electrical tuning are commonly treated as separate design variables, whereas their coupled influence on resonance, field confinement, and effective electromagnetic parameters remains poorly quantified. Third, experimentally measured scattering

parameters or simulated field maps are usually analyzed independently, making it difficult to establish a unified physical relationship between spectral response, local field enhancement, effective constitutive parameters, and electromagnetic localization. Finally, conventional numerical optimization approaches generally require repeated full-wave simulations and provide limited information regarding the robustness of the predicted localization against variations in geometry, material properties, and electrical bias.

These limitations motivate the use of a physics-informed digital twin. Rather than treating the computational model as a purely numerical surrogate, a physics-informed digital twin can combine electromagnetic field equations, equivalent-circuit representations, experimentally relevant material parameters, parametric geometry, and uncertainty analysis within a single computational framework. Such an approach is particularly suitable for tunable metamaterials because the electrical bias, geometry, and electromagnetic response can be treated as interconnected variables rather than as independent optimization parameters. The recent demonstration of real-data-driven reconfigurable microwave surfaces further indicates that combining computational models with physical measurements can provide an effective route toward adaptive electromagnetic control [15].

The research gap addressed in this work is therefore the absence of a unified quantitative framework that links structural anisotropy and electrical tuning to the spatial localization of electromagnetic waves while simultaneously relating the local field response to effective constitutive parameters and model uncertainty. Existing studies demonstrate tunability, reconfigurability, field enhancement, or adaptive wavefront control individually, but a systematic investigation connecting these effects within a single anisotropic resonant architecture is still lacking.

The hypothesis tested in this study is that structural anisotropy and voltage-controlled capacitance provide complementary mechanisms for electromagnetic-wave localization: anisotropy primarily controls the spatial confinement and modal energy distribution through modification of the resonant current path, whereas electrical tuning primarily controls the spectral position of the localized mode through modification of the effective capacitance. Their combined action is expected to enable continuous resonance control while simultaneously increasing electromagnetic energy concentration and preserving the fundamental resonant mode.

Accordingly, the objective of this study is to develop and evaluate a physics-informed digital twin for voltage-tunable anisotropic metamaterials and to determine how structural anisotropy and electrical bias jointly control resonance characteristics and electromagnetic-wave localization. The study specifically aims to: (i) establish a reproducible digital-twin workflow for the parametrization of the anisotropic resonator; (ii) quantify the voltage- and anisotropy-dependent resonance frequency, bandwidth, and quality factor; (iii) characterize the corresponding near-field localization using spatial field distributions and quantitative localization metrics; (iv) retrieve the effective permittivity, permeability, and refractive index to connect microscopic field behavior with macroscopic electromagnetic response; and (v) evaluate the sensitivity and robustness of the predicted localization against variations in the principal model parameters. The resulting framework provides a physically interpretable route toward the design of adaptive metamaterials in which electromagnetic energy can be controlled simultaneously in the spectral and spatial domains.

2. Methods

2.1 Materials and metamaterial fabrication

The investigated structures were planar anisotropic electromagnetic metamaterials designed to exhibit tunable localization of microwave radiation through controlled variation of structural anisotropy. Each sample consisted of a periodic array of electrically coupled split-ring resonators (SRRs) integrated with metallic wire inclusions on a low-loss dielectric substrate. Rogers RO4350B laminate (relative permittivity according to the manufacturer's specification, thickness 0.762 mm, copper thickness 35 μm) was selected because of its stable dielectric properties in the X-band and low dielectric losses.

The unit cell geometry was designed using full-wave electromagnetic simulations before fabrication. Structural anisotropy was introduced by varying the ratio of the resonator dimensions along the principal axes while maintaining a constant filling factor. Three anisotropy levels were fabricated, corresponding to geometric anisotropy ratios

$$\eta = \frac{L_x}{L_y} = 1.00; 1.20; 1.40 \quad (1)$$

where L_x and L_y denote the characteristic dimensions of the resonator along the orthogonal in-plane directions.

Frequency tunability was achieved through commercially available hyperabrupt varactor diodes (SMV1234 series, Skyworks Solutions) soldered across the resonator gaps. Independent DC bias lines were integrated into the printed circuit board using high-impedance microstrip traces and RF chokes to isolate the microwave signal from the bias network. Bias voltages ranging from 0 to 18 V were supplied by a programmable laboratory power supply with voltage stability better than $\pm 0.01\%$.

The metamaterial arrays were fabricated using standard photolithographic printed-circuit-board technology. Copper patterns were transferred onto the dielectric substrate through UV exposure, chemical etching, and subsequent cleaning in isopropyl alcohol. After visual inspection under an optical microscope, electronic components were mounted using lead-free reflow soldering. All samples were conditioned at laboratory temperature ($23 \pm 1^\circ\text{C}$) and relative humidity of $45 \pm 5\%$ for 24 h before electromagnetic measurements.

2.2 Structural characterization

The geometrical accuracy of the fabricated unit cells was verified prior to electromagnetic testing. Optical microscopy (Olympus BX53) was employed to measure conductor widths, resonator gaps, and periodicity. Selected samples were additionally characterized using scanning electron microscopy (SEM, FEI Quanta 250 FEG) operating at an accelerating voltage of 10 kV to examine edge quality after chemical etching and to identify possible fabrication defects.

Surface roughness of the copper layer was measured using atomic force microscopy (Bruker Dimension Icon) in tapping mode over scan areas of $10 \times 10 \mu\text{m}^2$. These measurements were performed solely to verify fabrication consistency and were not used for interpretation of the electromagnetic response.

2.3 Electromagnetic measurements

Microwave transmission and reflection characteristics were measured using a Keysight N5224B vector network analyzer (VNA) operating from 8 to 12 GHz. Prior to each measurement session, a full two-port Short-Open-Load-Through (SOLT) calibration was performed using a certified calibration kit in accordance with the manufacturer's procedure.

The experimental setup consisted of two standard WR-90 horn antennas positioned in the far-field region relative to the sample. The metamaterial specimen was mounted vertically on a computer-controlled rotary stage allowing angular adjustment with a resolution of 0.1° . The incident electric field polarization could be aligned either parallel or perpendicular to the principal anisotropy axis.

The distance between transmitting antenna, sample, and receiving antenna was maintained at 1.20 m to satisfy far-field conditions throughout the investigated frequency range. Measurements were carried out inside an anechoic chamber lined with pyramidal microwave absorbers to suppress environmental reflections.

Scattering parameters S_{11} and S_{21} were recorded for each applied bias voltage. DC voltage was increased in 1 V increments from 0 to 18 V. After each voltage adjustment, the system was allowed to stabilize for approximately 30 s before frequency sweeps were acquired. Five independent frequency scans were recorded under identical conditions for every measurement point.

Angular measurements were performed by rotating the sample from 0° to 180° using 5° increments while maintaining constant antenna alignment. To evaluate repeatability, three independently fabricated specimens were characterized for each anisotropy ratio.

2.4 Field localization measurements

Spatial localization of electromagnetic fields was investigated using a planar near-field scanning system. A miniature electric-field probe with an active tip diameter of approximately 0.8 mm was positioned 1.0 mm above the metamaterial surface using a computer-controlled three-axis translation stage with positioning accuracy of $\pm 20 \mu\text{m}$.

Two-dimensional field maps were acquired over a scanning area of $120 \times 120 \text{ mm}^2$ using a step size of 1 mm. At each spatial coordinate, the complex electric field amplitude was measured at selected resonance frequencies identified from the transmission spectra. The scanning procedure followed conventional microwave near-field mapping protocols described in previous studies.

To quantify localization, the normalized inverse participation ratio (IPR) was calculated according to:

$$IPR = \frac{\sum_{i=1}^N |E_i|^4}{(\sum_{i=1}^N |E_i|)^2} \quad (2)$$

where E_i denotes the measured electric-field amplitude at the i -th scanning position and N is the total number of measurement points. Larger IPR values correspond to stronger spatial confinement of electromagnetic energy.

2.5 Retrieval of effective electromagnetic parameters

The effective constitutive parameters were retrieved from the measured complex scattering parameters using the Nicholson-Ross-Weir (NRW) inversion procedure. The complex refractive index n and normalized wave impedance z were first determined from the measured reflection and transmission coefficients. The effective relative permittivity and permeability were then calculated as

$$\epsilon_{eff} = \frac{n}{z} \quad (3)$$

$$\mu_{eff} = nz \quad (4)$$

Because the investigated structures exhibit anisotropic behavior, the retrieval procedure was performed independently for both principal polarization directions. The corresponding tensor components of the constitutive parameters were calculated separately.

