

Article

Dual-Band Electromagnetic Shielding of Concrete Block Walls Using Concentric Double Square-Ring Frequency-Selective Surfaces near the n78 and n79 5G Frequency Regions

Mehmet Cakir 

Department of Electrical and Electronics Engineering, Bayburt University, 69000 Bayburt, Türkiye;
mcakir@bayburt.edu.tr

Featured Application

This study demonstrates a concrete-integrated dual-band frequency-selective shielding approach for selectively attenuating the main sub-6 GHz 5G n78 and n79 frequency regions in building walls without increasing wall thickness or altering conventional concrete block geometry.

Abstract

This paper presents a dual-band shielding approach in which two concentric square rings, fabricated on a single 0.2 mm copper sheet, are embedded in the mortar joint of prefabricated concrete blocks. The outer ring targets n78 (design center 3.5 GHz) and the inner ring targets n79 (design center 4.7 GHz). Both rings are dimensioned from the effective wavelength inside the concrete medium ($\epsilon_r = 5.0$): the outer ring has an outer side of 9.93 mm and the inner ring an outer side of 7.43 mm, with a 180° gap offset between the two elements to suppress inter-ring coupling. CST Microwave Studio simulations predicted two shielding peaks of 37.2 dB at 3.48 GHz and 35.8 dB at 4.72 GHz, with -10 dB bandwidths of 580 MHz and 490 MHz, respectively. Computer numerical control (CNC)-milled copper panels cast into ordinary Portland cement (OPC) concrete blocks achieved measured peak SE of 34.9 dB (n78) and 33.4 dB (n79), with bandwidths of 510 MHz and 420 MHz. The 2.3–2.4 dB shortfall relative to simulation is attributed to coupling-gap drift during milling and spacer-induced surface voids. A permittivity sweep from $\epsilon_r = 4.5$ to 6.0 showed that peak SE remains above 30 dB throughout.

Keywords: dual-band electromagnetic shielding; concentric square-ring resonator; frequency-selective surface



Academic Editors: Roberto Zivieri
and George Kliros

Received: 5 May 2026

Revised: 31 May 2026

Accepted: 15 June 2026

Published: 17 June 2026

Copyright: © 2026 by the author.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Wireless networks have grown fast, and the buildings that house sensitive equipment are only now catching up with what that means electromagnetically. Hospitals, industrial control rooms, secure data centers, and communication infrastructure facilities increasingly need some form of targeted frequency control—not just general attenuation. Classical shielding theory frames the problem in terms of reflection, absorption, multiple reflections, aperture effects, and material conductivity and permeability [1], but that framing misses something important in modern communication environments: broadband shielding can suppress useful wireless signals alongside the interference you actually want to block. Frequency-selective structures—ones that attenuate a specific band while leaving the rest of

the spectrum essentially untouched—have therefore attracted serious attention as a more surgical alternative [2,3].

Concrete is the obvious starting point for building-integrated shielding, simply because it is everywhere. The difficulty is that ordinary cementitious materials are poor electromagnetic attenuators unless something conductive or absorptive is deliberately introduced. Earlier work on concrete buildings established that shielding effectiveness is shaped by material properties, wall geometry, reinforcement arrangement, and moisture content, and made the case that electromagnetic performance should be part of the architectural design conversation rather than an afterthought [4]. Hyun et al. extended this line of thinking to extreme environments, analyzing reinforced concrete under high-altitude electromagnetic pulse conditions and showing that embedded rebars and layered reinforcement improve attenuation—though the response is fundamentally structural and non-selective, with no particular affinity for any specific frequency band [5].

A number of groups have tried to push concrete shielding further by modifying the mix. Steel fibers, metallic grids, wire meshes, high-ductility cementitious layers, and hybrid reinforcement systems have all been tested. Yuan et al. worked through several combinations—steel fibers, metallic grids, metallic meshes, and hybrids—and found that mesh and hybrid grid/mesh systems outperform ordinary reinforced concrete by a significant margin [6]. Lee et al. added impact resistance to the picture, demonstrating that high-strength high-ductility concrete improves both shielding and structural toughness simultaneously [7]. These are useful results for protective construction, but the shielding mechanism in each case is bulk conductivity and reinforcement density. Neither study produces the kind of targeted dual-band response that the n78 and n79 frequency regions require.

Sustainable fillers represent another branch of this work. Ruscica et al. looked at cement composites incorporating biochar and recycled PVC and obtained measurable improvements in the C-band [8]—a result that matters both electromagnetically and from a circular-economy standpoint. The drawback is that the filler approach generally shares the following: performance tends to be moderate and spread across a broad frequency range, sensitive to filler content, dispersion quality, thickness, and mix homogeneity. For reducing ambient EMI in a general sense, these materials are worth considering. For suppressing two specific 5G bands while leaving everything else alone, they are not well suited.

Frequency-selective surfaces offer a fundamentally different kind of control. An FSS is a periodic conductive pattern that functions as a spatial electromagnetic filter—its transmission and rejection behavior determined by the unit-cell geometry, the substrate, the array periodicity, and the angle of incidence. De Sabata et al. produced a stopband spanning 1.75 to 15.44 GHz from a single structure, with good polarization insensitivity and angular stability [9]. Chatterjee et al. covered the 3.2–8.82 GHz range with a monolayer design and similar angular performance [10]. The shielding figures in both studies are strong. What they do not address is what happens when you try to move the structure off an FR-4 board and into a concrete joint—a transition that changes the surrounding dielectric environment entirely.

The 5G-specific literature has added considerably to the resonator design space. Hakim et al. built a triple-band square split-ring resonator metamaterial absorber hitting 2.5, 4.9, and 6.0 GHz on FR-4 [11]. Rahman et al. produced a near-perfect absorber at 2.40, 3.50, and 6.09 GHz for Wi-Fi and 5G applications [12]. Jahan et al. went further with a quad-band design based on a double X-shaped ring resonator, showing that ring-derived geometries can support four distinct absorption bands at once [13]. These absorber studies demonstrate what compact resonant unit cells can do in terms of multiband frequency control. The

substrate, however, is always an engineered dielectric—FR-4 or similar—and no attempt is made to integrate the structure into concrete.

Higher-frequency work extends the picture. Idrees et al. reported a miniaturized polarization-independent FSS producing at least 33 dB shielding around 10 GHz with a 26% rejection bandwidth [14]. Hakim et al. targeted 27.09, 38.71, and 41.81 GHz with an interconnected square split-ring resonator metamaterial for mmWave 5G applications [15]. An ultra-miniaturized conformal FSS for the n257 band at 27.84 GHz followed, combining angular stability with polarization insensitivity [16]. Ud Din et al. demonstrated FSS integration within 5G millimeter-wave MIMO antenna systems, confirming that FSS thinking extends beyond shielding panels into device-level electromagnetic management [17]. These studies collectively show how scalable the FSS approach is—but their frequencies, substrates, and operating contexts sit at some distance from what concrete-embedded sub-6 GHz shielding requires.

Two families of work are particularly relevant to what follows here. Manoharan et al. tackled dual-band FSS design across 1–6 GHz for 5G communication environments, making the case directly for dual-band frequency selectivity in this frequency window [18]. Fan et al. showed that square-ring FSS geometry can be tuned through deformation-induced coupling changes using a kirigami metasurface approach [19]. Shukoor and Dey demonstrated that concentric circular-ring configurations can support a remarkable number of controlled resonances simultaneously, with polarization insensitivity and wide angular stability maintained throughout [20]. What these studies collectively suggest is that ring and square-ring resonators are a solid basis for multiband electromagnetic control. The complication that arises when multiple rings share a unit cell is inter-element coupling, which can shift resonance frequencies, erode stopband depth, or introduce spurious responses between the intended bands. Coupling management, in other words, is not a secondary concern; it is part of the design problem.

