

Article

An Ultra-Compact ARCL-Based MEMS Radar Filter for Mobile Robotic Platforms

Yan Ding ^{1,2,*}, Ruiqi Zhang ¹, Xing Fan ^{1,2}, Wenyu Chen ¹ and Zhe Yang ³

¹ School of Information and Control Engineering, University of Emergency Management, Langfang 101601, China; zhangruiqi@ncist.edu.cn (R.Z.); fanguan123@126.com (X.F.); 17526712912@163.com (W.C.)

² Key Laboratory of Brain-Computer Interface Technology Application of the Ministry of Emergency Management, Langfang 101601, China

³ Nanjing Electronic Devices Institute, Nanjing 210002, China; zheyang_nedi@163.com

* Correspondence: jilia.123@163.com

Abstract

To address the stringent requirements for miniaturization and high reliability in the perception systems of mobile robotic platforms, this article presents an ultra-compact band-pass filter based on air core recta-coax lines using micro-electro-mechanical systems technology. The proposed filter features an air-filled cavity structure with internal coupled lines and a fully enclosed metal shield, which effectively minimizes dielectric and radiation losses while achieving a highly compact footprint. This compactness is particularly critical for robotic radar front-ends, where limited payload capacity demands high integration density. By leveraging classical filter synthesis theory, the design achieves a high-order response within a minimized volume. Furthermore, the inherent high-Q characteristic of the air cavity significantly improves out-of-band rejection, thereby effectively suppressing interference in complex electromagnetic environments and enhancing the signal-to-noise ratio for robotic detection. A prototype operating at 75 GHz was fabricated and measured. The experimental results demonstrate a low insertion loss of 1.5 dB and a compact size of 0.875 mm³, showing reasonable agreement with simulations. The proposed design offers a promising solution for next-generation, high-performance sensing units in autonomous robotics.

Keywords: ARCL; MEMS; filter; miniaturization; low loss

Academic Editor: Jose Luis Sanchez-Rojas

Received: 1 June 2026

Revised: 6 July 2026

Accepted: 9 July 2026

Published: 11 July 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

Mobile robotic platforms, such as autonomous mobile robots (AMRs) and surgical assistive robots, increasingly rely on millimeter-wave radar sensors to achieve reliable perception in densely cluttered and dynamically changing environments [1,2]. To meet the stringent size, weight, and power constraints inherent to these platforms, the front-end modules of such radar systems demand core filtering components that simultaneously offer ultra-low insertion loss, high selectivity, extreme miniaturization, and robust interference suppression [3]. Among these, the bandpass filter (BPF), as a critical circuit block, directly determines the signal-to-noise ratio (SNR) and anti-interference capability of the entire radar receiver [4].

Conventional BPF implementations have been extensively explored using planar printed circuit boards (PCB), low-temperature co-fired ceramics (LTCC), substrate-

integrated waveguides (SIW), metallic waveguide resonators, and semiconductor-based integrated passive devices (IPDs) [5–10]. However, at millimeter-wave frequencies, each of these technologies exhibits inherent limitations. PCB and LTCC architectures suffer from substantial dielectric losses, which severely degrade insertion loss and radar detection range [5,6]. SIW structures, while offering better radiation suppression, still incur non-negligible dielectric and conductor losses; moreover, their miniaturization via half-mode or quarter-mode techniques compromises electromagnetic shielding and introduces additional radiation loss [7,8]. Metallic waveguide resonators provide high quality factors and power handling but at the cost of a prohibitively large footprint, which is incompatible with the limited payload capacity of mobile robots [9]. Conversely, semiconductor-based IPDs achieve high integration density but fundamentally sacrifice power handling and insertion loss performance due to lossy silicon substrates [10]. Consequently, novel filter architectures must be investigated to concurrently achieve miniaturization, low loss, and high selectivity—requirements that are increasingly critical for next-generation robotic radar front-ends.

Air-filled, fully enclosed metal cavities, implemented using high-precision micro-electro-mechanical systems (MEMS) technology, present a compelling alternative. By leveraging an air-gapped cavity and a continuous metal shield, these structures virtually eliminate dielectric loss and radiation loss, while maintaining high power handling capacity and broadband operation [11–13]. Among these, the air core recta-coax line (ARCL) has recently demonstrated significant advantages in low-loss phase shifters [14], broadband antenna arrays [15], and compact power splitters [16]. To date, several ARCL-based BPFs have been reported, primarily employing branch-line topologies. Specifically, the resonant unit in [17] consists of a metal cavity, a rectangular metal block suspended inside, and a grounded cylinder. The filter in [18] utilizes grounded and open stub lines, together with impedance transformation stub lines. The design in [19] adopts half-wavelength resonators and realizes coupling between resonant units by adding grounded cylinders. These works have fully exploited the advantages of ARCL, achieving low insertion loss and compact form factors. However, in the context of extreme miniaturization for robotic radar applications, it remains worth investigating whether more suitable topologies can be adopted based on the ARCL platform to achieve further size reduction without compromising electrical performance.

In response to the above challenges, this article proposes an ultra-compact ARCL-based MEMS bandpass filter specifically tailored for mobile robotic radar platforms. Unlike previous designs that rely on grounding cylinders or stub structures for inter-resonator coupling, the proposed filter adopts a parallel-coupled line configuration, where coupling is achieved through lateral gaps. This topological choice offers a more compact footprint and more precise coupling control. By applying classical filter synthesis theory, a high-order passband response is achieved while maintaining a minimized physical volume. The air-filled, metal-enclosed structure inherently provides ultra-low insertion loss of 1.5 dB and significantly improved out-of-band rejection, thereby enhancing the radar's ability to suppress interference in spectrally congested environments. A prototype operating at 75 GHz is fabricated using MEMS technology and measured. Experimental results show excellent agreement with simulations. The proposed design offers a promising path toward high-performance, compact, and interference-resilient perception modules for autonomous mobile robotics.

