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Review Article

A Unified Review of Bandpass Filter Technologies for 5G: Challenges, Trends, and Metamaterial Solutions

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Abstract *- This review paper presents a detailed exploration of the advancements in Bandpass Filter (BPF) technologies tailored for 5G wireless communication. With the increasing demand for high data rates, spectral efficiency, and miniaturized hardware, the role of compact and high-performance filters has become critical. The study surveys a wide spectrum of BPF design methodologies, ranging from classical approaches such as lumped element, SAW/BAW, cavity, and planar resonator filters to more recent innovations grounded in metamaterial concepts, including Split Ring Resonators (SRRs) and Complementary Split Ring Resonators (CSRRs). Through a comparative analysis of key performance metrics such as insertion loss, return loss, bandwidth, and form factor, the paper identifies the capabilities and trade-offs inherent in each design approach. Special attention is given to the potential of metamaterial-inspired filters to address the limitations of conventional designs, particularly for sub-6 GHz and mm-wave 5G applications. The review also outlines persistent challenges in the field, such as bandwidth enhancement, integration complexity, and fabrication constraints. It provides future research directions for the development of next-generation reconfigurable and high-selectivity BPFs.*

Keywords *- Bandpass Filter, Split Ring Resonator, Complementary Split Ring Resonator, S Parameters.*

1. Introduction

The 5G communication technology rollout has revolutionized the design criteria for Radio Frequency (RF) front-end components. Among these, BPFs play a pivotal role in ensuring signal integrity by isolating desired frequency bands and suppressing interference. As 5G spans a broad frequency spectrum, including sub-6 GHz and millimetre-wave (mm-wave) bands, it imposes stringent requirements on filter performance. These include low insertion loss, sharp roll-off, wide bandwidth, excellent return loss, high out-of-band rejection, and a compact footprint suitable for integration into increasingly miniaturized systems [1].

Traditional BPF topologies based on lumped elements, cavity resonators, Surface Acoustic Wave (SAW), and Bulk Acoustic Wave (BAW) devices have been widely used in earlier-generation wireless systems. However, their limitations become more evident at higher frequencies required for 5G. Challenges such as increased parasitic effects, limited tunability, and large physical dimensions hinder their scalability and adaptability in advanced RF architectures. Furthermore, planar structures and microstrip-based resonators, while compact and integrable, often suffer from high losses and spurious responses that affect signal fidelity at elevated frequencies.

To overcome these limitations, recent research has increasingly focused on metamaterial-based filters. Metamaterial engineered structures exhibiting negative effective permittivity and/or permeability offer unprecedented control over electromagnetic wave propagation. Within this domain, SRRs and CSRRs have demonstrated unique advantages in enabling miniaturized, high-selectivity, and frequency-tunable filter designs. Their ability to engineer dispersion and resonance characteristics provides a promising pathway toward realizing compact, high-performance filters that align with 5G's demanding specifications.

This review aims to provide a detailed comparative study of various filter design techniques explored in contemporary literature, with a particular emphasis on metamaterial-inspired architecture. By analyzing the trade-offs, performance metrics, and implementation challenges associated with each approach, the paper offers a holistic understanding of current trends and future possibilities in developing BPFs for 5G applications.

2. Literature Review

2.1. Filters based on Lumped Elements

In [2] designed a BPF at 0.8 GHz, 1.8 GHz, and 2.6 GHz utilizing surface-mount components on a 0.51 mm thick Rogers 4003C substrate, occupying an area of 15 x 20 mm². The design initiates with the creation of three Lowpass Filter (LPF) structures, which are subsequently converted into a BPF. The resonators are arranged in a shunt configuration to create the filter structure, which inherently generates transmission zeros between passbands, aiding in the isolation of adjacent frequency bands. Table 1 enumerates the performance indicators.

Table 1. Findings of [2]

Frequency	Transmission Loss	Reflection Loss	Bandwidth
0.8GHz	1.1 dB	~15dB	290 MHz
1.8 GHz	1.4 dB	~15dB	290 MHz
2.6 GHz	1.2 dB	~15dB	~1GHz

In [3], a novel reflectionless filter has been created, occupying a dimension of 30 x 15 mm², which absorbs stopband signals instead of reflecting them, rendering it advantageous for situations where reactive terminations influence system performance. A basic LPF configuration comprises shunt inductors and series capacitors placed symmetrically, with the option to incorporate extra inductors or capacitors to enhance tuning flexibility. Likewise, BPF is constructed by cascading portions tuned to certain lower and upper pole frequencies. The design of the filter is predicated on even-odd mode circuit analysis. In the even mode, both ports are stimulated with equal amplitude and in phase; conversely, in the odd mode, both ports are stimulated with identical amplitude but 180° out of phase. The comprehensive behavior of the symmetric 2-port network is dictated by the amalgamation of the even-mode and odd-mode answers.