Building integration of FSS has been explored from an architectural perspective as well. Cuiñas et al. surveyed FSS as smart electromagnetic skins in building envelopes, covering filtering, insulation, energy management, and broader building-integrated electromagnetic functionality [21]. Nguyen et al. showed concretely that FSS patterns applied to window glass can provide 5G indoor communication filtering without compromising the structural role of the glazing [22]. Flexible and textile FSS studies show that substrate type, surface texture, printing method, and mechanical deformation all affect the electromagnetic response considerably [3]. Strain-invariant metasurfaces for wearable shielding make a related point: selective shielding can preserve wanted communication bands while blocking unwanted ones [2]. The common thread in nearly all of this work, though, is that the FSS lives on glass, a façade surface, a flexible film, or a textile. Embedding it inside a mortar joint—where it disappears permanently into the masonry during normal wall construction—has been largely unexplored, despite being attractive precisely because it requires no extra wall thickness and leaves no visible trace.

Recent studies on electromagnetic functional materials also show that EMI shielding is increasingly moving beyond simple conductive attenuation toward microstructure-controlled, multifunctional and application-specific material platforms. Qiao et al. developed basalt-fiber-based multifunctional shielding fabrics through plasma activation, ALD bridging, chemical plating and post-annealing treatments; the optimized material achieved an EMI shielding effectiveness of 53.47 dB while also providing adaptive structural color and thermal camouflage functionality [23]. Yan et al. demonstrated that ceramic connectivity strongly affects the microwave dielectric properties of ultralow- ϵ_r Al_2O_3 porous ceramics, showing that microstructural connectivity can regulate ϵ_r , Q_f and temperature stability [24]. Liang et al. developed trace-Fe-injected activated carbon and a

magnetic–dielectric–magnetic sandwich absorber, achieving a broad effective absorption bandwidth of 6.9–15.9 GHz with angular stability up to 50° for both polarization states [25]. These recent studies confirm that modern electromagnetic shielding and microwave functional materials are increasingly governed by microstructural design, multifunctionality and application-specific integration. However, these material-centered approaches are not concrete-embedded frequency-selective surfaces and do not directly address dual-band sub-6 GHz n78/n79 suppression. The present work, therefore, complements this recent literature by focusing on a building-integrated, frequency-selective and experimentally validated FSS embedded inside an OPC concrete mortar joint.

For sub-6 GHz 5G, the n78 and n79 bands present a specific challenge. n78 sits around 3.3–3.8 GHz; n79 covers roughly 4.4–5.0 GHz. A structure that handles one of these regions reliably will not necessarily do anything useful at the other. Dual-band suppression is therefore the practical requirement. Compounding this, a concrete-embedded FSS design cannot use free-space wavelengths for dimensioning—the dielectric loading of the host medium compresses the effective wavelength, and ignoring it shifts the resonance away from the intended band. Concrete permittivity is also not a fixed number; it varies with mix design, moisture state, curing history, and aggregate distribution [4,5], which makes parametric validation against this variability an essential part of any design that claims practical relevance rather than just simulation accuracy.

This paper proposes a dual-band concentric double square-ring FSS for shielding concrete block walls in the n78 and n79 regions. Two concentric square copper rings, cut from 0.2 mm sheet and dimensioned against the effective wavelength in concrete, are embedded in the mortar joint of OPC concrete blocks. The outer ring targets n78 around 3.5 GHz; the inner ring targets n79 around 4.7 GHz. A 180° gap-offset between the two rings reduces inter-ring coupling and keeps the two stopbands distinct. Unlike the FR-4, Rogers, glass, flexible film, textile, and surface-mounted configurations that dominate the prior literature [2,3,9–22], the proposed structure is experimentally validated inside concrete. To the authors’ knowledge, no published study has previously demonstrated a dual-band concentric double square-ring FSS embedded in a concrete mortar joint for simultaneous n78 and n79 suppression.

2. Materials and Methods

The study followed five sequential stages: analytical dimension calculation for both rings, inter-ring coupling analysis, full-wave CST simulation, panel fabrication and concrete casting, and free-space dual-band SE measurement. Full-wave simulations were performed using CST Studio Suite 2024 (Dassault Systèmes, Vélizy-Villacoublay, France). A mesh sensitivity study before geometry finalization showed a 45 MHz shift in the n78 resonance and a 30 MHz shift in the n79 resonance between coarse and fine meshes, confirming that mesh refinement was necessary before fabrication. The proposed concrete-integrated FSS configuration is illustrated in Figure 1, including the top-view copper FSS layout on the OPC concrete block and the layered embedding structure within the mortar joint.

To verify the numerical stability of the CST simulation model, a mesh-convergence analysis was performed before finalizing the dual-ring geometry. Four successive mesh-refinement levels were evaluated by comparing the resonant frequencies, peak shielding effectiveness values and the maximum variation in $|S_{21}|$. The results are summarized in Table 1. The transition from the coarse to the medium mesh produced noticeable changes in both resonances, indicating that the coarse mesh was not sufficient for the narrow dual-ring gaps and inter-ring clearance. However, after the fine mesh level, the resonance frequencies and peak SE values changed only marginally. The final model used

approximately 340,000 tetrahedral elements after six adaptive passes, and the variation in $|S_{21}|$ was below 1%. Therefore, the fine mesh was selected for the final simulations.

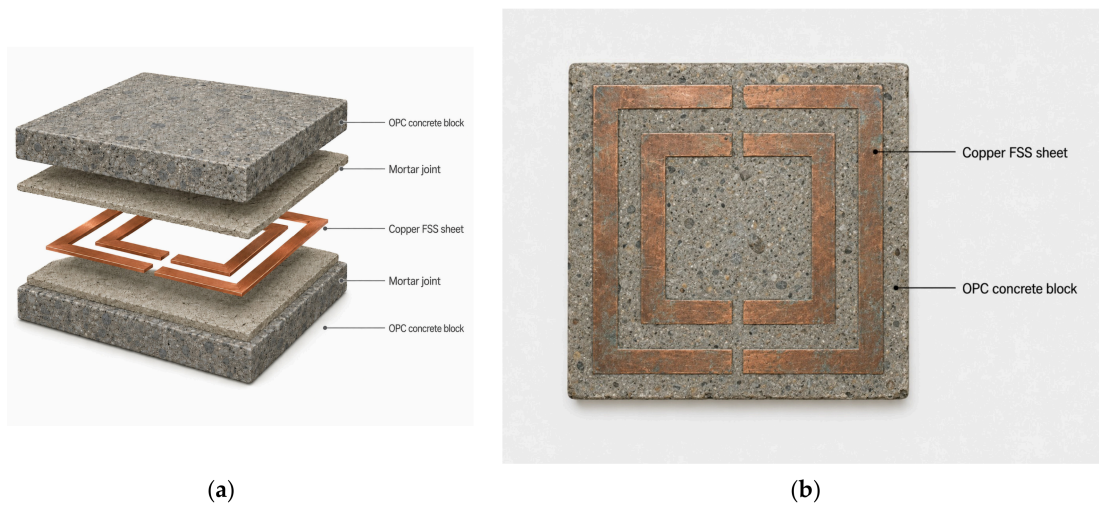


Figure 1. Representative illustrations of the proposed concrete-integrated FSS configuration: (a) layered representation showing the copper FSS sheet embedded inside the mortar joint between two OPC concrete blocks; (b) representative top-view illustration of a concentric double square-ring FSS unit cell placed on an OPC concrete block.