2. Design and Simulation

2.1. Filter Configuration

Figure 1a presents the 3D view of the proposed coupled ARCLs, comprising the outer conductor copper, the inner conductor copper, and the embedded dielectric support straps. Figure 1b,c illustrate the corresponding cross-sectional views of the transmission line structures fabricated using different lamination schemes. The structure is realized through a multilayer process where each metal layer has a thickness of 50 μm . As shown in Figure 1b, the structure spans from M1 to M5, with the inner conductor co-fabricated within the M3 layer. In contrast, Figure 1c depicts a structure extending from M1 to M11, where the inner conductor is integrated with layers M5–M7. It is worth noting that the thickness and vertical position of the inner conductor are flexible, which can be synchronously fabricated with other layer combinations, such as M6, M4–M8, or M3–M9, depending on the design requirements. While increasing the number of layers enhances the degrees of freedom for realizing complex high-performance devices, it inevitably increases the fabrication complexity. Furthermore, the release holes in the outer conductor are sized at $300\text{ }\mu\text{m} \times 250\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$ with a periodic arrangement of $750\text{ }\mu\text{m}$. Similarly, the dielectric support straps have a width of $150\text{ }\mu\text{m}$ and a period of $750\text{ }\mu\text{m}$. These dimensions are optimized to ensure sufficient mechanical strength while effectively facilitating the removal of the sacrificial photoresist during the release process.

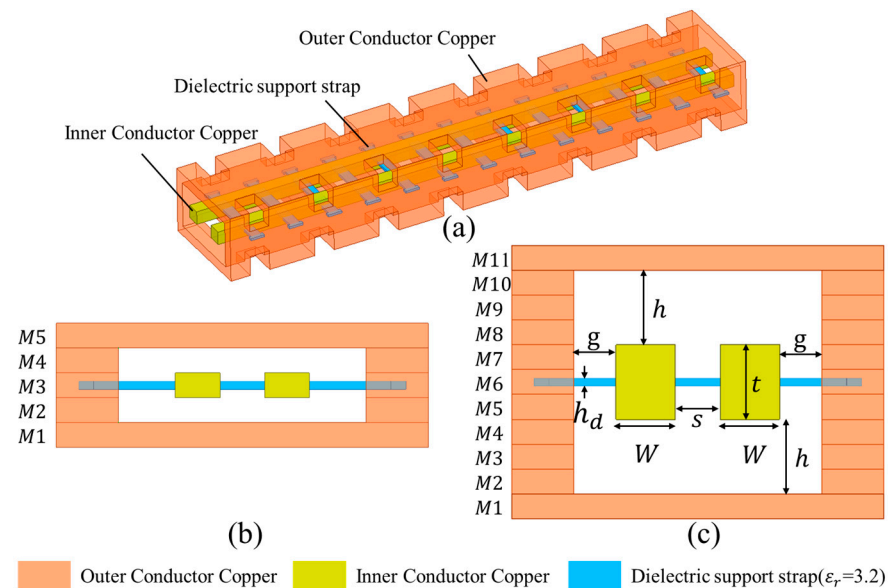


Figure 1. (a) 3D view, (b) half-height, and (c) full-height cross-sectional view of defined coupled ARCL.

To analyze the characteristics of a single signal line, the spacing s between the coupled lines is set to zero. This configuration effectively merges the two parallel conductors into a single equivalent conductor, and the structure operates as a standard ARCL. Prior to the analysis of coupled lines, we first investigate the characteristics of this single-conductor configuration. The characteristic impedance Z_0 is determined by [20]:

$$Z_0 = \frac{1}{v_p C_{\text{len}}} \quad (1)$$

where $v_p \approx 2.998 \times 10^8$ m/s is the phase velocity in the air medium, and C_{len} denotes the capacitance per unit length. For the physical dimensions defined in the cross-section where $2W \geq g$, $t \geq h$ and $2W \geq t$, C_{len} can be analytically calculated following the formulation in [21]:

$$C_{\text{len}} = 2\varepsilon \left(\frac{2W}{h} + \frac{t}{g} \right) + \frac{4\varepsilon}{\pi} \left[\ln \left(\frac{g^2 + h^2}{4h^2} \right) + 2 \frac{h}{g} \arctan \left(\frac{g}{h} \right) \right] + \frac{4\varepsilon}{\pi} \left[\ln \left(\frac{g^2 + h^2}{4g^2} \right) + 2 \frac{g}{h} \arctan \left(\frac{h}{g} \right) \right] \quad (2)$$

when $t < h$, C_{len} is determined by [21]:

$$C_{\text{len}} = 2 \frac{2\varepsilon W}{h} + \frac{4\varepsilon}{\pi \ln(2)} \ln \left[1 + \coth \left(\frac{\pi g}{2h + t} \right) \right] \cdot \left[\frac{t + 2h}{2h} \ln \left(\frac{4h + t}{t} \right) + \ln \left(\frac{t(4h + t)}{4h^2} \right) \right] \quad (3)$$

While the physical dimensions are initially synthesized using analytical equations, precise extraction and verification are performed using Ansys HFSS 2021R1. To achieve a characteristic impedance Z_0 of 50 Ω within the target frequency band, the geometric dimensions of the ARCLs were optimized. As illustrated in Figure 2a, three distinct cross-sectional configurations were investigated by varying the center conductor height h to 50 μm , 100 μm , and 200 μm . For each height, the conductor width W and gap g were tuned to maintain impedance matching. The analytical calculations yielded impedances of 49.9 Ω , 50.3 Ω , and 50.1 Ω , respectively, showing excellent agreement with the full-wave simulation results presented in Figure 2a. Figure 2b compares the ideal insertion loss for a 1 cm transmission line length across these three configurations. A significant reduction in insertion loss is observed as the center conductor height increases. Specifically, at 75 GHz, the structure with $h = 50 \mu\text{m}$ exhibits an insertion loss approximately 2.3 times that of the $h = 200 \mu\text{m}$ configuration. This degradation in loss performance for thinner conductors is primarily attributed to the increased conductor loss. A smaller cross-sectional height intensifies current density and exacerbates the skin effect, thereby raising the effective resistance. However, realizing a thicker center conductor inevitably entails a more complex fabrication process, involving additional lamination or plating steps. Consequently, a trade-off between electrical performance and manufacturing complexity is required. For the experimental validation in this work, the most fabrication-friendly 5-layer structure (M1–M5) with a fixed unit layer thickness of 50 μm was selected. By strictly controlling the width W and gap g , this study aims to verify the design methodology and process reliability. Once validated, this design framework can be extended to thicker, low-loss configurations for applications requiring ultra-low insertion loss.