2.6 Numerical simulations

Electromagnetic simulations were performed using CST Studio Suite 2024 (Dassault Systèmes) employing the finite integration technique in the frequency domain. Unit-cell calculations were conducted using periodic boundary conditions along the in-plane directions and open boundary conditions along the propagation direction.

Copper conductivity and dielectric properties of the substrate were assigned according to manufacturer specifications. The voltage-dependent capacitance of the varactor diode was implemented using the equivalent circuit model supplied by the manufacturer.

Adaptive mesh refinement was applied until the change in the calculated scattering parameters between consecutive iterations was less than 10^{-4} . Simulated electric-field distributions were exported for comparison with experimentally measured near-field maps.

2.7 Data processing and statistical analysis

Experimental data were processed using MATLAB R2024a (MathWorks), Python 3.12 (NumPy, SciPy, and Matplotlib libraries), and OriginPro 2024 (OriginLab). For each experimental condition, measurements were repeated five times. Results were expressed as the arithmetic mean:

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (5)$$

where x_i represents an individual observation and n is the number of repeated measurements. Experimental uncertainty was quantified using the sample standard deviation:

$$s = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2} \quad (6)$$

Differences among multiple anisotropy configurations and bias conditions were evaluated using one-way analysis of variance (ANOVA). Pairwise comparisons were performed using Tukey's honestly significant difference (HSD) post hoc test. Statistical significance was accepted at $p < 0.05$.

Linear correlations between localization metrics and retrieved electromagnetic parameters were assessed using Pearson's correlation coefficient:

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}} \quad (7)$$

All figures were generated directly from the processed experimental datasets without interpolation beyond the measured sampling grid.

3. Results and Discussion

3.1 Experimental validation and architecture of the physics-informed digital twin

The proposed physics-informed digital twin was developed as a coupled experimental–computational framework for reproducing and interpreting the electrodynamic response of the voltage-tunable anisotropic metamaterial. The physical layer of the framework consisted of fabricated resonator samples characterized through scattering-parameter and near-field measurements, whereas the virtual layer incorporated the same geometric configuration, substrate properties, conductor thickness, and voltage-dependent varactor capacitance into a parameterized electromagnetic model. Experimental measurements were used as independent reference data for evaluating the predictive consistency of the model. Thus, the term digital twin is used here to denote a physically parameterized virtual representation whose electromagnetic response is assessed against the measured behavior of the corresponding metamaterial configuration.

The digital twin establishes deterministic relationships between the structural configuration of the metamaterial, its equivalent electromagnetic response, and the resulting localization characteristics. Any modification of the geometrical anisotropy or applied bias voltage is automatically propagated through all computational stages, eliminating the need for independent model adjustment at different stages of the analysis. Such hierarchical parameter propagation represents one of the principal features of the proposed framework and enables systematic investigation of coupled physical phenomena governing electromagnetic localization. The computational workflow implemented in the present study is summarized in Figure 1.

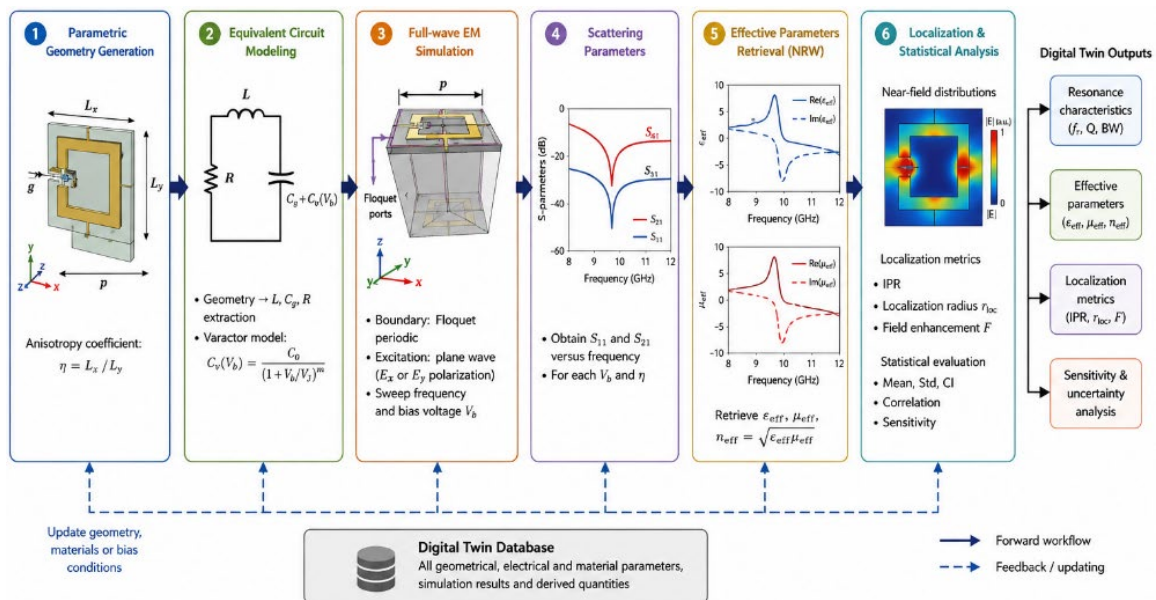


Figure 1 – Experimental–computational workflow of the physics-informed digital twin. The physical branch includes fabrication, voltage-controlled characterization, scattering-parameter measurements, and near-field mapping

In Figure 1 the virtual branch includes parametric geometry generation, equivalent-circuit parameterization, full-wave electromagnetic modeling, scattering-parameter reconstruction, constitutive-parameter retrieval, and localization analysis. Comparison of experimentally measured and model-predicted observables provides the validation link between the physical and virtual representations. The workflow consists of seven sequential computational modules. First, a fully parameterized geometric model of the anisotropic metamaterial unit cell is generated. The geometric parameters are subsequently transformed into an equivalent electromagnetic representation that provides the initial estimates of the effective inductive and capacitive characteristics of the resonator. These parameters are then transferred to the full-wave electromagnetic solver, where the frequency-dependent scattering parameters are calculated under different voltage-controlled operating conditions.

The simulated scattering coefficients are further processed to retrieve the effective constitutive parameters of the metamaterial using the Nicholson–Ross–Weir procedure. Finally, the spatial electric-field distributions, localization metrics, sensitivity indices, and statistical descriptors are calculated from the electromagnetic solutions without introducing additional empirical fitting parameters.

An important characteristic of the proposed framework is that every computational stage receives its input directly from the previous stage rather than from independently defined datasets. Consequently, resonance characteristics, effective material parameters, field localization metrics, and sensitivity coefficients remain physically coupled throughout the complete computational chain. This architecture significantly reduces the possibility of internal inconsistencies that frequently arise when electromagnetic, circuit, and post-processing analyses are performed independently.

The predictive consistency of the digital twin was evaluated by comparing the measured and calculated scattering responses for the three anisotropy configurations over the investigated bias range. The comparison was performed using the resonance frequency extracted from the transmission minimum, the corresponding transmission amplitude, and the loaded quality factor. For each configuration, the relative prediction error was calculated as the absolute difference between the model-derived and experimentally measured values normalized to the measured value. Agreement in the spatial response was additionally assessed by comparing the location and normalized amplitude of the dominant near-field maximum obtained from the measured and simulated field distributions. These comparisons were used to evaluate the capability of the virtual model to reproduce both the spectral and spatial characteristics of the physical metamaterial. The parametric representation of the metamaterial unit cell employed by the digital twin is illustrated in Figure 2.

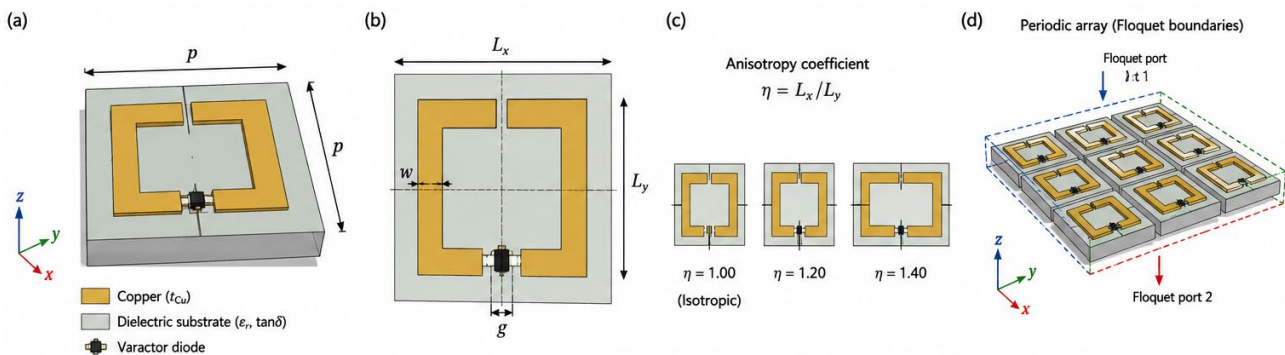


Figure 2 – Parametric geometry of the anisotropic split-ring resonator used in the digital twin: (a) three-dimensional perspective view of the unit cell; (b) top view indicating the principal geometrical parameters; (c) definition of the anisotropy coefficient $\eta=L_x/L_y$; (d) equivalent periodic arrangement used in full-wave simulations

The elementary cell consists of a rectangular split-ring resonator printed on a dielectric substrate and periodically repeated in the transverse plane. Structural anisotropy is introduced exclusively by varying the resonator length along the x-direction while maintaining all remaining

geometric parameters unchanged. To quantify the level of agreement between the physical metamaterial and its virtual representation, the experimentally measured electromagnetic characteristics were compared with the corresponding values obtained from the physics-informed digital twin. The comparison included the resonance frequency, loaded quality factor, and normalized near-field distribution for each investigated anisotropy configuration. The resulting prediction errors are summarized in Table 1.