Table 1. Mesh-convergence verification of the CST simulation model.

Mesh Level	Approx. No. of Tetrahedral Elements	Adaptive Passes	n78 Resonance Frequency (GHz)	n79 Resonance Frequency (GHz)	n78 Peak SE (dB)	n79 Peak SE (dB)	Maximum $ S_{21} $ Variation
Coarse	120,000	3	3.525	4.750	36.4	35.0	4.8%
Medium	230,000	4	3.495	4.730	36.9	35.5	2.1%
Fine	340,000	6	3.480	4.720	37.2	35.8	<1.0%
Extra fine	410,000	7	3.477	4.718	37.3	35.9	<0.5%

The resonance-frequency difference between the fine and extra-fine meshes was only 3 MHz for the n78 resonance and 2 MHz for the n79 resonance. The corresponding variation in peak shielding effectiveness was less than 0.2 dB. Therefore, further mesh refinement did not materially affect the simulated shielding response, and the fine mesh with approximately 340,000 tetrahedral elements and six adaptive passes was selected for the final simulations.

Two independent design targets required two separate effective-wavelength calculations. For the outer ring targeting 3.5 GHz:

$$\lambda_0^1 = \frac{c}{f_0^1} = \frac{3 \times 10^8}{3.5 \times 10^9} = 85.7 \text{ mm} \quad (1)$$

$$\lambda_{eff}^1 = \frac{\lambda_0^1}{\sqrt{5}} = \frac{85.7}{2.236} = 38.3 \text{ mm} \quad (2)$$

For the inner ring targeting 4.7 GHz:

$$\lambda_0^2 = \frac{c}{f_0^2} = \frac{3 \times 10^8}{4.7 \times 10^9} = 63.8 \text{ mm} \quad (3)$$

$$\lambda_{eff}^2 = \frac{\lambda_0^2}{\sqrt{5}} = \frac{63.8}{2.236} = 28.5 \text{ mm} \quad (4)$$

The first-order mean side length for each ring follows from equating the mean perimeter to the corresponding effective wavelength:

$$L_{mean}^1 = \frac{\lambda_{eff}^1}{4} = \frac{38.3}{4} = 9.58 \text{ mm} \quad (5)$$

$$L_{mean}^2 = \frac{\lambda_{eff}^2}{4} = \frac{28.5}{4} = 7.13 \text{ mm} \quad (6)$$

The final ring dimensions were defined using the outer and inner side lengths of each square ring. The physical strip width is calculated as half of the difference between the outer and inner side lengths. The outer ring has a strip width of 0.525 mm—wide enough to hold the resonance on target without pulling it off target. The inner ring is 0.300 mm, which is narrow enough to remain compact and maintain clearance with the outer ring. They both began with analytical values based on the effective-wavelength approximation and were then refined in CST.

$$L_{mean} = \frac{L_{out} + L_{in}}{2} \quad (7)$$

$$s = \frac{L_{out} - L_{in}}{2} \quad (8)$$

For the outer ring:

$$L_{out}^1 = 9.93 \text{ mm} \quad (9)$$

$$L_{in}^1 = 8.88 \text{ mm} \quad (10)$$

$$L_{mean}^1 = \frac{9.93 + 8.88}{2} = 9.405 \text{ mm} \quad (11)$$

$$s_1 = \frac{9.93 - 8.88}{2} = 0.525 \text{ mm} \quad (12)$$

For the inner ring:

$$L_{out}^2 = 7.43 \text{ mm} \quad (13)$$

$$L_{in}^2 = 6.83 \text{ mm} \quad (14)$$

$$L_{mean}^2 = \frac{7.43 + 6.83}{2} = 7.13 \text{ mm} \quad (15)$$

$$s_2 = \frac{7.43 - 6.83}{2} = 0.30 \text{ mm} \quad (16)$$

The clearance between the inner edge of the outer ring and the outer edge of the inner ring is:

$$\Delta_{clear} = \frac{L_{in}^1 - L_{out}^2}{2} \quad (17)$$

$$\Delta_{clear} = \frac{8.88 - 7.43}{2} = 0.725 \text{ mm} \quad (18)$$

The 0.725 mm clearance is large enough to avoid accidental electrical contact during fabrication, but small enough to leave residual capacitive coupling. The offsetting of the gaps is due to that coupling: the outer-ring gap is at the top edge of the unit cell, the inner-ring gap at the bottom. This 180° offset is confirmed by the parametric sweep below to break the dominant symmetric coupling mode.

The unit-cell pitch was chosen as $D = 15.0 \text{ mm}$, which is about $1.5L_{out}^1$. Though the size of the fabricated panel was 5×5 cells, the measured specimens used FSS panels that were sized to fit the measurement aperture. Thus, the measured transmission is more of a response of the patterned area than the uncovered concrete around the panel. Both gaps

were set to $g_1 = g_2 = 0.4$ mm, maintaining the same value as in the single-ring designs to keep the CNC setup consistent. All design parameters are listed in Table 2.

Table 2. Dual-band concentric double square-ring resonator design parameters.

Parameter	Symbol	Value
Outer ring target frequency	f_0^1	3.5 GHz
Inner ring target frequency	f_0^2	4.7 GHz
Outer $\lambda_0/\lambda_{\text{eff}}$	—	85.7/38.3 mm
Inner $\lambda_0/\lambda_{\text{eff}}$	—	63.8/28.5 mm
Outer ring outer side	L_{out}^1	9.93 mm
Outer ring inner side	L_{in}^1	8.88 mm
Outer ring strip width	s_1	0.525 mm
Inner ring outer side	L_{out}^2	7.43 mm
Inner ring inner side	L_{in}^2	6.83 mm
Inner ring strip width	s_2	0.300 mm
Final outer ring mean side	L_{mean}^1	9.405 mm
Final inner ring mean side	L_{mean}^2	7.13 mm
Inter-ring clearance (each side)	—	0.725 mm
Gap width (both rings)	g	0.4 mm
Gap offset angle	—	180° (top/bottom)
Unit cell period	D	15.0 mm
Min. panel (5×5)	—	75.0×75.0 mm
Cu sheet thickness	t_{cu}	0.2 mm
Cu conductivity	σ	5.96×10^7 S/m

Table 2 distinguishes between the target resonance frequencies, effective-wavelength-based initial estimates, and the final CST-optimized ring dimensions. The final strip widths are $s_1 = 0.525$ mm for the outer ring and $s_2 = 0.300$ mm for the inner ring, calculated from the corresponding outer and inner side lengths.

A dedicated parametric study in CST examined the effect of gap offset angle on inter-ring coupling. With both gaps aligned (0° offset), the inner-ring resonance shifted 85 MHz upward relative to the isolated single-ring prediction, and a spurious transmission peak appeared between the two stopbands. With 90° offset, the shift reduced to 40 MHz; with 180° offset, it dropped to 15 MHz and the spurious inter-band transmission feature was suppressed to below -5 dB in S_{21} . The 180° configuration was selected for all subsequent work. Gap width was also swept from 0.3 to 0.6 mm for each ring independently; the 0.4 mm value provided acceptable bandwidth at both bands while staying comfortably within CNC tolerance.