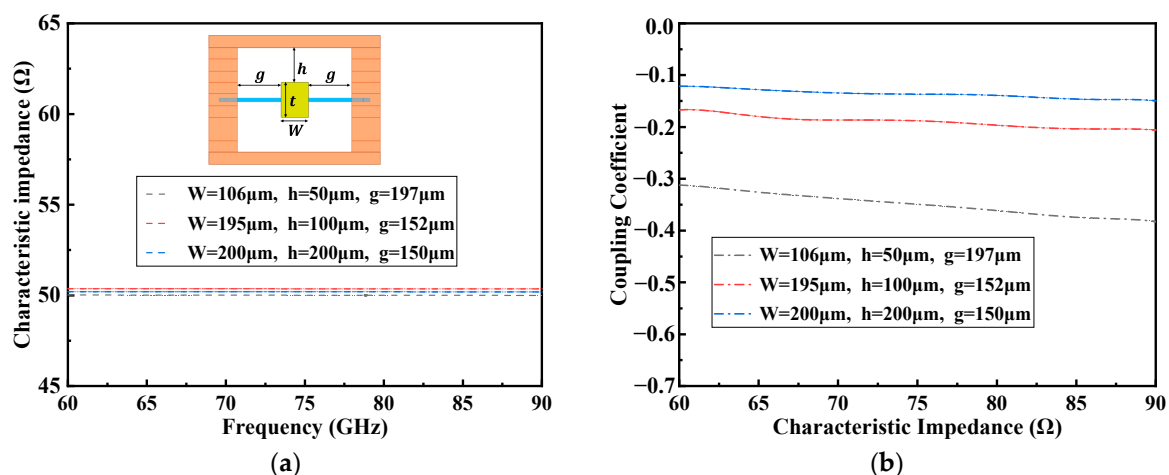


Figure 2. (a) Three cross-sectional dimension combinations under 50 Ω characteristic impedance, and (b) the ideal insertion loss of ARCL with a length of 1 cm for the three cross-sectional dimensions.

Building upon the validated single-line model, we extend the topology to coupled transmission lines by introducing a second inner conductor. The proximity of the two conductors alters the electric field distribution, thereby modifying the equivalent capacitance per unit length. To achieve a 50 Ω matched coupled line, we adopt the width

derived from the single-line analysis as the initial design value. Subsequently, EM optimization is performed to fine-tune both the width W and the spacing s to compensate for the coupling effects and ensure impedance matching. To evaluate the impedance and coupling coefficient of the coupled ARCL, finite-element method simulations are carried out at 75 GHz. The line length is initially set to a quarter of the guided wavelength to maximize the coupling coefficient.

The physical length of the ARCL l_{ARCL} corresponding to a full guided wavelength at the desired center frequency f_0 can be estimated by:

$$l_{\text{ARCL}} = \frac{c}{f_0} \quad (4)$$

where c is the speed of light in a vacuum. It should be noted that the actual physical wavelength in the fabricated ARCL will be slightly shorter than the value calculated by the equation above, due to the parasitic capacitance introduced by the dielectric support straps and the finite thickness of the conductors.

For a transmission line with a port impedance of Z_0 , the odd-mode and even-mode impedances, Z_{0o} and Z_{0e} , satisfy the well-known relations [22]:

$$Z_{0e}Z_{0o} = Z_0^2 \quad (5)$$

The coupling coefficient can be expressed in terms of Z_{0o} and Z_{0e} , as follows:

$$K = \frac{Z_{0e} - Z_{0o}}{Z_{0e} + Z_{0o}} \quad (6)$$

FEM simulation is employed to extract Z_{0o} and Z_{0e} , from which the relationship between the coupling coefficient and the characteristic impedance of the coupled ARCL structure is derived, as shown in Figure 3. With the conductor width W and height h fixed as defined in Figure 1c, reducing the coupling gap s enhances the electromagnetic interaction between the signal lines, thereby increasing the coupling coefficient, as shown in curves (a)–(c). When W and s are constant, increasing h alters the equivalent capacitance and inductance distribution. As observed in curves (d)–(f), a larger h leads to an increase in characteristic impedance, accompanied by a rising trend in the coupling coefficient. These characteristic curves provide a basis for the initial synthesis of broadband filters. For a given system impedance and target coupling strength, a smaller gap s is preferred, whereas h can be adjusted without significantly degrading the coupling performance. As the filter in this work is designed with both h and t fixed to $50 \mu\text{m}$, the curves in Figure 3a–c are adopted for selecting the impedance and coupling coefficient.

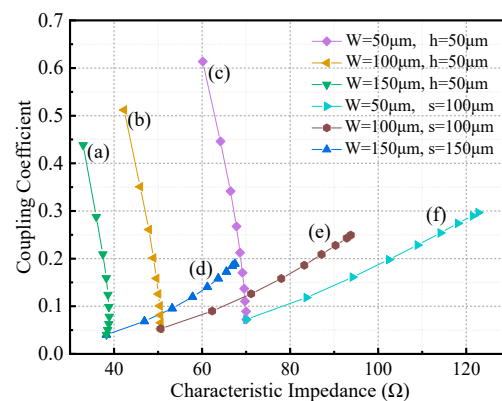


Figure 3. Coupling coefficient versus characteristic impedance for coupled ARCLs. (a–c) Variations in characteristic impedance with gap s for fixed W and h : (a) $W = 150 \mu\text{m}$, $h = 50 \mu\text{m}$ (b) $W = 100 \mu\text{m}$, $h = 50 \mu\text{m}$; (c) $W = 50 \mu\text{m}$, $h = 50 \mu\text{m}$. (d–f) variations in characteristic impedance with

height h for fixed W and s : (d) $W = 150\ \mu\text{m}$, $s = 150\ \mu\text{m}$; (e) $W = 100\ \mu\text{m}$, $s = 100\ \mu\text{m}$; (f) $W = 50\ \mu\text{m}$, $s = 100\ \mu\text{m}$.