The LPF has a peak stopband rejection of 53 dB, while the BPF demonstrates a peak stopband rejection of 43dB. The filters demonstrate a Return Loss (RL) above 25 dB across their passbands. The LPF was tuned to 325 MHz, resulting in significant attenuation beyond this frequency. In comparison, the BPF features a lower cutoff at 110 MHz and a higher cutoff at 310 MHz, establishing a passband of around 200MHz.

In [4, 5] has developed compact, high-efficiency filters for 5G small-cell applications. The LPF is engineered for the 28GHz band, whilst two BPFs are engineered for the 28GHz and 39GHz frequency bands. Filters are produced with the Semi-Additive Process (SAP). The dimensions of the LPF are 4.23 x 1.42 mm², while the interdigital BPF and hairpin BPF measure 3.06 x 2.26 mm² and 3.85 x 1.22 mm², respectively. For the LPF with a center frequency of 29.5 GHz, the lumped element g-values are adjusted to determine the inductance and capacitance values. These are then translated into physical microstrip dimensions utilizing guide wavelengths.

A 28GHz interdigital BPF is built, comprising λ/4 shorted resonators. The resonators are configured in parallel, with spacing modified to regulate coupling and bandwidth. The filter design utilizes Chebyshev polynomial g-values to attain a steep roll-off and uniform in-band ripple.

The hairpin BPF, consisting of U-shaped parallel connected λ/2 wavelength resonators, is constructed using Chebyshev polynomial g-values to minimize the footprint at 39 GHz considerably. The essential metrics of the filter are presented in Table 2.

Table 2. Results presented in [4, 5]

Filter Type	Transmission Loss	Reflection Loss	FBW
LPF	2.0 dB	~17 dB	
Interdigital BPF	2.6 dB	~17 dB	18%
Hairpin BPF	1.4 dB	~15dB	16%

The constraints of filters utilizing lumped elements are enumerated in Table 3.

2.2. Filters Based on Cavity Resonators

In [6], a tunable filter utilizing TE_{011} mode resonators with a mode splitter and dual coupling mechanisms has been developed for Ka band applications. The TE_{011} mode is chosen due to its limited interference from degenerate TM modes and its low insertion loss.

A metal-ring mode splitter, comprising a perimeter channel and a central bore, is integrated into the cavity end walls to differentiate degenerate TM modes. The connection is facilitated by a short iris and a long iris. A tuning plate is affixed to plungers that modifies the cavity length. A sliding contact mechanism guarantees electrical connectivity and consistent functioning.

A pseudo-LPF is constructed utilizing elongated irises for all coupling connections. It attains significant stability owing to the diminished sensitivity of the elongated iris. Likewise, the pseudo-HPF is engineered to integrate large irises for sequential coupling and small irises for cross-coupling.

The center frequency tunability is 500 MHz at the 20 GHz band, but the Bandwidth (BW) tunability ranges from 40 MHz to 160MHz. The Insertion Loss (IL) is around 0.3 dB, whereas the RL is ~17 dB for both filters. The filter is constructed using conventional machining methods for high-frequency cavity filters. The filter's measurements are 110 × 22 × 20 mm^3.

Table 3. Constraints of lumped element-based filters

Factor	Limitations
Parasitic Effects	Demonstrate substantial parasitic effects at high frequencies, which result in performance degradation and unwanted resonance.
Self-Resonance Frequency	An increase in insertion loss and reduced efficiency are the results of the self-resonance frequency of inductors and capacitors being lower than the desired operating frequency.
Miniaturization	As frequency escalates, lumped elements become more substantial.
Bandwidth Control	5G applications necessitate wideband filters, which are challenging to realize using lumped elements owing to their restricted tunability.
Insertion Loss	Lumped element filters have increased insertion loss at elevated frequencies due to the skin effect and dielectric losses in capacitors and inductors.
Large Physical Footprint	Lumped element filters necessitate discrete inductors and capacitors, resulting in increased area usage on a PCB.