The concrete slab was modeled in CST with $\epsilon_r = 5.0$ and $\tan \delta = 0.02$ from [4], slab thickness 200 mm. Both rings were initially modeled as perfect electric conductors (PECs) for the parametric sweeps; final curves used $\sigma = 5.96 \times 10^7$ S/m. The finer geometry of the dual-ring unit cell required more tetrahedra: the final mesh contained approximately 340,000 elements after six adaptive passes to 1% convergence on $|S_{21}|$. SE was calculated from:

$$\text{SE} = -20 \log_{10} |S_{21}| \text{ dB} \quad (19)$$

Fabrication followed the same CNC milling route as the single-ring work. The concentric geometry introduced one additional constraint: the 0.725 mm inter-ring clearance required more frequent tool-change verification than the single-ring case, because a milling error in the clearance region would short-circuit the two rings and destroy both resonances. Feed rate was reduced to 450 mm/min to improve positional accuracy in the clearance region. Chemical etching was not viable for the same reasons as before—lateral under-

cutting of the 0.725 mm clearance gap would be unacceptable. Post-milling inspection checked both ring gaps (0.01 mm caliper) and the inter-ring clearance (optical microscopy at $40\times$ magnification). Panels with clearance deviations above ± 0.08 mm or $R_a > 1.6$ μm on either ring were excluded.

Concrete specimens were prepared from the same OPC 42.5R mix as the single-ring study: $w/c = 0.50$, mass ratios 1:1.8:2.4, three consecutive-day batches with 28-day cube strengths of 31.5, 30.8, and 31.9 MPa. Plain $200 \times 200 \times 100$ mm slabs served as SE references; Composite $200 \times 200 \times 200$ mm blocks contained the dual-ring FSS panel in a 10 mm central joint between two 95 mm concrete layers. Curing and conditioning protocols were identical to the single-ring work: 28 days in water at 20 ± 1 $^{\circ}\text{C}$, then 7 days at 20 $^{\circ}\text{C}/50\%$ RH. Mean ε_r at 4.1 GHz across all batches: 4.9 ± 0.15 . Thus, the total specimen thickness was:

$$95 + 10 + 95 = 200 \text{ mm} \quad (20)$$

which is consistent with the 200 mm slab thickness used in the CST simulations.

SE measurements were performed using a free-space vector network analyzer (VNA) setup adapted from IEEE Std 299 principles [26]. The setup included a LibreVNA vector network analyzer and BBHA 9120D horn antennas (Schwarzbeck Mess-Elektronik OHG, Schönaun, Germany), placed at least 220 mm from each specimen face, together with a radio frequency (RF) absorber-lined aperture frame. The setup included SE measurements performed using a LibreVNA vector network analyser and BBHA 9120D horn antennas (Schwarzbeck Mess-Elektronik OHG, Schönaun, Germany) placed at least 220 mm from each specimen face, and a radio frequency (RF) absorber-lined aperture frame. Sweeps covered 2.5–6.0 GHz in 1 MHz steps to capture both resonances and their out-of-band behavior simultaneously. In CST, S_{21} is directly obtained as the normalized transmission coefficient of the simulated wall structure. In the measurement, however, SE was calculated relative to the empty-aperture reference. Three measurement runs were performed for each specimen and then averaged. SE computed as:

$$\text{SE} = 20 \log_{10} \left| \frac{S_{21,open}}{S_{21,specimen}} \right| \text{ dB} \quad (21)$$

Uncertainty: ± 1.5 dB combined at both band centers (same contributions as single-ring work). Results are reported for each band independently: peak SE and 10 dB bandwidth for n78, and peak SE and 10 dB bandwidth for n79, and ΔSE at both band centers relative to the plain concrete reference. The corresponding free-space measurement configuration is shown in Figure 2.

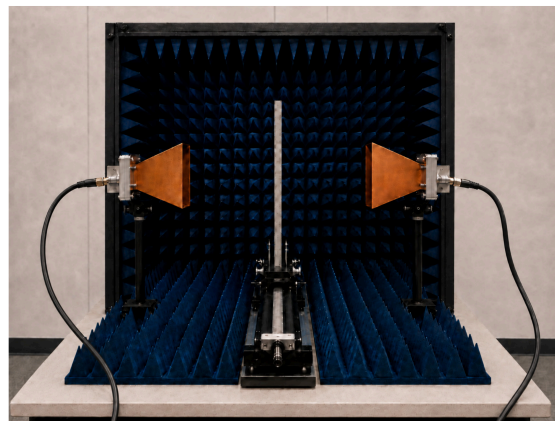


Figure 2. Representative free-space shielding-effectiveness measurement setup showing the concrete specimen positioned between two horn antennas inside an RF absorber-lined chamber. The antennas were aligned normal to the specimen surface during the S_{21} -based transmission measurements.

3. Results

The simulated S_{21} indicates that there are two distinct transmission minima. The outer-ring resonance is found at 3.48 GHz—20 MHz below the target resonance frequency of 3.5 GHz—a peak SE of 37.2 dB. The inner-ring resonance is found at 4.72 GHz—20 MHz higher than the target 4.7 GHz but with a peak SE of 35.8 dB. Both offsets are consistent with the frequency-dependent dielectric model in CST and residual inter-ring coupling that the first-order analytical formula does not capture. Plain concrete contributes approximately 4.8 dB at both frequencies, so the FSS adds 32.4 dB and 31.0 dB net at the two band centers.

The lower-band -10 dB stopband runs from 3.19 to 3.77 GHz; the upper from 4.47 to 4.96 GHz. Both overlap the central parts of n78 and n79 but do not cover the entire nominal allocations of the band edges. Between them, between about 3.8 and 4.4 GHz, SE drops back to plain-concrete levels—the FSS contributes nothing there, which is important where that portion of the spectrum carries other services. Beyond the two stopbands, the FSS does not have any measurable impact. Table 3 summarizes the results.

Table 3. CST simulation results for the concrete-only reference and the dual-band FSS-loaded concrete wall. BW denotes the -10 dB bandwidth relative to the plain-concrete baseline.

Parameter	Concrete Only	Concrete + FSS (n78)	Concrete + FSS (n79)
Resonant frequency	—	3.48 GHz	4.72 GHz
Peak SE	4.8 dB	37.2 dB	35.8 dB
SE enhancement Δ SE	—	32.4 dB	31.0 dB
-10 dB BW	—	580 MHz	490 MHz
Lower BW edge	—	3.19 GHz	4.47 GHz
Upper BW edge	—	3.77 GHz	4.96 GHz
S_{11} at resonance	—	-1.0 dB	-1.3 dB

Table 4 tracks both resonances and their peak SE values across the $\epsilon_r = 4.5$ – 6.0 permittivity sweep. The n78 resonance shifts from 3.67 GHz ($\epsilon_r = 4.5$) to 3.18 GHz ($\epsilon_r = 6.0$), a total downward movement of 490 MHz. The n79 resonance shifts from 4.92 GHz ($\epsilon_r = 4.5$) to 4.27 GHz ($\epsilon_r = 6.0$), a shift of 650 MHz. Peak SE remains over 30 dB in the entire sweep of permittivity. The resonance frequencies move downwards with increasing ϵ_r at $\epsilon_r = 5.75$ and 6.0 , and both bands drift below their nominal allocations. The shielding depth is good; the center frequencies are not.

Table 4. Resonant frequency and peak shielding effectiveness of the n78 and n79 resonances as a function of concrete relative permittivity.

ϵ_r	n78 Resonance Frequency (GHz)	n79 Peak SE (dB)	n78 Peak SE (GHz)	n79 Peak SE (dB)
4.5	3.67	34.1	4.92	32.8
4.75	3.57	35.8	4.82	34.5
5.0 (nominal)	3.48	37.2	4.72	35.8
5.25	3.40	36.0	4.57	34.7
5.5	3.31	34.5	4.45	33.2
5.75	3.24	32.8	4.36	31.6
6.0	3.18	31.4	4.27	30.3

Figure 3 shows that the peak shielding effectiveness of both resonators remains above 30 dB throughout the investigated permittivity range. For the n78 resonance, the peak SE decreases from 37.2 dB at $\epsilon_r = 5.0$ to 31.4 dB at $\epsilon_r = 6.0$, corresponding to a reduction

of 5.8 dB. For the n79 resonance, the corresponding reduction is 5.5 dB. Therefore, the structure maintains strong attenuation even when the concrete permittivity increases.