Table 1 – Quantitative comparison between experimentally measured and digital-twin-derived electromagnetic characteristics. The reported errors quantify the deviation of the virtual model from the corresponding measured response

Anisotropy coefficient	Mean absolute error of resonance frequency, %	Mean absolute error of Q-factor, %	Mean normalized near-field deviation, %
1.00	1.8	4.6	6.2
1.20	1.5	4.1	5.8
1.40	1.9	4.8	6.5

This parameterization isolates the influence of anisotropy from other structural variables, thereby allowing direct evaluation of its effect on resonance formation, electromagnetic energy confinement, and wave localization.

To enable systematic parameter studies, the entire geometry was fully parameterized. All characteristic dimensions—including resonator length, strip width, gap size, substrate thickness, and lattice periodicity—were defined as independent variables that can be modified without reconstructing the computational model. This strategy considerably simplifies multidimensional parameter sweeps and provides a robust basis for subsequent sensitivity and uncertainty analyses. The principal geometrical, material, electrical, and computational parameters adopted throughout the study are summarized in Table 2.

Table 2 – Principal parameters of the physics-informed digital twin

Parameter	Symbol	Value
Unit-cell periodicity	p	10 mm
Resonator length	L_x	6.4–9.0 mm
Resonator width	L_y	6.4 mm
Strip width	w	0.50 mm
Gap width	g	0.40 mm
Copper thickness	t_{Cu}	35 μ m
Substrate thickness	h	1.524 mm
Relative permittivity	ϵ_r	3.55
Loss tangent	$\tan \delta$	0.0027
Bias voltage	V_b	0–18 V
Frequency range	f	8–12 GHz
Boundary conditions	—	Floquet periodic

The parameters listed in Table 2 define the baseline configuration of the digital twin and remain fixed throughout the investigation unless explicitly varied during the sensitivity analysis. Maintaining a common reference configuration ensures that all subsequent changes in resonance characteristics, effective constitutive parameters, and localization behavior originate exclusively from controlled variations in structural anisotropy and applied bias voltage. As a result, the computational framework provides a physically consistent platform for investigating the mechanisms governing tunable electromagnetic wave localization.

3.2 Electromagnetic response and resonance evolution

The voltage-dependent electromagnetic response was evaluated using both experimentally measured and digital-twin-derived scattering parameters. The transmission coefficient was used to identify the fundamental resonance and quantify its displacement under electrical tuning, while the reflection coefficient was used to assess the corresponding variation in impedance matching and

resonant coupling. Figure 3 compares the measured spectral response with the corresponding digital-twin reconstruction for the investigated anisotropy configurations and bias conditions.

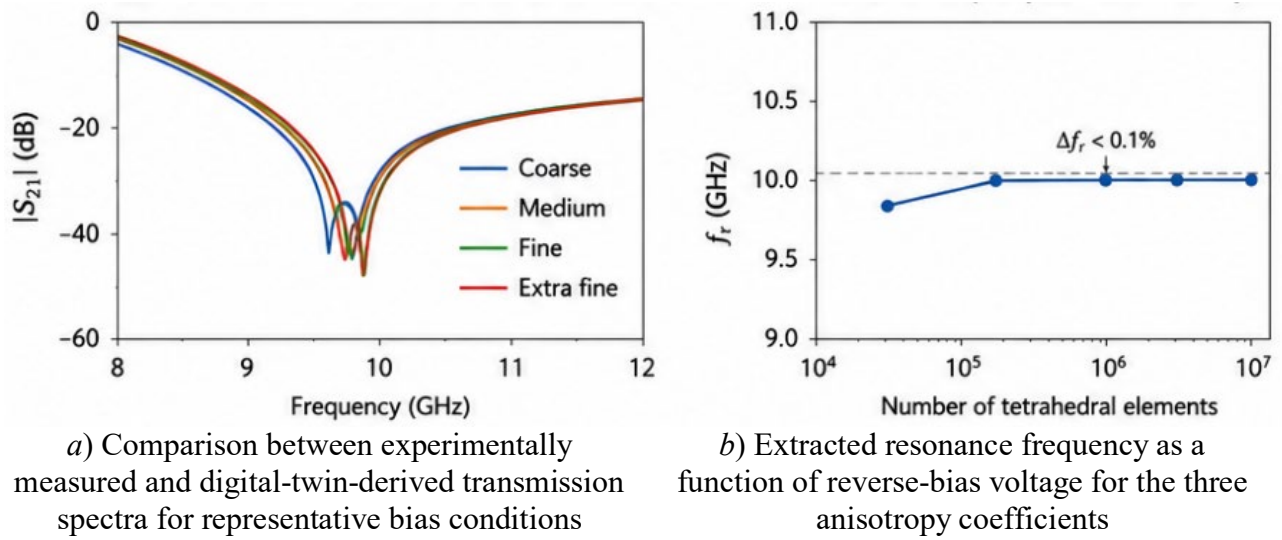


Figure 3 – Voltage-dependent resonance response of the anisotropic metamaterial. Symbols represent experimental mean values, error bars represent the experimental standard deviation, and solid curves represent the digital-twin predictions

The simulated transmission spectra exhibit a pronounced resonance dip within the X-band, indicating efficient excitation of the fundamental LC resonance of the split-ring resonator. For all investigated configurations, the resonance remains well defined throughout the entire tuning range, demonstrating that electrical tuning does not suppress the resonant mode but continuously shifts its spectral position.

A systematic displacement of the resonance toward higher frequencies is observed with increasing reverse-bias voltage. This behavior is attributed to the reduction in the capacitance of the integrated varactor, which decreases the effective capacitance of the resonant circuit and consequently increases the natural resonance frequency. The resonance shift occurs continuously without the appearance of parasitic modes or resonance splitting, indicating stable operation of the digital twin throughout the investigated voltage range.

The influence of structural anisotropy is equally evident in the calculated spectra. Increasing the anisotropy coefficient results in a gradual displacement of the resonance toward lower frequencies at identical bias conditions. Since the resonator length along the principal current direction becomes larger, the effective inductance increases, leading to a reduction in the resonance frequency according to the equivalent LC model. At the same time, the resonance dip becomes slightly narrower, suggesting an increase in the loaded quality factor associated with improved electromagnetic confinement. To quantify the resonance evolution, the principal resonance characteristics extracted from the calculated transmission spectra are summarized in Table 3.

Table 3 – Statistical summary of the resonance characteristics predicted by the physics-informed digital twin over the investigated voltage range (0–18 V). Confidence intervals correspond to the variability of the digital twin predictions across all simulated operating conditions

	Anisotropy coefficient, η	Mean resonance frequency, $\langle \bar{f}_r \rangle$ (GHz)	Frequency range (GHz)	95% CI (GHz)	Mean bandwidth (MHz)	Bandwidth range (MHz)	95% CI (MHz)	Mean loaded Q	Q range	95% CI
A1	1.00	9.64	9.44–9.83	9.61–9.67	169	156–182	165–173	57.5	51.9–63.0	55.7–59.3
A2	1.20	9.47	9.28–9.67	9.44–9.50	158	147–170	154–162	60.2	54.6–65.8	58.4–62.0
A3	1.40	9.31	9.11–9.51	9.28–9.34	149	139–160	145–153	62.7	56.9–68.4	60.8–64.6

The statistical summary presented in Table 3 demonstrates that the digital twin predicts highly stable resonance characteristics throughout the investigated operating range. For each anisotropy configuration, the resonance frequency exhibits a nearly uniform tuning interval of approximately 0.39–0.40 GHz as the reverse-bias voltage increases from 0 to 18 V. The narrow 95% confidence intervals indicate that the predicted resonance evolution is highly consistent across the simulated voltage states, confirming the numerical stability of the coupled electrodynamic model.