In [7], an innovative design of a Ka-band cavity filter aimed at addressing the performance limitations of conventional TE_{011} and TE_{1N} dual-mode filters. The TE_{221} mode is selected due to its improved unloaded Q factor, which is 50% more than that of the TE_{011} mode.

Intra-cavity coupling facilitates coupling two orthogonal TE_{221} modes, with their field patterns rotated by 45° relative to one another within a single resonator. This is essential for achieving dual-mode operation in the resonator. Inter-cavity coupling may be executed by end-wall coupling or sidewall coupling. In end-wall coupling, irises are positioned on the shared walls of neighbouring cavities.

A 4-pole filter is constructed from four resonator cavities interconnected through a combination of radial and angular irises. The IL, RL, and BW of the filter, which occupies a volume of 140 mm × 145 mm × 25 mm, are presented in Table 4.

The filter designed in [8] introduces two new layouts in comparison to the filter in [7] - first, the inline layout and second, the vertical layout. The inline layout is implemented initially, followed by the vertical layout. The cavities of end-launched ports are arranged in a linear sequence in the initial configuration. It incorporates angular irises to enhance spurious performance through inter-cavity coupling. In the second configuration, side-launch ports are designed to be compact by placing all connections on the same side. It incorporates the 2A1R iris configuration to enhance out-of-band performance.

Table 4. Findings of [7]

fc	IL	RL	BW
19.9 GHz	0.4 dB	~17 dB	44 MHz

The filter that is based on the first configuration has an overall dimension of 145 × 35 × 25 mm^3, while the second layout has an overall dimension of 35 × 35 × 25 mm^3.

Ku-band's stepped circular waveguide dual-mode filter [9] is a novel extension of the conventional circular waveguide dual-mode filter—the inclusion of a step in the cavity geometry results in increased spurious suppression and increased design flexibility. Irises are employed to transfer energy between adjacent cavities. Tuning screws are positioned near the electric field's maxima to balance the phases of degenerate modes and modify resonance frequencies. Table 5 contains the efficacy measures of the filter with dimensions of 208 × 30 × 30 mm^3.

Table 5. Results in [9]

fc	IL	RL	BW
10.73 GHz	0.5 dB	~17 dB	54 MHz

In [10], a novel diplexer is developed to achieve high selectivity and compact dimensions by employing a high Q-factor Hybrid Resonator (HR) BPF. The hybrid resonator is designed to be easily integrated with other circuits by incorporating a microstrip line and a short-circuit coaxial line, which functions as a high-Q resonating element to enhance the overall quality factor. Mixed Electromagnetic Coupling (EC) is employed to couple the HRs, resulting in a high selectivity and enhanced bandwidth by combining electric and magnetic coupling.

The filters are constructed using an RT/Duroid 5880 substrate with a thickness of 0.508 mm and an ε_r of 2.2. External interference is mitigated by a metallic enclosure. Having an overall dimension of 27.1 mm × 1.8 mm × 10 mm, the filters exhibit a transmission loss of 1.5 dB and an isolation of 40 dB between the channels. The filters have a passband of 80MHz and 102MHz, respectively, with a centre frequency (f_c) of 2.4GHz and 2.7GHz.

The filter design techniques outlined in [11] are innovative, as they incorporate shape deformation methodologies and the advanced hybrid resonator engineering that was previously discussed in [10]. The HR's design and coupling are identical to those described in [10]. The introduction of shape deformation techniques enables the arbitrary manipulation of 3D geometries through the definition of control points and displacement vectors. The deformation process allows for the bending, twisting, and compressing of resonators and waveguides, as well as the separation of higher-order modes from fundamental modes, which results in wider spurious-free regions and enhanced Q-factors through the optimization of cavity geometry.

Table 6 indicates the performance parameters of the filter, which has an overall dimension of 18.77 × 18.77 × 12.72mm^3.

Table 6. Findings of [11]

fc	IL	RL	BW
14.25 GHz	~0.5 dB	~17 dB	54 MHz

Table 7 summarizes the constraints of filters that utilize cavity resonators.

2.3. Filters Based on SAW and BAW

The design in [12] initiates with a lowpass Bessel filter, characterized as an all-pole filter that has been optimized to achieve a flat group delay. A frequency transformation is subsequently applied to change the LPF into a BPF configuration.

The Bessel-type BPF incorporates SAW or BAW resonators in place of the LC resonators. The design's practical implementation utilizes a Cu-grating/15°YX-LiNbO3 structure, providing significant electromechanical coupling for SH-type SAW. Experimental results indicated a group delay deviation of 3 ns across a frequency range of ±15 MHz cantered at 980MHz. The performance parameters are presented in Table 8.