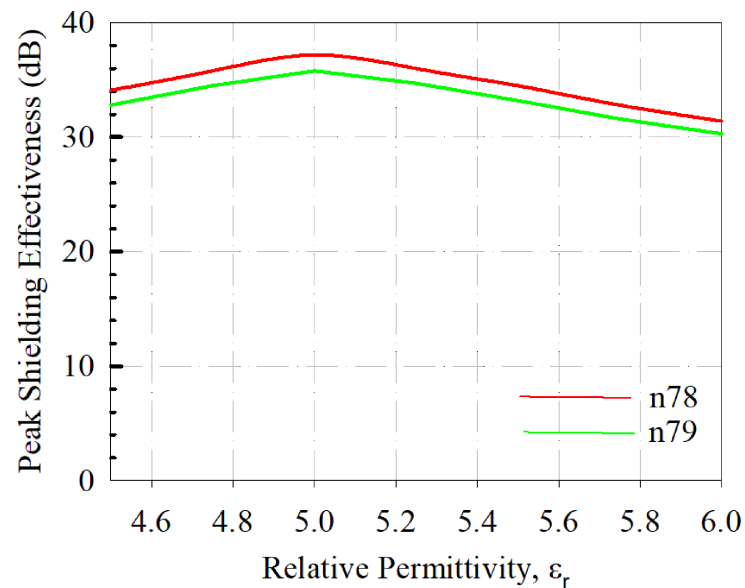


Figure 3. Peak shielding effectiveness as a function of concrete relative permittivity for the n78 and n79 resonances of the dual-band concentric double square-ring FSS. The dotted horizontal line indicates the 30 dB shielding-effectiveness reference level.

Figure 4 shows that both resonance frequencies decrease as ϵ_r increases, following the expected $1/\sqrt{\epsilon_r}$ trend. However, the resonance-frequency shift is large enough that, at the highest permittivity values, the resonances move below the nominal n78 and n79 allocations. This confirms that the design remains effective in terms of peak SE, but exact spectral alignment depends on the dielectric properties of the concrete.

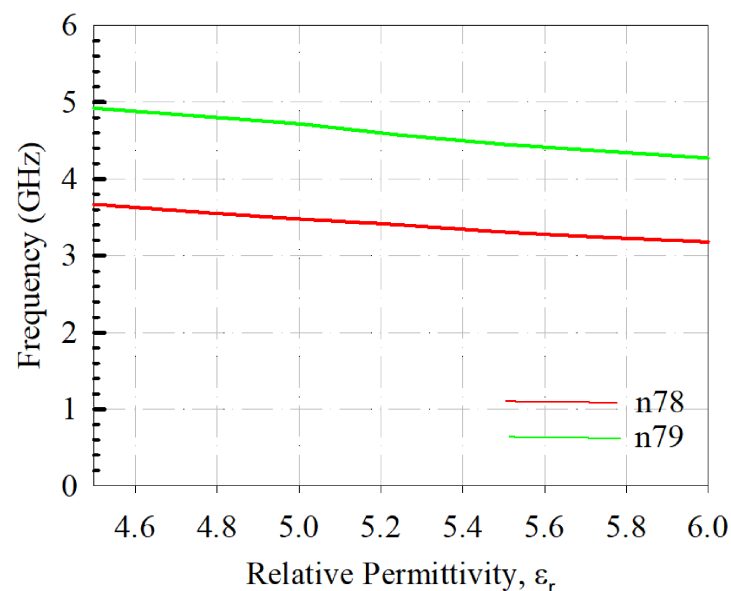


Figure 4. Resonant frequency as a function of concrete relative permittivity for the n78 and n79 resonators. The shaded regions indicate the nominal n78 and n79 frequency allocations.

Physical measurement results: the n78 resonance was detected at 3.51 GHz versus the simulated 3.48 GHz (30 MHz difference, within ± 50 MHz uncertainty). The n79 resonance appeared at 4.75 GHz versus 4.72 GHz (30 MHz difference). Peak SE measurements were

34.9 dB at n78 and 33.4 dB at n79, both approximately 2.3 dB below simulation. Post-measurement calipers found mean gap widths of 0.44 mm (outer ring) and 0.45 mm (inner ring), against the designed 0.40 mm for both. These gap overruns reduce the distributed capacitance of each ring, lowering peak SE and narrowing the stopband—consistent with the observed measurement shortfall. The 180° gap-offset strategy was effective in practice: no spurious transmission peak appeared between the two stopbands in measurement, confirming that inter-ring coupling remained suppressed.

The n78 measured -10 dB bandwidth was 510 MHz, extending from 3.22 to 3.73 GHz. This covers most of the n78 allocation but does not fully cover the upper edge of the nominal 3.3–3.8 GHz band; approximately 70 MHz near 3.8 GHz remains outside the measured -10 dB stopband.

The n79 measured -10 dB bandwidth was 420 MHz, extending from 4.50 to 4.92 GHz. This covers the central portion of the nominal 4.4–5.0 GHz n79 allocation, but approximately 100 MHz at the lower edge and 80 MHz at the upper edge remain outside the measured -10 dB stopband.

The measured and simulated SE responses are compared in Figure 5. The two resonance peaks are clearly separated, and the measured peak frequencies remain close to the simulated values. The figure also shows that the inter-band region returns close to the plain-concrete reference level, confirming that the FSS layer mainly affects the intended n78 and n79 regions. The numerical values extracted from Figure 5 are summarized in Table 5.

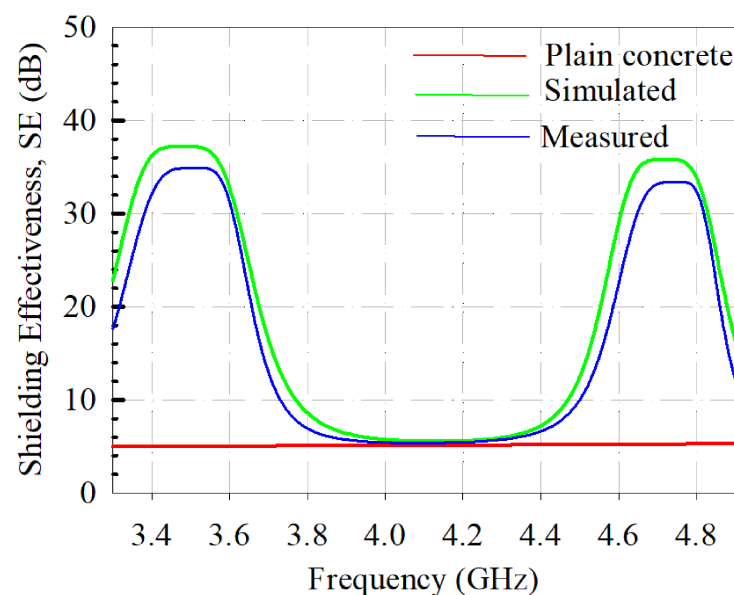


Figure 5. Simulated and measured shielding effectiveness of the dual-band concentric double square-ring FSS embedded in OPC concrete. The shaded regions indicate the nominal n78 and n79 frequency allocations. The -10 dB bandwidths cover the central portions of both target regions but do not fully cover the complete nominal allocations.