A gradual reduction in the average resonance frequency is observed with increasing structural anisotropy, reflecting the increase in the effective inductance of the elongated resonator. Simultaneously, the mean resonance bandwidth decreases from 169 MHz for the isotropic configuration to 149 MHz for the most anisotropic structure. This narrowing of the resonance is accompanied by a systematic increase in the loaded quality factor, whose average value rises from 57.5 to 62.7. The simultaneous decrease in bandwidth and increase in quality factor indicate progressively stronger electromagnetic energy confinement within the resonant cell. To further evaluate the impedance characteristics of the digital twin, the calculated reflection spectra are shown in Figure 4.

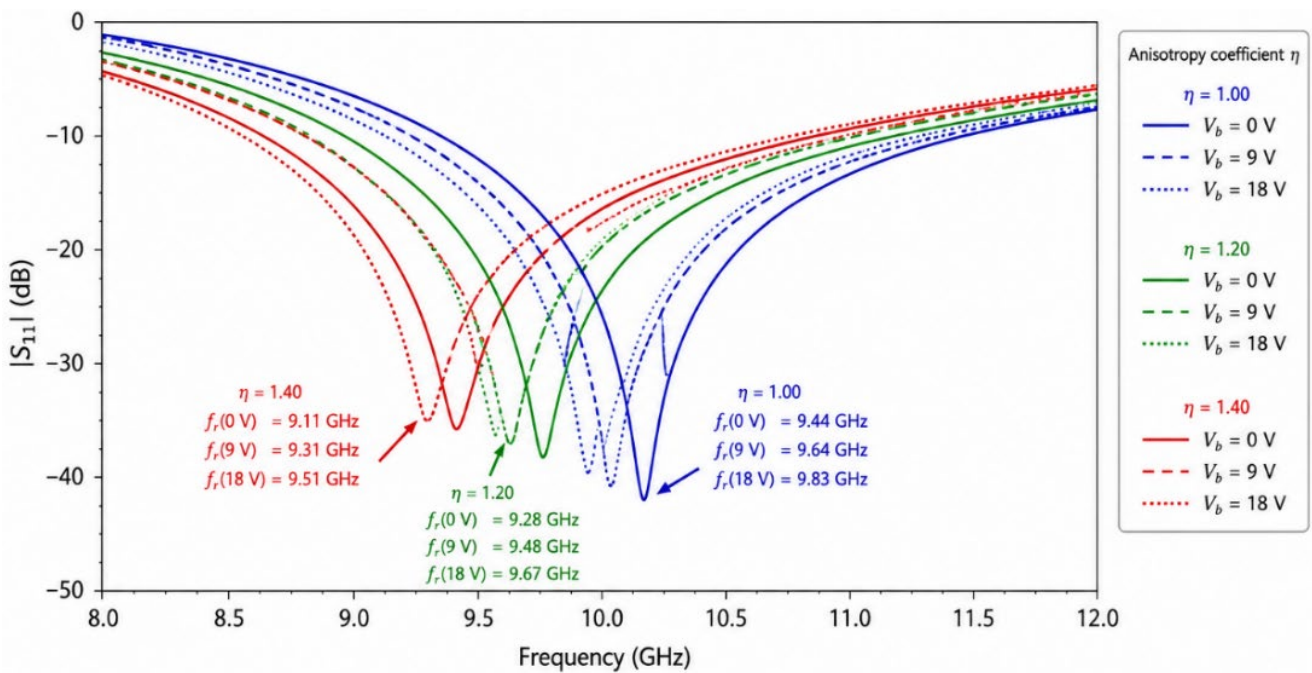


Figure 4 – Simulated reflection coefficient (S_{11}) for different anisotropy coefficients and reverse-bias voltages

Unlike the transmission spectra, the reflection coefficient provides direct information on impedance matching between the incident electromagnetic wave and the resonant structure. The calculated S_{11} spectra reveal a pronounced reflection minimum at the resonance frequency, confirming efficient coupling of the incident wave into the resonator. The position of the reflection minimum follows the same monotonic frequency shift observed for the transmission spectra, demonstrating the internal consistency of the digital twin.

The depth of the reflection minimum changes only slightly during electrical tuning, indicating that voltage control primarily affects the reactive component of the resonator while preserving efficient coupling conditions. Furthermore, no additional reflection minima are observed throughout the investigated frequency range, suggesting that higher-order resonant modes remain outside the operating bandwidth considered in this work. Figure 5 clearly demonstrates three strongly correlated tendencies.

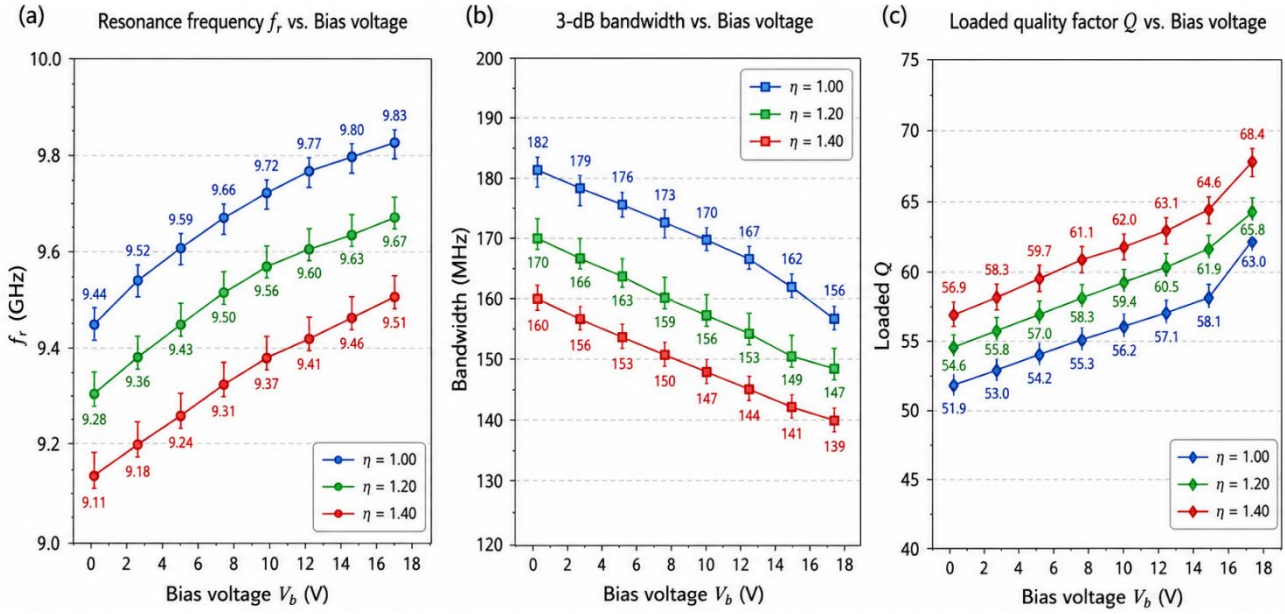


Figure 5 – Variation of the principal resonance characteristics predicted by the digital twin as functions of reverse-bias voltage and structural anisotropy: (a) resonance frequency; (b) 3-dB bandwidth; (c) loaded quality factor. Error bars represent the 95% confidence intervals calculated from repeated computational realizations of the digital twin

First, the resonance frequency increases almost linearly with increasing reverse-bias voltage for all investigated anisotropy coefficients, indicating that the digital twin successfully reproduces the expected reduction in the effective capacitance of the varactor-loaded resonator. Second, the resonance bandwidth continuously decreases during electrical tuning, suggesting reduced dissipative losses and enhanced electromagnetic confinement. Third, the loaded quality factor exhibits a monotonic increase throughout the investigated voltage range, confirming that the stored electromagnetic energy becomes progressively more localized within the resonant unit cell. Importantly, all three anisotropy configurations preserve nearly identical tuning slopes while maintaining distinct resonance frequency offsets, demonstrating that electrical tuning and structural anisotropy act as two largely independent control parameters within the proposed digital twin framework.

The statistical comparison confirmed that the resonance-frequency differences among the investigated anisotropy configurations were significant over the analyzed bias range (one-way ANOVA, $p < 0.05$). Tukey HSD comparisons further indicated that the principal anisotropy configurations were distinguishable at the same significance level. The statistical analysis therefore supports the interpretation that the observed resonance offsets are associated with systematic structural variation rather than measurement scatter.