2.2. Filter Design, Tuning, and Analysis

In this work, a fifth-order resonant circuit operating at W-band ($f_0 = 75\ \text{GHz}$) is designed. It achieves a 10 GHz bandwidth and a return loss greater than 15 dB, while maintaining sufficient out-of-band rejection. As shown in Figure 4a, the circuit consists of five resonator units (R_1, R_2, R_3, R_4, R_5) arranged in a staggered parallel configuration. The resonators are characterized by widths W_m ($m = 1, 2, \dots, 5$) and lengths l_n ($n = 1, 2, \dots, 5$), with the gap between adjacent resonators denoted as s_{ij} ($i = 1, 2, \dots, 4$; $j = i + 1$). The mutual coupling strength between adjacent resonators is governed by their geometric parameters, particularly the widths and spacing. The prototype filter coefficients g_i ($i = 0, 2, \dots, 6$) are derived from standard low-pass prototype tables [22] as $g_0 = g_6 = 1$, $g_1 = g_5 = 1.1468$, $g_2 = g_4 = 1.3712$, $g_3 = 1.975$. The coupling coefficients K_{ij} and the external quality factor Q_e at the input are derived by the following equations:

$$k_{ij} = \frac{BW}{f_c \sqrt{g_i g_{i+1}}} \quad (7)$$

$$Q_e = \frac{g_0 g_1}{BW} f_c \quad (8)$$

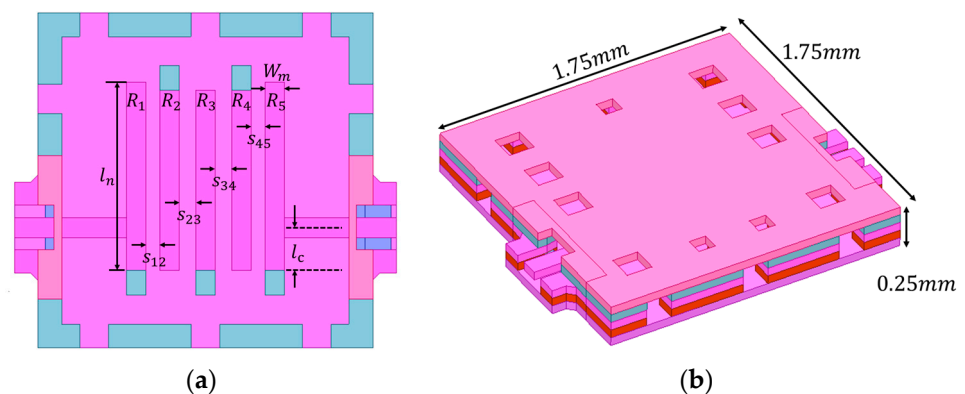


Figure 4. Configuration of the proposed W-band fifth-order MEMS cavity filter: (a) Key dimensions of the center conductor, and (b) 3D view.

Based on the target design specifications, the coupling coefficients and external quality factor are calculated using Equations (7) and (8), yielding $K_{12} = 0.11$, $K_{23} = 0.08$, and $Q_e = 8.6$. Due to the symmetry of the topology, the corresponding values K_{34} , K_{45} and the external quality factor at the output port are also obtained. The design of the first two resonators is initiated by targeting a coupling coefficient $K_{12} = 0.11$. As illustrated in Figure 3a–c, for a fixed width W and height h , a coupling of 0.11 is satisfied at characteristic impedances of $39\ \Omega$ and $52\ \Omega$. The results further indicate that for an inner conductor width W ranging from $50\ \mu\text{m}$ to $100\ \mu\text{m}$, appropriate coupling gaps can be found to achieve the desired coupling. Balancing fabrication complexity, conductor loss, and impedance matching with the feed line, the initial dimensions for these resonators are selected as a width of $100\ \mu\text{m}$ and a coupling gap of $65\ \mu\text{m}$. Based on these initial values, full-wave simulations are performed to refine the resonator dimensions for the target resonant frequency.

Figure 4 shows the configuration of the proposed W-band fifth-order MEMS cavity filter. Figure 4a illustrates the key dimensions of the center conductor, where the dashed lines indicate the feed length l_c at the input and output ports. According to the topology,

each resonator unit is open-circuited at one end and grounded at the other. The open end is realized by maintaining sufficient horizontal and vertical distance from the outer conductor, while the ground connection is established by stacking the center conductor M3 with metal layers M2 and M4, and directly connecting to M1 and M5. Figure 4b presents a 3D view of the filter. To enable robust on-chip characterization and facilitate integration with external planar circuits, ground-signal-ground (GSG) probe pads designed in previous work [23] are adopted at both the input and output ports.

To extract the resonant frequency, a simulation model consisting of a quarter-wave-length metal conductor and an air cavity is established for a single resonator, as shown in Figure 5a. The outer walls of the air cavity are set as finite good conductors, serving as the inner walls of the outer conductor. Here, l_0 and W_0 denote the length and width of the resonator, with initial values set to $1000\ \mu\text{m}$ and $100\ \mu\text{m}$, respectively. Figure 5a plots the variation in the resonant frequency as a function of l_0 . As l_0 increases, the equivalent capacitance rises, leading to a decrease in the resonant frequency. Specifically, a length of approximately $952\ \mu\text{m}$ yields a resonant frequency of 75 GHz, which aligns well with the target specification.

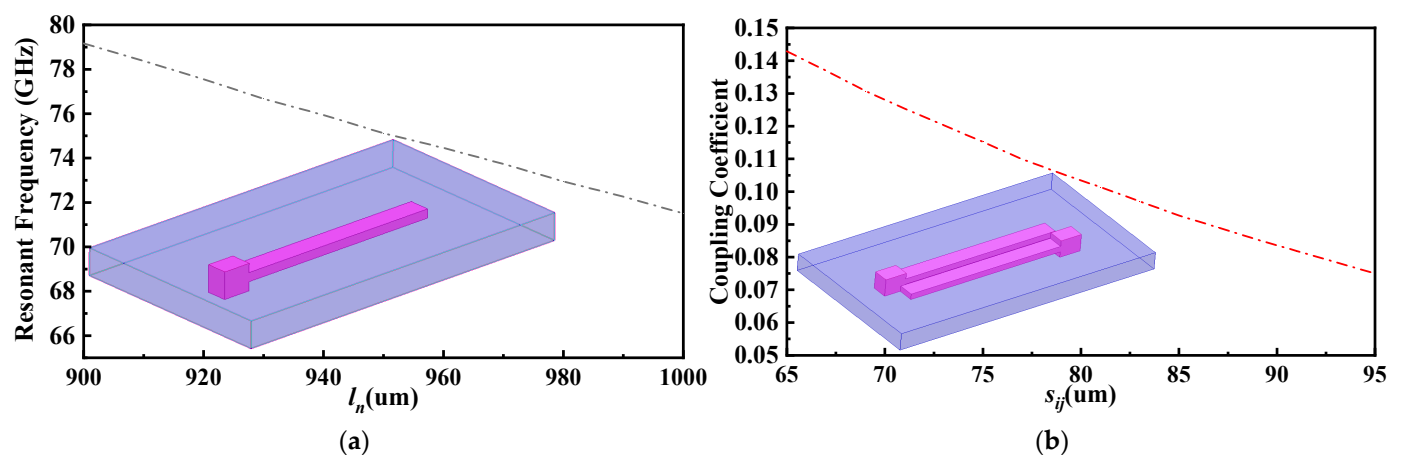


Figure 5. (a) Variation in the resonant frequency as a function of l_0 (black solid line), and (b) coupling coefficient K_{ij} as a function of the coupling gap s_{ij} (red dashed line). The magenta solid model boxes represent the inner conductors, and the dark blue regions represent the outer conductor walls with ideal conductor boundaries.