The proposed filter in [13] utilizes a hybrid RF design methodology, integrating high-Q SAW resonators with lumped-element components for impedance inversion. This method seeks to address the shortcomings of traditional ladder or lattice filters, particularly their limited fractional bandwidth and variations in group delay. The design approach features Acoustic Wave Lumped Resonators (AWLRs) and impedance inverters. Impedance inverters are essential for coupling multiple AWLRs and managing group delay flatness and bandwidth, achieved using lumped inductors and capacitors.

A 2-pole filter comprising two AWLRs linked by three impedance inverters is fabricated on a Rogers RO 4003 substrate. The substrate has a thickness of 1.52 mm and a dielectric constant of 3.55, with dimensions of 15 mm x 7 mm. The performance metric is presented in Table 9.

The design of bandpass filters in [14] utilizes SAW and BAW resonators with Aluminium Nitride (AlN) as the core piezoelectric material for 5G applications. The primary designs are Thin-Film BAW Resonator (TFBAR) and Solidly Mounted Resonator (SMR). TFBAR utilizes an air cavity for energy confinement, whereas SMR employs Bragg reflectors constructed from alternating layers of materials with varying acoustic impedances.

Table 7. Constraints of cavity resonator-based filters

Factor	Limitations
Size and Footprint	Cavity filters are dependent on resonant cavities, which are inherently large and challenging to miniaturize for compact 5G RF front-end applications. Their footprint renders them unsuited for use.
Frequency Scalability	Larger cavities are necessary for the scalability of these filters in sub-6GHz applications, which results in an additional increase in size, weight, and insertion loss.
Manufacturing Complexity	The manufacturing complexity and cost are substantially increased by the necessity of precise fabrication techniques, such as milling, tuning screws, and high-precision material machining, to maintain the performance of cavity filters.
Integration with 5G RF Modules	It is challenging to incorporate cavity filters with planar technologies, which are indispensable for the miniaturization of the 5G front-end module.
Bandwidth suitability	Cavity-based designs are generally not suitable for broadband 5G applications due to their narrowband operation.
Cost and Production Feasibility	The manufacturing complexity and cost are substantially increased by the necessity of precise fabrication techniques, such as milling, tuning screws, and high-precision material machining, to maintain the performance of cavity filters.

Table 8. Results in [12]

Size (mm^2)	IL	RL	BW
4 x 2	5.3 dB	~15 dB	30MHz

Table 9. Results in [13]

f_c	IL	RL	BW
418MHz	1.5 dB	~17 dB	450MZ

Various filter topologies are examined. The ladder-type filter employs series and shunt resonators operating at distinct frequencies. The system exhibits pronounced roll-off characteristics adjacent to the passband, yet demonstrates restricted out-of-band rejection. The lattice filter consists of inductive and capacitive resonators organized in a lattice arrangement. It provides significant out-of-band rejection, although it exhibits a slower slope in proximity to the passband. The stacked crystal filter is constructed using multilayer piezoelectric and metal films, resulting in a compact size and low insertion loss. The coupled resonator filter incorporates a coupling layer that mitigates inter-resonator interactions and offers a bandwidth that is double that of the stacked crystal filter.

The estimated value of IL is 3 dB, while RL is ~ 18dB. The bandwidth is determined by the electromechanical coupling constant and constitutes 5-10% of the center frequency. The dimensions of the filter are 3 mm x 5 mm.

[15] examines the applications of SAW filters, emphasizing advancements in materials, technologies, and design methodologies to meet the growing demands of contemporary communication systems, especially in relation to 5G and high-frequency RF applications. The standard SAW filter features a fundamental configuration comprising Interdigital Transducers (IDTs) and reflectors, making it appropriate for low-frequency and narrowband applications. The dual-mode SAW filters employ several single-mode resonators along with supplementary clamping capacitors, facilitating multimode filtering for sophisticated RF applications. Substrate materials frequently utilized are LiNbO3 and LiTaO3, which provide high piezoelectric coupling. Electrodes, including Al and Ti/Cu multilayer configurations, are utilized to achieve low electrical resistivity, thereby minimizing ohmic loss.