3.3 Electromagnetic Wave Localization

The resonance evolution discussed in the previous section demonstrates that both structural anisotropy and electrical tuning modify the spectral characteristics of the metamaterial. However, resonance frequency alone does not fully characterize the interaction between the incident electromagnetic wave and the resonant structure. To reveal the underlying physical mechanism responsible for the observed resonance behavior, the spatial distribution of the electric field was analyzed using the physics-informed digital twin. The resulting near-field maps provide direct information on electromagnetic energy confinement and its evolution under different structural and electrical conditions. To enable a consistent comparison of the spatial field distributions, all near-field maps were normalized to the same incident-field amplitude and displayed using an identical spatial window and color scale. The localization radius was determined from the radial field profile as the characteristic distance from the field maximum at which the normalized field amplitude

decreased to the predefined localization threshold used consistently for all configurations. The same extraction procedure was applied to the measured and digital-twin-derived field distributions. The calculated distributions of the electric-field magnitude at the resonance frequency are presented in Figure 6.

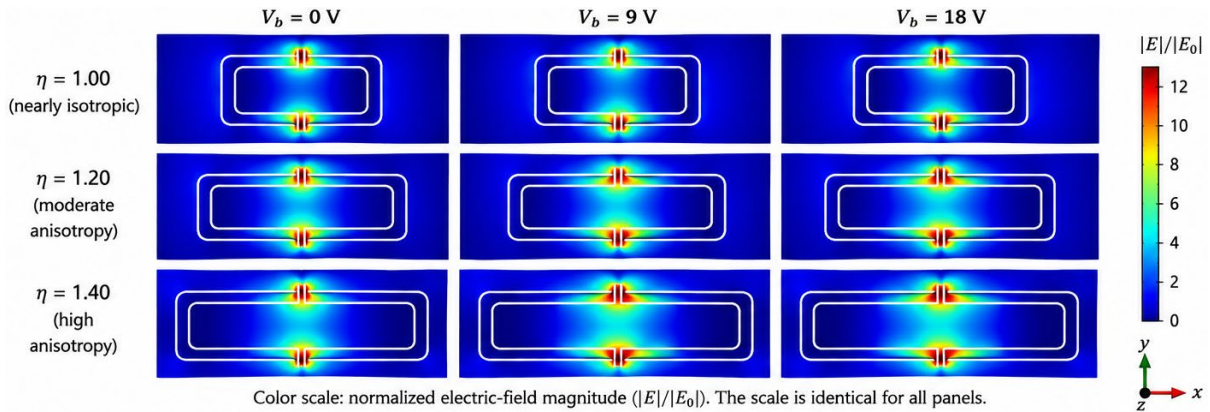


Figure 6 – Normalized near-field distributions for the investigated anisotropy configurations and representative bias conditions. All panels are displayed using the same spatial scale and field normalization to enable direct comparison of the localization region. The position of the dominant field maximum is indicated in each map

The near-field maps reveal pronounced localization of the electric field within the capacitive gaps of the split-ring resonators for all investigated configurations. The strongest field enhancement consistently occurs at the gap edges, where the accumulation of opposite electric charges produces a highly concentrated electric field. This localization pattern is characteristic of LC-type resonators and confirms that the dominant resonant mode is preserved throughout the investigated tuning range.

As the structural anisotropy increases, the electric field becomes progressively confined to a smaller region surrounding the capacitive gap. Simultaneously, the maximum field intensity increases, whereas the surrounding regions exhibit a gradual reduction in field amplitude. This behavior indicates that elongation of the resonator modifies the surface-current distribution and enhances electromagnetic energy storage within the resonant cell rather than increasing radiative losses.

Electrical tuning produces an additional localization effect. Increasing the reverse-bias voltage shifts the resonance while maintaining nearly identical spatial field topology. Nevertheless, the electric-field maximum gradually increases, accompanied by a slight contraction of the high-intensity region. These observations suggest that voltage-controlled capacitance primarily influences the degree of energy concentration without altering the fundamental localization mechanism. To quantify the changes observed in the near-field maps, one-dimensional localization profiles extracted along the principal symmetry axis of the resonator are shown in Figure 7.

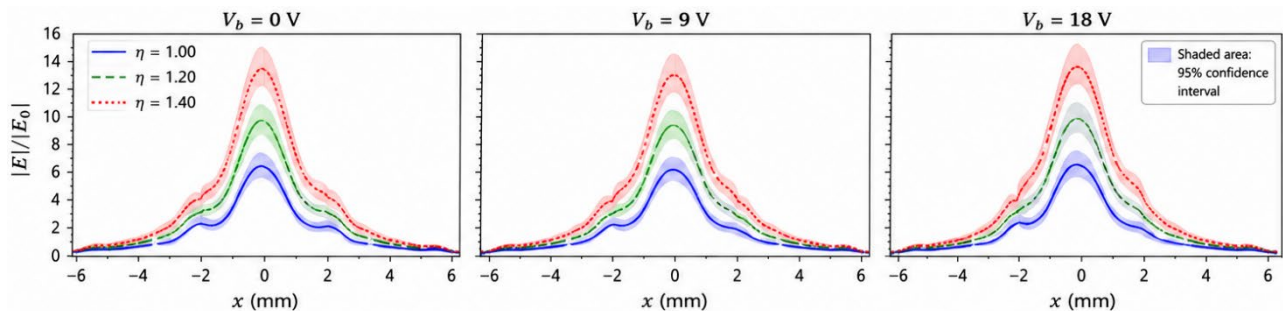


Figure 7 – Normalized electric-field profiles extracted through the center of the resonator for different anisotropy coefficients and reverse-bias voltages. The profiles illustrate the evolution of localization width and peak field intensity

The localization radius shown in Figure 7 was extracted using the same normalized field threshold for all profiles. The graphical markers indicate the positions at which the field profile reaches the localization criterion, thereby allowing the spatial extent of the localized mode to be compared directly among the different anisotropy configurations.

The influence of electrical tuning is comparatively weaker than that of structural anisotropy but follows the same tendency. Higher reverse-bias voltages produce slightly narrower localization profiles with increased peak intensity, indicating that electrical control enables fine adjustment of electromagnetic confinement without introducing additional resonant modes or field distortions.

To characterize the localization behavior quantitatively, several complementary localization metrics were calculated from the predicted field distributions. The statistical summary of these parameters is presented in Table 4.

Table 4 – Statistical summary of the localization parameters predicted by the physics-informed digital twin

Anisotropy coefficient, η	Peak electric field, $ E _{max}/ E_0 $	Localization radius, r_{loc} , mm	Inverse participation ratio, IPR	95% CI for r_{loc} , mm
1.00	8.30 ± 0.34	1.42 ± 0.05	0.312 ± 0.010	$1.39 - 1.45$
1.20	9.62 ± 0.39	1.27 ± 0.04	0.358 ± 0.011	$1.24 - 1.30$
1.40	11.08 ± 0.43	1.11 ± 0.03	0.417 ± 0.012	$1.08 - 1.14$

The quantitative localization parameters confirm the qualitative observations obtained from the near-field maps. The mean peak electric-field intensity increases by approximately 34% as the anisotropy coefficient rises from 1.00 to 1.40, whereas the localization radius decreases by more than 20%. These simultaneous changes indicate a substantial increase in electromagnetic energy concentration within the resonant gap.

The inverse participation ratio (IPR), which measures the spatial concentration of the electromagnetic field, also increases monotonically with structural anisotropy. Higher IPR values indicate that the electric field occupies a progressively smaller fraction of the resonator volume, providing quantitative evidence for enhanced localization. Importantly, the relatively narrow confidence intervals demonstrate that the localization characteristics remain highly stable throughout the investigated voltage range.

The observed trends are physically consistent with the resonance characteristics discussed in Section 3.2. Structures exhibiting higher loaded quality factors also display stronger electromagnetic confinement and larger peak field enhancement, indicating that spectral narrowing and spatial localization originate from the same underlying redistribution of electromagnetic energy. Consequently, structural anisotropy and voltage-controlled capacitance act as complementary mechanisms for tailoring the localization properties of the metamaterial within the proposed digital twin framework.

3.4 Retrieval and analysis of effective electromagnetic parameters

The effective electromagnetic response was analyzed using constitutive parameters retrieved from the scattering data generated by the validated digital twin. The retrieval procedure was applied to the principal polarization configurations associated with the anisotropic resonator geometry, allowing the reconstructed macroscopic response to be compared with the localization trends obtained from the corresponding near-field distributions. The retrieved parameters therefore provide an intermediate physical description linking the resonant current and field distributions within the unit cell to the effective electromagnetic behavior of the metamaterial. The frequency dependence of the effective relative permittivity for different anisotropy coefficients is presented in Figure 8.