Based on the optimized length of the single resonator, a two-resonator model was constructed with its initial spacing determined from the curves in Figure 3. Figure 5b plots the simulated coupling coefficient K_{ij} as a function of the coupling gap s_{ij} , from which the required s_{ij} can be obtained. From the simulated curve in Figure 5b, the initial coupling gaps corresponding to the target coefficients $K_{12} = 0.11$ and $K_{23} = 0.08$ are read as approximately $s_{12} = 76\ \mu\text{m}$ and $s_{23} = 91\ \mu\text{m}$, respectively.

With the dimensions of the first two resonators determined, the design proceeds to the remaining resonator units. Owing to the structural symmetry of the fifth-order filter topology, the coupling coefficients satisfy $K_{34} = K_{23}$ and $K_{45} = K_{12}$. Consequently, the geometric parameters for the third, fourth, and fifth resonators are directly derived from those already obtained for the first two resonators, following the same design procedure. Once all resonators are dimensioned, the input and output tap-feed structures are designed. The tap position and stub length l_c annotated in Figure 4 are optimized by matching the simulated group delay τ to its theoretical value derived from the external quality factor Q_e . The group delay at resonance is given by [24]:

$$Q_e = \frac{\omega_0 \tau(\omega_0)}{4} \quad (9)$$

where ω_0 is the angular frequency at the center frequency, and $\tau(\omega_0)$ denotes the group delay at the center frequency. Using the designed Q_e value, the target group delay at the center frequency is calculated to be 73 ps. A parametric simulation is then performed to evaluate the relationship between the feed length l_c and the resulting group delay τ . Based on the simulation, a feed length l_c of 225 μm is found to yield a group delay closest to the analytical prediction of 73 ps and is therefore adopted as the optimal feed geometry. By symmetry, the same tap dimensions are applied to the output port. The complete filter model is then assembled and verified through full-wave simulation.

The simulated S-parameters of the optimized filter model are presented in Figure 6. Figure 6a illustrates the wideband frequency response from 50 GHz to 300 GHz. It can be observed that the filter maintains excellent suppression across a broad stopband up to 200 GHz. A spurious passband emerges at approximately 225 GHz, which corresponds to the third harmonic of the fundamental resonance at 75 GHz. This spurious response is inherent to the quarter-wavelength resonator topology, where the third harmonic inevitably re-energizes the resonators. Figure 6b provides a detailed view of the operating band from 50 GHz to 100 GHz. Within the passband from 70 GHz to 80 GHz, the minimum insertion loss is 1.17 dB, and the return loss exceeds 18 dB. Notably, five distinct transmission zeros are visible within the passband, confirming the realization of a fifth-order Chebyshev response. Regarding out-of-band performance, the filter exhibits sharp roll-off characteristics, with rejection levels better than 60 dB at both 50 GHz and 100 GHz, demonstrating effective suppression of unwanted signals.

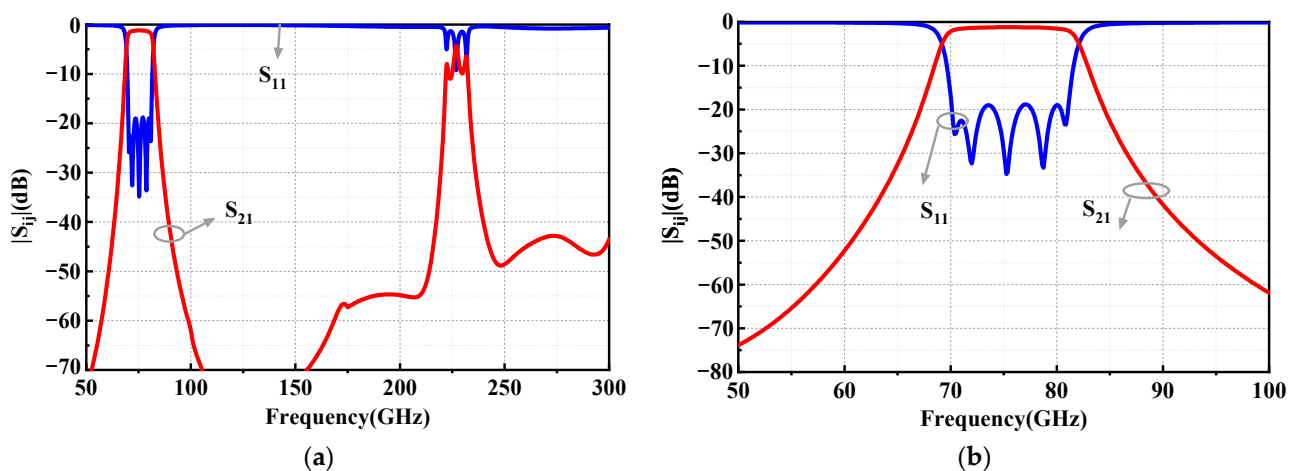


Figure 6. Simulated performance of the optimized filter model (a) 50–300 GHz, and (b) 50–100 GHz. The blue and red lines represent S_{11} and S_{21} , respectively.

Figure 7 illustrates the electric field distribution at 75 GHz and 90 GHz, as computed using Ansys HFSS 2021R1. The distinct patterns provide physical insight into the operating and rejection mechanisms of the proposed ARCL-based filter. Within the passband at 75 GHz, the electric field is strongly concentrated along the internal coupled transmission lines, with maximum intensity observed between the adjacent coupling sections. This confirms that the dominant mode of the filter follows a coupled-line coupling mechanism, where electromagnetic energy is efficiently transferred from the input to the output port via the parallel-coupled ARCL segments. Notably, the field remains well confined within the fully shielded air cavity, with negligible leakage into the surrounding substrate or air regions, which is a direct consequence of the enclosed metal shield and contributes to the observed low insertion loss and high selectivity. In contrast, at 90 GHz, which lies in the

upper stopband, the electric field distribution exhibits a pronounced change. The field concentration along the coupled lines is substantially diminished, and instead, localized standing-wave patterns emerge with field maxima appearing at the input and output feed regions. This shift indicates that the coupled-line section no longer provides an efficient coupling path at this frequency. Consequently, energy becomes trapped at the ports rather than being transmitted across the filter, effectively creating a transmission zero in the upper stopband. Such decoupling behavior is essential for achieving wide stopband rejection, which is critical for suppressing out-of-band interference in dense spectral environments, such as those encountered in surgical and autonomous mobile robotic platforms. The final geometric parameters of the 70–80 GHz ARCL-based bandpass filter are summarized in Table 1.