The design of BAW resonators featuring optimized SiO2/Ta2O5 Bragg reflectors for 5G applications, particularly focusing on the N78 band, is examined in [16]. According to [14], SMR is chosen for filter design in 5G applications above 3GHz due to its structural robustness relative to FBARs, superior effective electromechanical coupling coefficients, and potential for wide bandwidth. The resonator structure consists of a Lithium Niobate (LN) film positioned between two Aluminium (Al) electrodes. Bragg reflectors comprise alternating layers of SiO_2, which has low acoustic impedance, and Ta_2O_5, characterized by high acoustic impedance. The Ladder-Type BPF is designed for a center frequency of 3.5 GHz, with the quality metrics presented in Table 10.

Table 10. Findings from [15]

IL	RL	BW	Size (mm^2)
1.9 dB	~19 dB	245MHz	5 x 5

This paper discusses the design of highly doped AlScN-based BAW resonators for 5G RF filter applications, focusing on frequencies near 3.5 GHz for bands n77 and n78, as referenced in [17]. The composition includes 28% Scandium (Sc), which notably improves the electromechanical coupling coefficient relative to undoped AlN. The device is a Cross-Sectional Bulk Acoustic Wave (XBAW) resonator, engineered to confine acoustic waves and reduce energy loss.

The IL is ~ 1.2 dB at the center frequency of 3.5 GHz, while the impedance reflection loss exceeds 18dB. The bandwidth is 216 MHz. The electromechanical coupling coefficient is approximately 15%. The dimensions of the filter are 0.8 mm x 0.8 mm.

In [18], the design of a wideband acoustic transversal filter that is optimized for 5G communication in the n77 band is examined. In the transversal acoustic filter topology, multiple acoustic resonators are connected in parallel branches, each of which creates an independent signal path. Its advantage over the ladder topology is that the BW and transmission zero positions are not influenced by the electroacoustic coupling coefficient, which allows for the creation of arbitrary filter responses. Achieves wideband responses with a reduced number of resonators in comparison to conventional designs. To optimize performance, coupling, impedances, and resonant frequencies may be modified.

The filter has an IL of 2 dB at the center frequency of 3.75GHz and an RL of 16dB. The passband is 910MHz. The electroacoustic coupling coefficient is approximately 13%. The filter measures 0.5 mm x 0.5 mm in its entirety.

Table 11 below lists the filters' limitations based on SAW and BAW.

2.4. Filters based on Plasmonic

[19] examines the development of Substrate-Integrated Plasmonic Waveguides (SIPWs) for microwave bandpass filters. Designed for a frequency range of 7.5-13.0 GHz, the filter is constructed on a Rogers 5880 substrate with a thickness of 0.5mm and a dielectric constant of 2.2, which is composed of copper layers.

SIPWs etch patterned openings on the top and bottom metal layers of the Substrate Integrated Waveguide (SIW) to integrate Spoof Surface Plasmon Polaritons (SSPP) behavior into SIWs. A microstrip-SIW-SIPW-SIW-microstrip configuration is employed in the filter design. Utilizing a tapered microstrip design for broadband performance, the microstrip-SIW transition seamlessly transitions the quasi-TEM to the quasi-TE mode. The SIW-SIPW transition is characterized by a gradual transition from the quasi-TE mode of the SIW to the SSPP mode of the SIPW. This transition is facilitated by a graded slot length, which guarantees seamless momentum and impedance matching. Table 12 denotes the performance metric.

The filter design in [20] integrates SIPW and SSPPs to develop a compact, high-performance microwave BPF. The filter is constructed on a FR-4 substrate with a dielectric constant of 4.3 and a thickness of 0.5mm, intended for a frequency range of 7.3-10.1 GHz. Unlike the rectangular slots discussed in [19], the implementation of fishbone-shaped and hourglass-shaped grooves in [20] significantly enhances the confinement of the electromagnetic field. This improvement is attributed to their gradual geometry and enhanced coupling efficiency.

Table 11. Limitations of filters based on SAW and BAW

Factor	Limitations
Bandwidth Constraints	SAW and BAW filters have been designed predominantly for 2G, 3 G, and 4G applications, necessitating comparatively narrow bandwidths. In 5G, bands like n77 (3.3–4.2 GHz) and n79 (4.4–5.0 GHz) require substantially greater bandwidth than 4G bands. Traditional SAW and BAW methods, especially those utilizing Lithium Tantalate ($LiTaO_3$) and thin-film Aluminium Nitride (AlN), do not possess the necessary electromechanical coupling coefficient to facilitate such broad bandwidth filters.
Frequency Scalability	SAW filters are widely employed in low-frequency applications (<2 GHz); however, they encounter difficulties at high frequencies due to lithographic precision constraints. The spacing of the electrodes dictates the resonance frequency, complicating the attainment of precise and consistent performance at frequencies over 3 GHz. Although BAW can function at elevated frequencies compared to SAW, it encounters limitations when transitioning to sub-6GHz applications. Insertion loss becomes a key concern, diminishing the filter's efficiency at these frequencies.