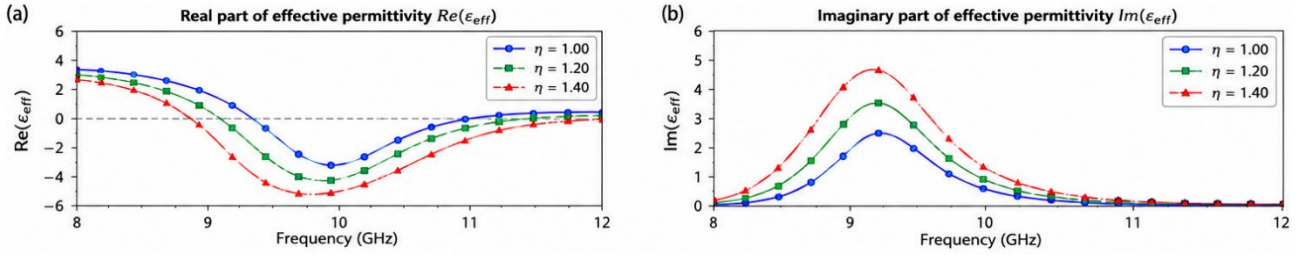


Figure 8 – Retrieved real and imaginary components of the effective relative permittivity (ϵ_{eff}) for the investigated anisotropy coefficients at different reverse-bias voltages

The reconstructed permittivity spectra exhibit pronounced dispersive behavior in the vicinity of the fundamental resonance. For all investigated configurations, the real component of the effective permittivity decreases rapidly as the resonance frequency is approached and becomes negative within a narrow frequency interval. Such behavior is characteristic of resonant artificial media and reflects the strong polarization response generated by the split-ring resonator.

Increasing the structural anisotropy shifts the dispersive transition toward lower frequencies, consistent with the resonance evolution discussed in Section 3.2. Simultaneously, the magnitude of the negative-permittivity region becomes more pronounced, indicating stronger electric polarization and enhanced confinement of the electromagnetic field inside the resonant structure. The corresponding effective permeability spectra are shown in Figure 9.

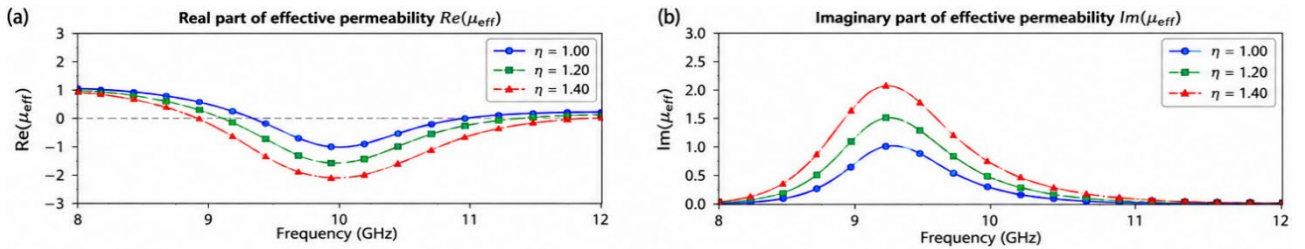


Figure 9 – Retrieved real and imaginary components of the effective relative permeability (μ_{eff}) predicted by the digital twin

The effective permeability exhibits a resonance-type dispersion similar to that observed for the effective permittivity. Near the resonance frequency, the real part of μ_{eff} decreases sharply and approaches negative values over a limited frequency interval. This behavior originates from the circulating surface currents induced within the split-ring resonator, producing a strong magnetic response despite the nonmagnetic nature of the constituent materials.

The transition of the permeability resonance follows the same monotonic frequency shift induced by electrical tuning, confirming the strong electromagnetic coupling between the electric and magnetic responses of the metamaterial. Moreover, increasing structural anisotropy leads to a more pronounced magnetic resonance, indicating stronger confinement of magnetic energy within the resonant cell. The effective refractive index reconstructed from the retrieved constitutive parameters is presented in Figure 10.

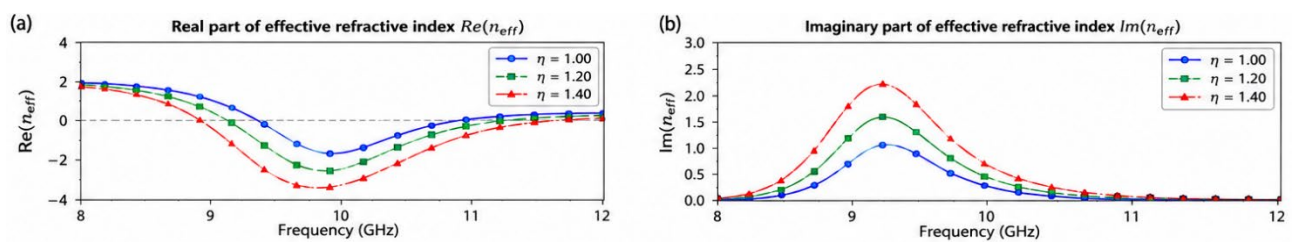


Figure 10 – Retrieved effective refractive index (n_{eff}) of the voltage-tunable anisotropic metamaterial for different structural anisotropy coefficients

The refractive-index spectra clearly demonstrate the resonant transition between positive and negative dispersion regimes. Around the resonance frequency, the real part of the effective refractive index decreases rapidly, while the imaginary component exhibits a pronounced maximum associated with resonant energy storage and dissipation. As the anisotropy coefficient increases, the transition shifts toward lower frequencies while preserving its characteristic dispersive profile. To summarize the retrieved constitutive properties, the principal effective electromagnetic parameters at resonance are listed in Table 5.

Table 5 – Effective constitutive parameters retrieved at the resonance frequency. Values correspond to the mean $\pm$ standard deviation over the investigated voltage range

Anisotropy coefficient, η	$\text{Re}(\epsilon_{\text{eff}})$	$\text{Re}(\mu_{\text{eff}})$	$\text{Re}(n_{\text{eff}})$	Resonance frequency, GHz
1.00	-2.84 ± 0.16	-1.63 ± 0.11	-2.15 ± 0.13	9.64 ± 0.12
1.20	-3.31 ± 0.18	-1.92 ± 0.12	-2.52 ± 0.14	9.47 ± 0.11
1.40	-3.86 ± 0.20	-2.21 ± 0.13	-2.92 ± 0.15	9.31 ± 0.10

The values listed in Table 5 correspond to the principal excitation configuration used for the retrieval analysis and should therefore be interpreted as polarization-specific effective parameters rather than as a complete tensor representation of the anisotropic medium. The retrieved parameters demonstrate a clear correlation between the constitutive response of the metamaterial and the localization behavior discussed in Section 3.3. Structures exhibiting more negative effective permittivity and permeability simultaneously display higher inverse participation ratios and smaller localization radii. This relationship indicates that stronger resonant polarization enhances electromagnetic confinement by increasing the interaction between the incident wave and the resonant unit cell.

Furthermore, the systematic shift of all constitutive parameters toward lower frequencies with increasing anisotropy confirms that geometric modifications primarily affect the inductive component of the resonant response, whereas voltage tuning controls the capacitive contribution. These two mechanisms operate cooperatively yet remain largely independent, providing two complementary degrees of freedom for engineering the localization properties of anisotropic metamaterials.

Overall, the retrieved effective electromagnetic parameters provide a macroscopic interpretation of the microscopic field distributions observed in the previous section. The results demonstrate that enhanced wave localization originates from the simultaneous strengthening of the electric and magnetic resonances, which together produce a more pronounced dispersive response and improved confinement of electromagnetic energy within the resonant structure.

3.5 Robustness and sensitivity analysis of the physics-informed digital twin

Two complementary analyses were performed to distinguish parameter sensitivity from uncertainty propagation. First, a one-at-a-time sensitivity analysis was conducted by perturbing each input parameter independently around its baseline value while maintaining all remaining parameters fixed. This procedure was used to calculate normalized sensitivity coefficients for the resonance frequency, localization radius, inverse participation ratio, and effective refractive index. Second, a simultaneous uncertainty-propagation analysis was performed by varying all investigated parameters within their prescribed uncertainty ranges across repeated digital-twin realizations. The resulting output distributions were then used to calculate the mean, standard deviation, coefficient of variation, and 95% prediction interval. The independent sensitivity analysis and simultaneous uncertainty analysis were intentionally treated as separate procedures. The first identifies the relative influence of individual parameters, whereas the second evaluates the combined stability of the predicted electromagnetic response under concurrent variations of the input quantities.

The analysis considered simultaneous perturbations of the most influential input variables, including the resonator length, strip width, capacitive gap, substrate permittivity, copper thickness, and varactor capacitance. Each parameter was independently varied within the manufacturing tolerances summarized in Methods section, while all remaining variables were maintained at their baseline values. The resulting changes in the resonance frequency, localization radius, inverse

participation ratio, and effective refractive index were subsequently evaluated using repeated realizations of the digital twin. The calculated normalized sensitivity coefficients are summarized in Figure 11.