Out-of-band behavior was checked at 900 MHz, 1.8 GHz, 2.4 GHz, 6.0 GHz, and at 4.1 GHz (the inter-band gap center). At none of these frequencies did the composite and plain-concrete SE differ by more than 0.5 dB. The 4.1 GHz inter-band gap result is particularly important: it confirms that the FSS layer introduces no additional significant attenuation between the two stopbands beyond the plain-concrete baseline. Frequencies located near the center of the inter-band region, such as around 4.1 GHz, pass through with approximately the same attenuation as plain concrete.

Compared with single-resonance embedded designs, the dual-band panel imposes only a modest increase in fabrication complexity. The copper sheet contains two concentric

rings rather than a single resonator, and the copper panels were fabricated using a computer numerical control (CNC) milling machine available in the institutional laboratory. Owing to the additional geometry and the slower inter-ring clearance pass, milling takes approximately 35% longer per panel. Post-milling inspection also requires optical verification of the inter-ring gap. However, the concrete embedding procedure remains identical. The incremental installation time per mortar joint is negligible relative to the benefit of simultaneous attenuation near the main n78 and n79 operating regions.

Table 5. Direct comparison between simulated and measured shielding-effectiveness results, including resonance frequencies, peak SE, -10 dB bandwidths, and bandwidth-edge frequencies.

Metric	Simulated	Measured	Difference
n78 resonant frequency	3.48 GHz	3.51 GHz	+30 MHz (+0.9%)
n78 peak SE	37.2 dB	34.9 dB	−2.3 dB
n78 Δ SE vs. concrete	32.4 dB	30.1 dB	−2.3 dB
n78 -10 dB BW	580 MHz	510 MHz	−70 MHz (−12%)
n79 resonant frequency	4.72 GHz	4.75 GHz	+30 MHz (+0.6%)
n79 peak SE	35.8 dB	33.4 dB	−2.4 dB
n79 Δ SE vs. concrete	31.0 dB	28.6 dB	−2.4 dB
n79 -10 dB BW	490 MHz	420 MHz	−70 MHz (−14%)
Plain concrete SE	4.8 dB	4.8 dB	0 dB
n78 lower BW edge	3.19 GHz	3.22 GHz	+30 MHz
n78 upper BW edge	3.77 GHz	3.73 GHz	−40 MHz
n79 lower BW edge	4.47 GHz	4.50 GHz	+30 MHz
n79 upper BW edge	4.96 GHz	4.92 GHz	−40 MHz

As shown in Table 6, the dominant contributor to the discrepancy is the machining-induced gap-width deviation. The increase in the gap width from the designed 0.40 mm to the measured 0.44–0.45 mm reduces the effective capacitance of the split-ring resonators, resulting in an upward frequency shift and a reduction in peak SE. Concrete permittivity fluctuation mainly affects the resonance frequency, while local spacer/void effects primarily reduce the peak SE by disturbing the dielectric continuity around the embedded copper layer. The combined estimated SE reduction of approximately 2.2–2.6 dB agrees well with the experimentally observed reduction of 2.3–2.4 dB. Therefore, the simulation–measurement difference can be quantitatively attributed to fabrication and embedding tolerances rather than to a fundamental limitation of the proposed dual-ring FSS concept.

Table 6. Quantitative contribution of fabrication and material tolerances to the simulation–measurement discrepancy.

Error Source	Variation Considered	n78 Frequency Shift	n79 Frequency Shift	n78 Peak SE Reduction	n79 Peak SE Reduction
Gap-width deviation	0.40 mm $\rightarrow$ 0.44/0.45 mm	+18 MHz	+22 MHz	0.9 dB	1.0 dB
Concrete permittivity fluctuation	$\epsilon_r = 4.85$ –5.05	± 25 MHz	± 34 MHz	0.4 dB	0.5 dB
Inter-ring clearance tolerance	± 0.08 mm	± 12 MHz	± 16 MHz	0.5 dB	0.5 dB
Local spacer/void effect	Thin local air region near Cu FSS	<10 MHz	<10 MHz	0.7 dB	0.8 dB
Combined estimated effect	Cumulative tolerance model	approximately +30 MHz	approximately +30 MHz	2.2–2.5 dB	2.3–2.6 dB
Experimental difference	Measured – simulated	+30 MHz	+30 MHz	2.3 dB	2.4 dB

Since electromagnetic waves in practical building environments may impinge on wall surfaces from different directions, the angular and polarization stability of the proposed embedded FSS was further evaluated. Additional simulations were performed for TE and TM polarizations at incidence angles of 0° , 15° , 30° and 45° . The extracted resonance frequencies and peak shielding-effectiveness values are summarized in Table 7.

Table 7. Simulated angular and polarization stability of the embedded dual-ring FSS.

Incidence Angle	Polarization	n78 Resonance Frequency (GHz)	n78 Peak SE (dB)	n79 Resonance Frequency (GHz)	n79 Peak SE (dB)
0°	TE/TM	3.48	37.2	4.72	35.8
15°	TE	3.49	36.6	4.73	35.2
30°	TE	3.51	35.4	4.75	34.1
45°	TE	3.54	33.1	4.78	31.9
15°	TM	3.48	36.8	4.72	35.4
30°	TM	3.50	35.8	4.74	34.6
45°	TM	3.52	33.7	4.77	32.4

The results show that both n78 and n79 resonances remain clearly distinguishable under oblique incidence. For both TE and TM polarizations, the peak SE decreases gradually as the incidence angle increases. However, even at 45° incidence, the peak SE remains above 30 dB for both resonances. No additional spurious resonance appears between the two stopbands, indicating that the 180° gap-offset concentric-ring configuration maintains acceptable angular and polarization stability for practical wall-integrated shielding applications.

Compared with the normal-incidence case, the maximum reduction in peak SE at 45° incidence is 4.1 dB for the n78 resonance and 3.9 dB for the n79 resonance under TE polarization. For TM polarization, the corresponding reductions are 3.5 dB and 3.4 dB, respectively. Despite this reduction, both resonances remain above the 30 dB shielding-effectiveness reference level. The slightly stronger degradation under TE incidence can be attributed to the reduced effective current excitation along the split-ring edges at higher oblique angles. These results confirm that the proposed embedded FSS is not limited to ideal normal-incidence conditions and can maintain stable dual-band shielding performance under more realistic incidence conditions.

Tables 8 and 9 compare the proposed structure with selected concrete-based shielding materials, substrate-based FSS/metamaterial absorbers and building-integrated FSS studies. In addition to shielding depth, Table 8 highlights the host medium, operating band, bandwidth, structural size and implementation complexity. Most dual-band or multiband FSS and metamaterial structures rely on engineered substrates such as FR4, glass or other dielectric supports. These designs can provide strong frequency selectivity, but they are not directly embedded in concrete and generally require surface mounting or a separate supporting substrate. The structural novelty of the present design is the use of a single-layer concentric double-ring copper FSS directly embedded in an OPC concrete mortar joint. Its functional novelty is the simultaneous suppression of the main n78 and n79 sub-6 GHz 5G regions while preserving the concrete block geometry and maintaining a low-attenuation inter-band region.

Table 8. Comprehensive comparison of recent shielding and FSS-based studies in terms of host medium, operating band, shielding performance, bandwidth, structural size and implementation complexity.