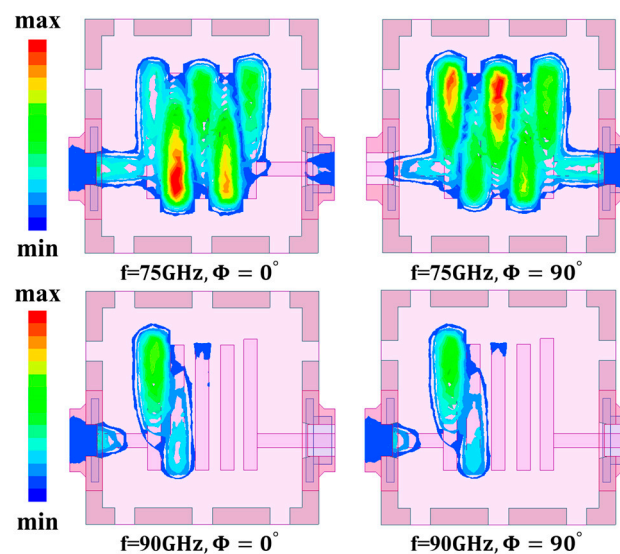


Figure 7. Electric field distribution at 75 GHz and 90 GHz, simulated by Ansys HFSS 2021R1.

Table 1. Geometric parameters of the 70–80 GHz MEMS cavity filter after optimization (Unit: μm).

Symbol	Value/ μm	Symbol	Value/ μm
$W_m (m = 1, 2 \dots 5)$	100	S_{12}, S_{45}	73.5
$l_n (n = 1, 5)$	984	S_{23}, S_{34}	86.5
$l_n (n = 2, 3, 4)$	942	l_c	225

3. Results and Discussion

The proposed filter based on ARCL is realized on a $700 \mu\text{m}$ thick silicon wafer through standard MEMS fabrication techniques. A sequence of PVD deposition, thick photoresist lithography, electroplating, and CMP processes was used in the fabrication, as shown in Figure 8. For the $50 \mu\text{m}$ -thick single-layer electroplating process, the foundry can achieve a metal sidewall verticality better than 88° by using positive thick photoresist with optimized exposure and baking conditions. This ensures well-defined conductor profiles and reliable multilayer stacking. A metal seed layer is deposited and patterned on the substrate via PVD (a). The bottom metal structure is formed by electroplating (b). The surface is planarized by CMP to ensure a flat foundation (c). A supporting layer is defined by spin-coating and lithography to create the air cavity (d). The metal layers M2–M5 are constructed via a multi-layer stacking process (e). Finally, the sacrificial photoresist is removed by wet stripping to release the structure (f).

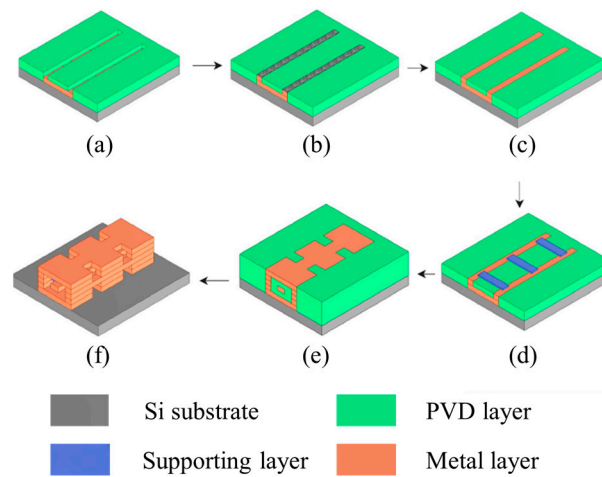


Figure 8. MEMS-based fabrication steps of ARCL: (a) lithography, (b) electroplating, (c) CMP, (d) spin-coating and patterning, (e) multi-layer stacking, and (f) release.

Figure 9 presents the microscopic photograph of the proposed bandpass filter. The multilayer conductors stacked vertically on top of each other, as well as the strategically placed release holes for sacrificial layer removal, can be clearly observed. The overall chip footprint is $2000\ \mu\text{m} \times 1750\ \mu\text{m} \times 250\ \mu\text{m}$.

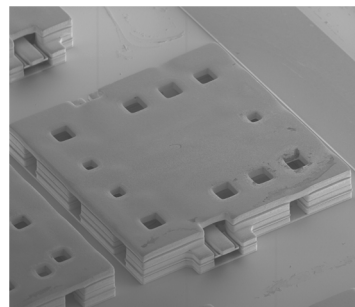


Figure 9. Microscopic photograph of the proposed filter.

Figure 10 presents the simulated and measured frequency responses of the proposed filter. The measured results reveal a center frequency of 75 GHz with a 3 dB fractional bandwidth of 15.2%, and a shift of 0.95 GHz is observed between the simulated and measured results. Within the passband, five distinct resonant poles are clearly observable. The measured in-band return loss exceeds 15 dB, and the minimum insertion loss is 1.5 dB, which is slightly higher than the simulated value of 1.17 dB.

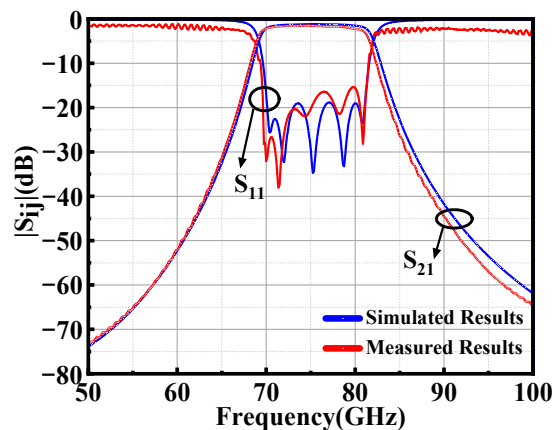


Figure 10. Simulated and measured results for proposed ARCL-based filter.