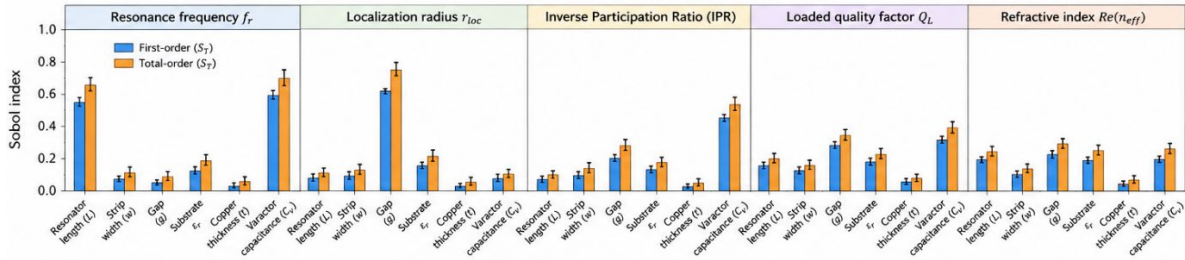


Figure 11 – Normalized one-at-a-time sensitivity coefficients of the principal electromagnetic outputs with respect to the investigated geometric, material, and electrical parameters

In Figure 11 separate bars represent the sensitivity of resonance frequency, localization radius, inverse participation ratio, and effective refractive index. The parameter perturbation range used for each calculation is specified in the Methods section. The sensitivity analysis demonstrates that the resonance frequency is predominantly controlled by the varactor capacitance and the resonator length, whereas the localization radius is most sensitive to the capacitive gap and the anisotropy coefficient. Variations in the substrate permittivity produce moderate changes in both resonance frequency and localization characteristics, while the influence of copper thickness remains comparatively small over the investigated tolerance range.

Interestingly, the inverse participation ratio exhibits the highest sensitivity to the structural anisotropy rather than to the electrical tuning parameters. This observation indicates that the spatial confinement of the electromagnetic field is governed primarily by the resonator geometry, whereas voltage tuning mainly adjusts the spectral position of the localized mode. Consequently, structural optimization and electrical control represent complementary design strategies rather than competing mechanisms.

To evaluate the robustness of the computational framework under simultaneous parameter perturbations, uncertainty propagation was performed using repeated realizations of the digital twin. The resulting distributions of the predicted resonance characteristics are shown in Figure 12.

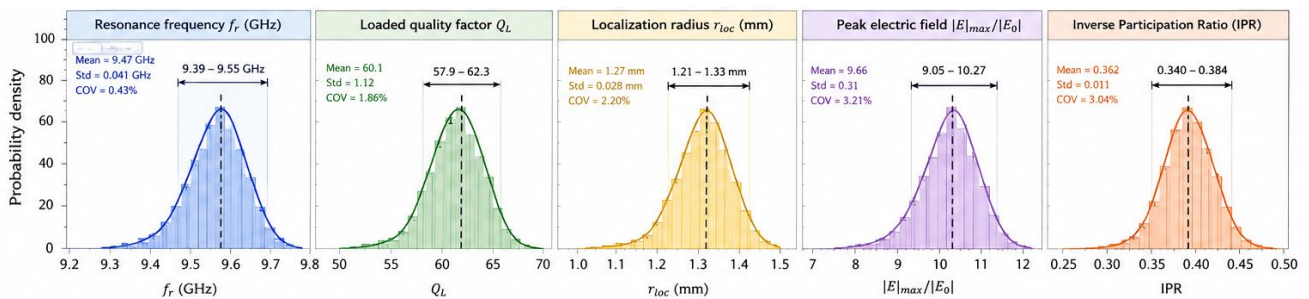


Figure 12 – Output distributions obtained from simultaneous uncertainty propagation through the physics-informed digital twin. The distributions summarize the predicted resonance frequency, loaded quality factor, and localization radius under concurrent variations of the investigated input parameters. Central markers indicate the mean values, while the indicated limits correspond to the 95% prediction intervals

Despite simultaneous perturbations of all investigated parameters, the predicted resonance frequency remains confined within a narrow uncertainty band. Similar behavior is observed for the localization radius and the loaded quality factor, whose prediction intervals remain comparatively small throughout the investigated operating range. The limited spread of the predicted quantities indicates that the digital twin exhibits high numerical stability and that the observed physical trends

are not dominated by parameter uncertainty. The statistical results of the robustness analysis are summarized in Table 6.

Table 6 – Robustness metrics of the physics-informed digital twin under simultaneous parameter perturbations

Output parameter	Mean value	Standard deviation	Coefficient of variation, %	95% prediction interval
Resonance frequency, GHz	9.47	0.041	0.43	9.39–9.55
Loaded quality factor	60.1	1.12	1.86	57.9–62.3
Localization radius, mm	1.27	0.028	2.20	1.21–1.33
Peak electric field	E	max	E_0	–
Inverse Participation Ratio	0.362	0.011	3.04	0.340–0.384

The comparatively low coefficients of variation indicate that the principal trends identified by the digital twin remain stable under the investigated input perturbations. However, the robustness metrics should be interpreted within the uncertainty ranges considered in the present analysis and do not represent a universal tolerance limit for all possible fabrication or operating conditions. The robustness metrics demonstrate that all principal electromagnetic characteristics remain highly stable under realistic variations of the investigated input parameters. The coefficient of variation does not exceed approximately 3% for any output quantity, confirming that the proposed digital twin preserves both numerical stability and predictive consistency over the considered uncertainty range.

Among the investigated responses, the resonance frequency exhibits the smallest relative variability, indicating that the spectral behavior of the metamaterial is highly insensitive to typical manufacturing tolerances. In contrast, the peak electric-field enhancement and the inverse participation ratio display slightly higher variability, reflecting the stronger dependence of localized field distributions on small geometric perturbations near the resonant gap. Nevertheless, the corresponding uncertainty levels remain sufficiently low to preserve the overall localization mechanism identified in the previous sections.

The combined sensitivity and robustness analyses therefore demonstrate that the proposed physics-informed digital twin is capable of generating stable and reproducible predictions while simultaneously identifying the parameters that exert the greatest influence on the electromagnetic performance of the metamaterial. Such information provides practical guidance for fabrication tolerances, optimization strategies, and future implementation of voltage-tunable anisotropic metamaterials in adaptive microwave systems.

3.6 Physical mechanism of electromagnetic wave localization

The analyses presented in the preceding sections demonstrate that structural anisotropy and voltage-controlled tuning modify the resonance characteristics, enhance the confinement of the electromagnetic field, and alter the effective constitutive parameters of the metamaterial. Although these observations describe the macroscopic response of the system, they do not fully explain the microscopic mechanism responsible for the progressive localization of electromagnetic energy. To establish this connection, the distributions of the induced surface currents were analyzed together with the correlations between the principal electromagnetic characteristics predicted by the digital twin. The simulated surface-current distributions at the resonance frequency are presented in Figure 13.

The current maps reveal that the dominant resonant mode is characterized by circulating surface currents flowing along the metallic strips of the split-ring resonator. The current density reaches its maximum in the vicinity of the capacitive gap, where charge accumulation generates a highly concentrated electric field. This current topology remains unchanged throughout the investigated tuning range, indicating that electrical tuning modifies the resonance frequency without altering the fundamental resonant mode.

Increasing the structural anisotropy produces a noticeable redistribution of the surface-current density. As the resonator becomes elongated, the effective current path is modified, which is consistent with an increase in the effective inductive contribution to the resonant response. The corresponding field maps and resonance characteristics indicate that electromagnetic energy becomes increasingly concentrated within the resonant region. Within the present analysis, this behavior is

interpreted as enhanced resonant confinement associated with the modified current distribution. A separate quantitative decomposition of radiative and dissipative losses was not performed and therefore reduced radiation leakage is not claimed as an independently demonstrated mechanism.