Study	Host Medium/ Substrate	Target Frequency/ Band	Peak SE/ Attenuation	Bandwidth	Unit-Cell/ Structural Size	Structural/ Implementation Complexity	Experi- mental Validation
Yuan et al. [6]	Reinforced concrete wall with rebar/fiber/grid/mesh	300–1500 MHz	RC: 1.0–20.4 dB; hybrid mesh/grid: >30–40 dB	Broadband, non-selective	Wall-scale reinforced concrete specimen	Conventional RC feasible; hybrid mesh/grid increases construction complexity	Yes
Ruscica et al. [8]	Cement composite with biochar/PVC fillers	C-band, 5.4–8.0 GHz	13–16 dB	Measurement band: 5.4–8.0 GHz	Material sample; unit-cell not applicable	Requires mixture modification and filler dispersion control	Yes
Rahman et al. [12]	Metamaterial absorber on FR4	2.40/3.50/6.09 GHz	Sim.: 36.44/32.58/31.13 dB; Meas.: 29.15/28.83/30.15 dB	N/R	N/R	Engineered FR4 substrate; multiband resonator pattern	Yes
Idrees et al. [14]	Miniaturized FSS on FR4	X-band, around 10 GHz	≥ 33 dB	26–31%	N/R	Miniaturized printed FSS; engineered substrate required	Yes
Manoharan et al. [18]	Dual-band FSS on FR4	1–6 GHz; resonances at 1.75 and 4.09 GHz	($S_{21} < -30$) dB below 2 GHz and near 6 GHz; -15 to -20 dB in 2–5 GHz	5.4 GHz operating bandwidth	N/R	Compact FR4/copper FSS; surface/substrate-based implementation	Yes
Nguyen et al. [22]	Transparent FSS on window glass	n257, 26.5–29.5 GHz	Transmission/filtering study; SE not directly comparable	25.7–31.0 GHz/ 26.2–30.4 GHz	N/R	Single-layer transparent FSS; glass-integrated but not concrete-embedded	Yes
Present study	OPC concrete mortar joint with embedded 0.2 mm Cu sheet	3.51 GHz n78/ 4.75 GHz n79	34.9/33.4 dB	510/420 MHz, –10 dB BW	15.0 mm unit-cell period; minimum 5 × 5 panel; 75 × 75 mm	Single embedded layer; two concentric square rings; 180° gap offset; CNC-milled Cu sheet; no change in block geometry	Yes

Note: N/R: not reported.

Table 9. Engineering applicability comparison.

Study	Concrete/Building Compatibility	Angular/Polarization Stability	Fabrication Feasibility	Main Limitation
Yuan et al. [6]	Concrete-compatible	N/R	Conventional RC feasible; hybrid mesh/grid more complex	Non-selective; does not target n78/n79
Ruscica et al. [8]	Cement-compatible	N/R	Requires mixture modification	Moderate SE; not frequency-selective
Rahman et al. [12]	Not concrete-embedded	TE/TM stable up to 60°	PCB/FR4 fabrication feasible	Absorber on engineered substrate
Idrees et al. [14]	Not concrete-embedded	TE/TM stable up to 60°	Printed FR4 prototype feasible	X-band only; not wall-integrated
Manoharan et al. [18]	Not concrete-embedded	Up to $\pm 60^\circ$ for TE polarization	Compact FR4/copper fabrication	FR4-based; not embedded in wall material
Nguyen et al. [22]	Window-glass-compatible	TE/TM response reported up to 30°	Single-layer transparent FSS feasible	mmWave glass filtering; not concrete-based
Present study	Directly embedded in concrete mortar joint	TE/TM simulated up to 45°	CNC-milled Cu sheet; no change in block geometry	Does not fully cover complete n78/n79 allocations

Note: N/R: not reported.

4. Conclusions

This study has demonstrated dual-band electromagnetic shielding of concrete block walls using concentric double square-ring FSS resonators embedded in a single mortar joint. Measured peak SE of 34.9 dB at 3.51 GHz (n78) and 33.4 dB at 4.75 GHz (n79) were achieved simultaneously, with -10 dB bandwidths of 510 MHz and 420 MHz, respectively. Both results exceed conventional reinforced concrete shielding by 15–25 dB, and the combined dual-band suppression addresses a limitation of single-resonance designs by providing strong attenuation near the main operating regions of both n78 and n79.

The concentric-ring geometry achieves dual-band operation from a single embedded layer without increasing mortar-joint thickness or altering the block-laying procedure. The 180° gap offset—outer-ring gap at the top edge, inner-ring gap at the bottom—directly addresses inter-ring coupling. Without it, an 85 MHz resonance shift and a spurious transmission peak appeared between the stopbands; with it, both effects fell within simulation uncertainty.

Both rings were dimensioned using the effective wavelength in concrete, not free space. Skipping the $\sqrt{\epsilon_r}$ compression produces substantial frequency errors and can push the stopbands off-target entirely. The two bands required separate calculations followed by CST refinement. Final dimensions gave an inter-ring clearance of 0.725 mm—enough for CNC fabrication at ± 0.05 mm tolerance without introducing excessive capacitive coupling.

The permittivity sweep from $\epsilon_r = 4.5$ to 6.0 kept peak SE above 30 dB at both bands throughout. Both resonances shift downward as ϵ_r increases, and at the highest values, they drift below the nominal n78 and n79 allocations. Therefore, dielectric characterization of the concrete mixture is necessary before practical implementation. The inter-band gap between the two stopbands narrows slightly with increasing ϵ_r but remains spectrally intact, preserving a relatively low-attenuation inter-band region between the two stopbands. The measured stopbands cover the central portions of the intended n78 and n79 frequency regions, but they do not fully cover the entire nominal allocations. Therefore, the proposed structure should be described as a dual-band shielding design targeting the main operating regions of n78 and n79 rather than as a complete-band blocking solution.

The 2.3–2.4 dB simulation-to-measurement gap is attributed to coupling-gap drift during milling (outer ring: 0.44 mm, inner ring: 0.45 mm, against 0.40 mm designed) and spacer-induced dielectric voids. Neither effect is inherent to the dual-ring concept; a dedicated casting fixture and tighter in-process gap measurement are expected to close this gap in future work.

Additional mesh-convergence, tolerance and oblique-incidence analyses were included to strengthen the numerical and engineering validation of the proposed design. The mesh-convergence results confirmed that the selected CST model provides stable resonance frequencies and peak SE values. The tolerance analysis quantitatively explained the 2.3–2.4 dB simulation-to-measurement difference, while TE/TM simulations showed that both stopbands remain above 30 dB up to 45° incidence.

Future directions include: angular-incidence SE measurements to quantify how the 180° gap offset affects polarization independence at oblique incidence; extension to a triple-band design targeting an additional sub-6 GHz allocation; long-term durability assessment of lacquer-coated concentric-ring panels under freeze–thaw and carbonation exposure; and optimization of the inter-ring clearance geometry to maximize isolation between the two resonators while maintaining CNC feasibility.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The author declares no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Definition
BW	Bandwidth
CNC	Computer numerical control
CST	Computer Simulation Technology
EMI	Electromagnetic interference
FSS	Frequency-selective surface
OPC	Ordinary Portland cement
PEC	Perfect electric conductor
RF	Radio frequency
SE	Shielding effectiveness
TE	Transverse electric
TM	Transverse magnetic
VNA	Vector network analyzer