The observed discrepancies between measured and simulated results primarily stem from cumulative manufacturing inaccuracies inherent to the MEMS fabrication process. These fabrication errors include deviations in conductor linewidth and layer thickness, over-etching or under-etching, random surface roughness on metal sidewalls, and incomplete removal of sacrificial photoresist due to insufficient reaction with the etchant. Such structural imperfections alter the equivalent capacitance and inductance of the coupled-line sections, as well as the effective permittivity of the air cavity, thereby degrading the overall frequency response. Additionally, assembly-related misalignments and measurement uncertainties, such as variations in GSG probe contact position on the input/output pads, may contribute to port impedance mismatches, particularly given the high sensitivity of S-parameters at millimeter-wave frequencies.

To evaluate the performance of the proposed design, a comparative analysis with recently reported W-band bandpass filters is provided in Table 2. The GaAs-based SIW filter [25] achieves a slightly smaller on-chip footprint using ICP etching, but suffers from a relatively high insertion loss of 4.3 dB due to dielectric dissipation in the semiconductor substrate. The E-plane waveguide filter using a compact beeline resonator [26] demonstrates low insertion loss and high selectivity, yet its integration with planar front-ends is hindered by the requirement for a bulky WR-10 waveguide housing. The gap-waveguide filter employing the MEMS technique [27] features a lightweight and surface-mountable package, but its large volume limits its suitability for highly compact robotic radar modules. Compared with the ARCL-based filters in [17,28], the proposed design achieves a comparable insertion loss and a wider fractional bandwidth, while occupying a significantly smaller volume. Specifically, the third-order Chebyshev filter using open/short stubs in [17] and the fifth-order dual-behavior resonator filter using five paralleled DBRs in [28] both require larger footprints to realize their responses. In contrast, the proposed topology enables a more compact layout without sacrificing electrical performance. This compactness makes it particularly attractive for integration into autonomous robotic perception systems where payload capacity is severely constrained.

Table 2. Performance comparison of the proposed filter with state-of-the-art designs.

Ref	Form	Process	f_0 (GHz)	FBW (%)	IL (dB)	Size (mm ³)
Prop.	ARCL	MEMS	75	15.2	1.5	$2 \times 1.75 \times 0.25$
[25]	SIW	GaAs ICP	93	3.4	4.3	$4.2 \times 2.2 \times 0.07$
[26]	E-Plane Waveguide	Quartz PCB	88.55	3.6	1.15	$4.85 \times 1.7 \times 0.5$
[27]	Gap Waveguide	MEMS	93.6	8	2	$20 \times 10 \times 0.6$
[17]	ARCL	Surface micromachining	94.75	7.3	1.5	$3.21 \times 1.27 \times 0.127$
[28]	ARCL	Surface micromachining	96	8	2.05	$5.4 \times 2.19 \times 0.5$

4. Conclusions

This article presents an ultra-compact W-band bandpass filter based on a MEMS air-cavity structure. Measurement results demonstrate that the proposed filter exhibits a miniature footprint, low insertion loss, and high selectivity. These characteristics confirm its excellent suitability and promising potential for integration into high-resolution mobile robotic radar systems and next-generation millimeter-wave sensing applications.

Author Contributions: Y.D.: Writing—original draft preparation, project administration, funding acquisition. R.Z.: performed the validation and visualization. X.F.: conducted the investigation and designed the methodology. W.C.: formal analysis, data curation. Z.Y.: participated in the writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Natural Science Foundation of Hebei Province, grant number F2025508015; the National Key R&D Program of China, grant number 2024YFB2908803; the Science and Technology Support Project of Langfang, grant number 2025011037 and 2025011023; and the Fundamental Research Funds for the Central Universities, grant numbers 3142025013 and 3142023023.

Data Availability Statement: Data will be made available on request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