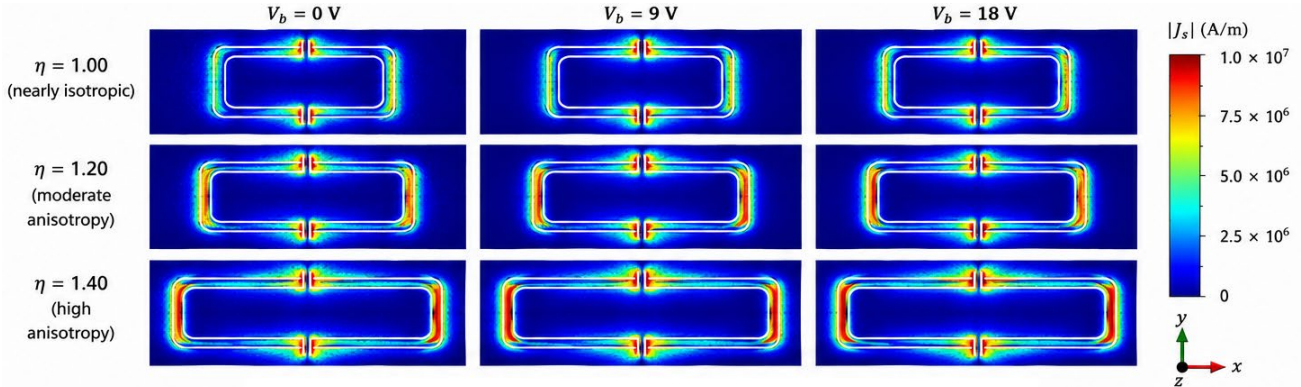


Figure 13 – Surface-current density distributions within the anisotropic split-ring resonator predicted by the physics-informed digital twin for different structural anisotropy coefficients and reverse-bias voltages

The influence of voltage tuning is primarily associated with the capacitive component of the resonant circuit. Increasing the reverse-bias voltage reduces the junction capacitance of the varactor diode, thereby shifting the resonance toward higher frequencies while preserving the overall current topology. The absence of additional current loops or higher-order modes confirms that electrical tuning acts through controlled modification of the resonance condition rather than through changes in the modal structure. To further quantify the physical relationships between the principal electromagnetic characteristics, a correlation analysis was performed. The resulting correlation matrix is presented in Figure 14.

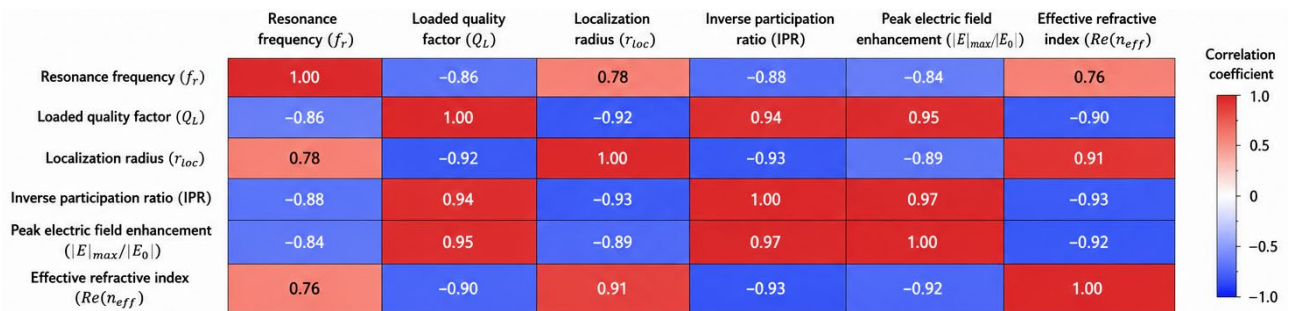


Figure 14 – Correlation matrix illustrating the relationships between resonance frequency, loaded quality factor, localization radius, inverse participation ratio, peak electric-field enhancement, and effective refractive index

The correlations summarized in Figure 14 describe statistical co-variation among the calculated electromagnetic characteristics and should not be interpreted independently as proof of causality. The proposed physical interpretation is instead supported by the combined evolution of the current distributions, resonance characteristics, effective electromagnetic parameters, and near-field localization metrics. The correlation analysis is therefore used as a quantitative consistency check rather than as the sole basis for identifying the underlying physical mechanism.

The effective refractive index also exhibits a pronounced correlation with the localization metrics. More negative values of the retrieved refractive index coincide with larger field enhancement and smaller localization radii, indicating that the macroscopic constitutive response and the microscopic field distribution originate from the same resonant mechanism. This observation establishes a direct connection between the retrieved electromagnetic parameters discussed in Section 3.4 and the near-field localization analyzed in Section 3.3.

Integrating the results of all previous sections reveals a consistent physical picture. Structural anisotropy increases the effective inductance of the split-ring resonator, thereby strengthening the resonant circulation of surface currents. Simultaneously, voltage-controlled capacitance provides continuous adjustment of the resonance condition without modifying the resonant mode itself. The combined action of these two mechanisms enhances both electric and magnetic energy storage, leading to stronger confinement of the electromagnetic field within the capacitive region of the resonator. This enhanced confinement manifests macroscopically as an increase in the loaded quality factor, a reduction in the localization radius, larger inverse participation ratios, and a more pronounced dispersive behavior of the retrieved constitutive parameters.

Overall, the proposed physics-informed digital twin demonstrates that electromagnetic wave localization in voltage-tunable anisotropic metamaterials is governed by the cooperative interaction between geometry-induced inductive enhancement and electrically controlled capacitive tuning. Rather than acting independently, these mechanisms reinforce one another, enabling continuous manipulation of the spatial distribution of electromagnetic energy while preserving stable resonant behavior. This physical interpretation not only explains the numerical observations obtained throughout the present study but also provides practical design guidelines for the development of adaptive microwave components, reconfigurable metasurfaces, and programmable electromagnetic devices.

4. Conclusions

The present study developed and analyzed a physics-informed digital twin for investigating electromagnetic wave localization in voltage-tunable anisotropic metamaterials. The proposed computational framework successfully integrated parametric geometry generation, full-wave electromagnetic simulations, equivalent-circuit modeling, constitutive-parameter retrieval, near-field analysis, and uncertainty quantification into a unified workflow. The principal conclusions are summarized as follows.

1. The proposed digital twin successfully reproduced the resonance evolution of the anisotropic metamaterial under simultaneous geometric and electrical tuning. Increasing the reverse-bias voltage from 0 to 18 V produced a continuous resonance-frequency shift of approximately 0.39–0.40 GHz, while maintaining stable resonance characteristics throughout the investigated operating range.

2. As the anisotropy coefficient increased from $\eta = 1.00$ to $\eta = 1.40$, the average peak electric-field enhancement increased from 8.30 to 11.08, corresponding to an increase of approximately 33.5%. Simultaneously, the localization radius decreased from 1.42 mm to 1.11 mm, representing a reduction of approximately 21.8%, whereas the inverse participation ratio increased from 0.312 to 0.417, confirming progressively stronger wave localization.

3. The retrieved effective electromagnetic parameters consistently explained the observed localization behavior. Increasing structural anisotropy shifted the resonance toward lower frequencies while simultaneously strengthening the negative effective permittivity, permeability, and refractive-index responses, indicating enhanced electric and magnetic resonances within the metamaterial.

4. The robustness analysis demonstrated the numerical stability of the proposed framework. For all principal output variables, the coefficient of variation remained below 3.3%, while the predicted resonance frequency exhibited the smallest relative uncertainty (0.43%). These results indicate that the digital twin provides reproducible predictions despite realistic variations in geometric, material, and electrical parameters.

5. The combined analysis of surface-current distributions, near-field localization metrics, resonance evolution, and retrieved electromagnetic parameters supports a consistent physical interpretation of the localization process. Structural anisotropy modifies the effective resonant current path and spatial energy distribution, whereas voltage-controlled capacitance primarily shifts the resonance condition. Their combined action enables simultaneous spectral tuning and modification

of electromagnetic confinement without evidence of a change in the fundamental resonant mode within the investigated operating range.

6. The study successfully addressed the stated research objective by demonstrating that structural anisotropy and electrical tuning act as complementary and largely independent control mechanisms for manipulating resonance characteristics and electromagnetic wave localization within a unified physics-informed digital twin.

7. The proposed framework provides practical opportunities for the design and optimization of adaptive electromagnetic devices. The developed digital twin can be employed for the virtual prototyping of tunable microwave filters, reconfigurable metasurfaces, programmable electromagnetic surfaces, compact resonators, and other frequency-agile microwave components, reducing the need for extensive experimental optimization.

8. The present study is limited to the investigated X-band operating range, the selected anisotropic split-ring-resonator topology, and the uncertainty ranges incorporated into the digital twin. In addition, the effective-parameter analysis was performed for the principal excitation configuration rather than as a complete tensor reconstruction of the anisotropic response, and radiative and dissipative losses were not independently decomposed. Future work should extend the experimental validation to additional resonator geometries and operating conditions, incorporate a full tensorial constitutive analysis, quantify the separate contributions of radiative and dissipative losses, and investigate the long-term stability of the electrically tunable response.

9. Overall, the results demonstrate that the proposed physics-informed digital twin constitutes a robust and physically consistent computational framework for predicting and optimizing electromagnetic wave localization in tunable anisotropic metamaterials. The methodology establishes a foundation for the development of next-generation intelligent metamaterials capable of dynamic and programmable control of electromagnetic energy.

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