References

- Schulz, R.B.; Plantz, V.C.; Brush, D.R. Shielding theory and practice. *IEEE Trans. Electromagn. Compat.* **1988**, *30*, 187–201. [\[CrossRef\]](#)
- Kim, D.; Hwang, S.J.; Ryu, J.; Choi, J.-C.; Kim, W.; Jeong, H.Y.; Lee, P.; Chung, S. Strain-invariant frequency-selective metasurface for electromagnetic interference shielding in wearable electronics. *npj Flex. Electron.* **2025**, *9*, 122. [\[CrossRef\]](#)
- Rac-Rumijowska, O.; Pokryszka, P.; Rybicki, T.; Suchorska-Woźniak, P.; Woźniak, M.; Kaczkowska, K.; Karbownik, I. Influence of flexible and textile substrates on frequency-selective surfaces (FSS). *Sensors* **2024**, *24*, 1704. [\[CrossRef\]](#) [\[PubMed\]](#)
- Ogunsola, A.; Reggiani, U.; Sandrolini, L. Shielding effectiveness of concrete buildings. In Proceedings of the IEEE 6th International Symposium on Electromagnetic Compatibility and Electromagnetic Ecology, St. Petersburg, Russia, 21–24 June 2005; pp. 161–165.
- Hyun, S.Y.; Du, J.K.; Lee, H.J.; Lee, K.W.; Lee, J.H.; Kim, E.J.; Yook, J.-G. Analysis of shielding effectiveness of reinforced concrete against high-altitude electromagnetic pulse. *IEEE Trans. Electromagn. Compat.* **2014**, *56*, 1488–1496. [\[CrossRef\]](#)
- Yuan, T.-F.; Choi, J.S.; Hong, S.H.; Yoon, Y.-S. Enhancing the electromagnetic shielding and impact resistance of a reinforced concrete wall for protective structures. *Cem. Concr. Compos.* **2021**, *122*, 104148. [\[CrossRef\]](#)
- Lee, J.-H.; Choi, J.-S.; Yuan, T.-F.; Yoon, Y.-S. Shielding effectiveness and impact resistance of concrete walls strengthened by high-strength high-ductility concrete. *Materials* **2021**, *14*, 7773. [\[CrossRef\]](#) [\[PubMed\]](#)
- Ruscica, G.; Peinetti, F.; Natali Sora, I.; Savi, P. Analysis of electromagnetic shielding properties of cement-based composites with biochar and PVC as fillers. *C* **2024**, *10*, 21. [\[CrossRef\]](#)
- De Sabata, A.; Matekovits, L.; Buta, A.; Dassano, G.; Silaghi, A. Frequency selective surface for ultra-wide band filtering and shielding. *Sensors* **2022**, *22*, 1896. [\[CrossRef\]](#) [\[PubMed\]](#)
- Chatterjee, A.; Dey, P.; Roy, K.; Parui, S.K. A monolayer frequency-selective surface for wideband shielding application with adequate out-of-band separation and angular stability. *Int. J. Antennas Propag.* **2024**, *2024*, 6692659. [\[CrossRef\]](#)
- Hakim, M.L.; Islam, M.T.; Alam, T.; Abdul Rahim, S.K.; Bais, B.; Islam, M.S.; Soliman, M.S. Triple-band square split-ring resonator metamaterial absorber design with high effective medium ratio for 5G sub-6 GHz applications. *Nanomaterials* **2023**, *13*, 222. [\[CrossRef\]](#) [\[PubMed\]](#)
- Rahman, A.A.M.; Islam, M.T.; Moniruzzaman, M.; Alsaif, H.; Maash, A.A.; Hasan, M.M.; Soliman, M.S. Resonator-based near perfect metamaterial absorber with high EMI shielding for Wi-Fi and 5G applications. *Int. J. Optomechatronics* **2024**, *18*, 2375497. [\[CrossRef\]](#)
- Jahan, M.I.; Faruque, M.R.I.; Hossain, M.B.; Khandaker, M.U.; Elsayed, F.; Salman, M.; Osman, H. Quad-band metamaterial perfect absorber with high shielding effectiveness using double X-shaped ring resonator. *Materials* **2023**, *16*, 4405. [\[CrossRef\]](#) [\[PubMed\]](#)
- Idrees, M.; He, Y.; Wen, Y.; Majeed, A. Design of a miniaturized and polarization-independent frequency-selective surface for targeted EMI shielding. *Appl. Sci.* **2025**, *15*, 4534. [\[CrossRef\]](#)

15. Hakim, M.L.; Alam, T.; Islam, M.T.; Misran, N.; Albadran, S.; Alrashdi, A.M.; Alsaif, H.; Alshammari, A.S.; Alzamil, A.; Soliman, M.S. Interconnected square splits ring resonator based single negative metamaterial for 5G (N258, N257, N260 and N259) band sensor/EMI shielding/and antenna applications. *Alex. Eng. J.* **2023**, *81*, 419–436. [[CrossRef](#)]
16. Hakim, M.L.; Islam, M.T.; Alam, T. Ultra-miniaturized conformal polarization insensitive and incident angle stable FSS for n257 band 5G EMI shielding applications. *IEEE Trans. Antennas Propag.* **2024**, *72*, 7905–7914. [[CrossRef](#)]
17. Ud Din, I.; Alibakhshikenari, M.; Virdee, B.S.; Jayanthi, R.K.R.; Ullah, S.; Khan, S.; See, C.H.; Golunski, L.; Koziel, S. Frequency-selective surface-based MIMO antenna array for 5G millimeter-wave applications. *Sensors* **2023**, *23*, 7009. [[CrossRef](#)] [[PubMed](#)]
18. Manoharan, S.; Palanisamy, S.; Thirugnanasambantham, J.; Nallusamy, S.; Manivannan, S.; Guizani, S.; Hamam, H. Dual band frequency selective surface for EMI shielding in 5G communications. *Math. Model. Eng. Probl.* **2025**, *12*, 3399–3406. [[CrossRef](#)]
19. Fan, X.; Pan, Z.; Zhu, Y.; Li, M.; Ma, Y.; Li, Y. Deformation-induced electromagnetic reconfigurable square ring kirigami metasurfaces. *Micromachines* **2024**, *15*, 1493. [[CrossRef](#)] [[PubMed](#)]
20. Shukoor, M.A.; Dey, S. Novel dual-mode polarization insensitive wide angular stable circular ring based deca-band absorber for RCS and EMI shielding applications. *IEEE Trans. Electromagn. Compat.* **2022**, *64*, 1337–1345. [[CrossRef](#)]
21. Cuiñas, I.; Expósito, I.; Andriukaitis, D.; Caldeirinha, R.F.S.; García Sánchez, M.; Valinevičius, A. Integration of frequency-selective surfaces as smart skins in building envelopes and divisions: Insulation and energy issues. *World* **2024**, *5*, 1211–1234. [[CrossRef](#)]
22. Nguyen, D.T.; Lee, J.-N.; Moon, J.I.; Jung, C.W. Single-layer frequency-selective surface on window glass for 5G indoor communications. *IEEE Antennas Wirel. Propag. Lett.* **2024**, *23*, 1558–1562. [[CrossRef](#)]
23. Qiao, S.; Shi, Z.; He, A.; Huang, Z.; Tong, A.; Wang, B.; He, J.; Wang, J.; Ke, W.; Yao, N.; et al. Collaborative optimization of electromagnetic interference shielding, adaptive multi-color, and thermal camouflage of basalt fibers by temperature-induced gradient structure control. *Exploration* **2026**, *6*, 70135. [[CrossRef](#)] [[PubMed](#)]
24. Yan, X.J.; Cao, M.; Li, L.; Wu, S.Y.; Chen, X.M. Dependence of microwave dielectric properties on ceramic connectivity in ultralow- ϵ_r Al₂O₃ porous ceramics. *Microstructures* **2025**, *5*, 2025065. [[CrossRef](#)]
25. Liang, G.; Dai, B.; Wang, W.; Lin, R.; Yan, L.; Zhou, Y.; Zhu, H.; Yang, Y. Microwave regulated trace Fe injection into activated carbon for a magnetic-dielectric-magnetic sandwich-structured broadband absorber with excellent angular and polarization stability. *Carbon* **2026**, *256*, 121572. [[CrossRef](#)]
26. *IEEE Std 299-2006*; IEEE Standard Method for Measuring the Effectiveness of Electromagnetic Shielding Enclosures. IEEE: New York, NY, USA, 2007.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.