- Huang, X.; Patel, N.; Tsoi, K.P. Application of mmWave Radar Sensors for Autonomous Robotics Navigation. In Proceedings of the 2023 IEEE Asia-Pacific Conference on Computer Science and Data Engineering (CSDE), Nadi, Fiji, 4–6 December 2023; pp. 1–7. <https://doi.org/10.1109/CSDE59766.2023.10487689>.
- Albaba, A.; Bauduin, M.; Verbelen, T.; Sahli, H.; Bourdoux, A. Forward-looking MIMO-SAR for enhanced radar imaging in autonomous mobile robots. *IEEE Access* **2023**, *11*, 66934–66948. <https://doi.org/10.1109/ACCESS.2023.3291611>.
- Lee, B.; Koh, B.; Nam, S.; Lee, T.-H.; and Lee, J. Band-Switchable Substrate-Integrated Waveguide Resonator and Filter. *IEEE Trans. Microw. Theory Tech.* **2018**, *66*, 147–156. <https://doi.org/10.1109/TMTT.2017.2737989>.
- Cai, W.; Li, W.; Zhu, C.; Yu, D.; Ye, L. Compact Slotline Bandpass Filter With Wide Upper Stopband Without Spoof Surface Plasmon Polariton Gradient Transitions. *IEEE Trans. Microw. Theory Tech.* **2026**, *74*, 4589–4600. <https://doi.org/10.1109/TMTT.2026.3667592>.
- Li, Y.; Liao, S.; Xu, J.; Yang, C.; Che, W. A Novel Sub-Terahertz Dielectric Waveguide Bandpass Filter Using PCB Technology. *IEEE Microw. Wirel. Technol. Lett.* **2026**, *36*, 63–66. <https://doi.org/10.1109/LMWT.2025.3613717>.
- Hao, L.; Wu, Y.; Wang, W.; Yang, Y. Design of On-Chip Dual-Band Bandpass Filter Using Lumped Elements in LTCC Technology. *IEEE Trans. Circuits Syst. II Express Briefs* **2022**, *69*, 959–963. <https://doi.org/10.1109/TCSII.2021.3113790>.
- Jones, T.R.; Daneshmand, M. Miniaturized Folded Ridged Half-Mode and Quarter-Mode Substrate Integrated Waveguides for Filter Design. *IEEE Trans. Microw. Theory Tech.* **2019**, *67*, 3141–3426. <https://doi.org/10.1109/TMTT.2019.2918519>.
- Lin, G.; Dong, Y.; Luo, X. Miniaturized Quarter-Mode SIW Filters Loaded by Dual-Mode Microstrip Resonator with High Selectivity and Flexible Response. *IEEE Microw. Wirel. Compon. Lett.* **2022**, *32*, 660–663. <https://doi.org/10.1109/LMWC.2022.3161619>.
- Garcia-Martinez, S.; Santiago, D.; Tamayo-Dominguez, A.; Sanchez-Olivares, P.; Arregui, I.; Lopetegui, T. Robust Filter Design Built in a Contactless Metallic Multilayer Waveguide at W-Band. *IEEE Trans. Microw. Theory Tech.* **2025**, *73*, 5841–5850. <https://doi.org/10.1109/TMTT.2025.3564144>.
- Kim, D.-M.; Min, B.-W.; Yook, J.-M. Compact mm-Wave Bandpass Filters Using Silicon Integrated Passive Device Technology. *IEEE Microw. Wirel. Compon. Lett.* **2019**, *29*, 638–640. <https://doi.org/10.1109/LMWC.2019.2936688>.
- Tian, Y.; Wang, H.; Liu, Z.; Meng, Q.; Lee, K. Low-Loss Microcoaxial Rat-Race Hybrid for Si-Based Microwave Integrated Circuits. *IEEE Microw. Wirel. Compon. Lett.* **2016**, *26*, 162–164. <https://doi.org/10.1109/LMWC.2016.2524657>.
- Wu, J.-B.; Wu, L.-S.; Mao, J.-F. Microfabrication of Air-Filled Rectangular Waveguide Using Dry Film as Sacrificial Layer. In Proceedings of the 2023 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP), Chengdu, China, 13–15 November 2023; pp. 1–3. <https://doi.org/10.1109/IMWS-AMP57814.2023.10381254>.
- Liang, R.; Shi, G.; Shu, M.; Wu, Z.; Guo, C.; Zhang, A. Micromachined W-band Eight-way Power Divider Based on Micro-coaxial Lines. In Proceedings of the 2021 51st European Microwave Conference (EuMC), London, UK, 4–6 April 2022, pp. 374–376. <https://doi.org/10.23919/EuMC50147.2022.9784254>.
- Sholiyi, O.; Williams, J.D. Microrectangular-coaxial phase shifter for microwave devices. *Int. J. RF Microw. Comput.-Aided Eng.* **2015**, *25*, 502–509. <https://doi.org/10.1002/mmce.20885>.
- Liang, R.; Chang, L.; Guo, C.; Shi, G.; Wang, Z.; Zhang, A. Air-Filled High-Efficiency W-Band Metasurface Antennas Using the Microcoaxial Additive Manufacturing Process. *IEEE Trans. Antennas Propag.* **2025**, *73*, 7045–7050. <https://doi.org/10.1109/TAP.2025.3576983>.
- Xu, L.; Xu, L.; Zhang, C.-T.; Wu, W.-J.; Zhang, H.-L.; Lv, Y.; Li, B. Design of 3D stacked wideband Wilkinson power divider based on rectangular micro-coaxial process. *IET Microw. Antennas Propag.* **2023**, *17*, 421–430. <https://doi.org/10.1049/mia2.12353>.
- Huang, Z.; Jiang, Y.; Wu, W.; Liu, B.; Hu, W.; Yuan, N. W-Band Bandpass Filter Using Rectangular Microcoaxial Structure. *IEEE Microw. Wirel. Compon. Lett.* **2021**, *31*, 957–960. <https://doi.org/10.1109/LMWC.2021.3092144>.

18. Ding, Y.; Ding, J.; Fan, X.; Wang, J.; Yang, Y. An air-gapped cavity filter based on MEMS process for 5G millimeter wave applications. *Informacije MIDEM* **2025**, *55*, 167–172. <https://doi.org/10.33180/InfMIDEM2025.303>.
19. Huang, Z.; Liu, B.; Jiang, Y.; Ye, Y.; Zhang, X.; Hu, W.; Yuan, N. Miniaturized W-band bandpass filter based on rectangular micro-coaxial structure. *Int. J. RF Microw. Comput.-Aided Eng.* **2021**, *31*, e22884. <https://doi.org/10.1002/mmce.22884>.
20. Chen, T.-S. Determination of the Capacitance, Inductance, and Characteristic Impedance of Rectangular Lines. *IRE Trans. Microw. Theory Tech.* **1960**, *8*, 510–519. <https://doi.org/10.1109/TMTT.1960.1124779>.
21. Reid, J.R.; Marsh, E.D.; Webster, R.T. “Micromachined rectangular-coaxial transmission lines. *IEEE Trans. Microw. Theory Tech.* **2006**, *54*, 3433–3442. <https://doi.org/10.1109/TMTT.2006.879133>.
22. Pozar, D.M. *Microwave Engineering*, 4th ed.; Wiley: Hoboken, NJ, USA, 2012.
23. Ding, Y.; Liang, X.; Yan, Y.; Wang, X. Design and comprehensive analysis of a novel structure of ARCL-to-SCL GSG transition for millimeter wave applications. *IEICE Electron. Express* **2022**, *20*, 20220526. <https://doi.org/10.1587/elex.19.20220526>.
24. Hong, J.-S. *Microstrip Filters for RF/Microwave Applications*, 2nd ed.; Wiley: Hoboken, NJ, USA, 2011.
25. Xiao, Y.; Shan, P.; Zhao, Y.; Sun, H.; Yang, F. Design of a W -Band GaAs-Based SIW Chip Filter Using Higher Order Mode Resonances. *IEEE Microw. Wirel. Compon. Lett.* **2019**, *29*, 104–106. <https://doi.org/10.1109/LMWC.2018.2890265>.
26. Jiang, Y.; Huang, Z.; Liu, B.; Zhang, X.; Wang, C.; Wu, W. W-Band E-Plane Waveguide Filter Using Compact Beeline Resonator. *IEEE Microw. Wirel. Compon. Lett.* **2022**, *32*, 289–292. <https://doi.org/10.1109/LMWC.2021.3125048>.
27. Shi, Y.; Zhang, J.; Zhou, M.; Feng, W.; Cao, B.; Che, W. Miniaturized W-Band Gap Waveguide Bandpass Filter Using the MEMS Technique for Both Waveguide and Surface Mounted Packaging. *IEEE Trans. Circuits Syst. II: Express Briefs* **2019**, *66*, 938–942. <https://doi.org/10.1109/TCSII.2018.2873236>.
28. Wu, Z.; Shi, G.; Lu, X.; Liang, R.; Wen, X.; Wang, J.; Zhou, B.; Wang, Z.; Guo, C.; Zhang, A. A W-band air-filled coaxial bandpass filter employing micro metal additive manufacturing technology. *Int. J. RF Microw. Comput.-Aided Eng.* **2021**, *31*, e22768. <https://doi.org/10.1002/mmce.22768>.

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.