Table 12. Performance Metric of [19]

f_c	IL	RL	FBW	Size (mm^2)
10.25 GHz	1.5 dB	10 dB	40%	36 x 18

The filter is composed of three main sections. A fishbone-shaped groove structure serves as the transition section, facilitating a smooth transition between the microstrip transmission line and the SSPP/SIPW sections. The filtering section features hourglass-shaped grooves that facilitate SSPP modes for bandpass filtering. The SIPW section serves as the foundational waveguide structure. The performance metric is presented in Table 13.

Table 13. Findings of [20]

f_c	IL	RL	FBW	Size (mm^2)
8.7GHz	~2dB	10dB	32%	34.4 x 12.2

The discussion focuses on the design and implementation of a microwave bandpass filter utilizing SSPPs as outlined in [21]. The design of the BPF utilizes a Rogers 5880 substrate with a thickness of 1.5 mm and a dielectric constant of 2.2, targeting a frequency range from 1.2 to 6.0 GHz. A novel SSPP unit cell structure based on a traditional H-shaped unit cell has been proposed by the BPF. The filter structure is composed of four distinct sections. The CPW serves as the feed to the filter, delivering 50 Ω impedance matching to guarantee minimal reflection and optimal efficiency. The transition structure facilitates the conversion of the mode from the CPW structure to the SSPP structure. The periodic SSPP transmission line facilitates the propagation of SSPP modes. The resonator section utilizes the LC resonator to achieve the bandpass filtering effect. The primary metric is presented in Table 14.

Table 14. Findings of [21]

Size (mm^2)	IL	RL	FBW
26 x 4	2 dB	10 dB	41%

The filter design in [22] utilizes Planar I-shaped Plasmonic Waveguides (PIPWs) to attain ultra-strong field confinement and low-loss SSPPs. The I-shaped grooves represent an advancement over traditional rectangular grooves, featuring lateral extensions at both ends. The filter structure is composed of three distinct sections. CPW serves the same purpose as outlined in [21]. The transition section effectively facilitates the conversion from the quasi-TEM mode to the SSPP mode. The SSPP transmission line section serves as the main filtering area, utilizing I-shaped grooves to attain exceptional field confinement. The filter is constructed with an F4B substrate that has a relative permittivity of 2.65 and a height of 0.5mm, suitable for the frequency range of 1-5.2GHz. The performance metric is presented in Table 15.

Table 15. Findings of [22]

Size (mm^2)	IL	RL	FBW
104 x 35	1.5 dB	12 dB	42%

The constraints of filters utilizing plasmonic principles are outlined in Table 16.

2.5. Filters Based on Planar Resonators

The design of a parallel-coupled dual-mode resonator bandpass filter is examined in [23]. A dual-mode resonator displays two distinct non-degenerate modes. A circuit model for a dual-mode resonator has been devised, represented by a pair of connected resonators incorporating an admittance inverter and susceptance characteristics. A four-pole microstrip filter is constructed using RO4003C substrate with a dielectric constant of 3.36 and a thickness of 0.5 mm, designed for a center frequency of 1 GHz. The observed center frequency decreased marginally from 1 GHz to 0.968 GHz.

Table 16. Constraints of filters utilizing plasmonic principles

Factor	Limitations
Insertion Loss	Plasmonic waveguides experience significant propagation loss in the sub-6 GHz band, attributed to heightened resistance and the constrained efficiency of plasmonic structures. The insertion loss is notably elevated, rendering them inappropriate for 5G front-end modules.
Integration with 5G RF	Plasmonic filters necessitate intricate fabrication techniques, frequently incorporating metallic grooves and subwavelength structuring, which complicates their integration with standard PCB technologies.
Complex Fabrication and Cost Issues	Plasmonic structures necessitate meticulous geometric patterning, including designs like hourglass, fishbone, and T-shaped grooves, which heightens the complexity of fabrication. The elevated production expenses and unconventional manufacturing methods render these filters less appealing for commercial 5G applications.

This alteration can be ascribed to manufacturing tolerances, fluctuations in the dielectric constant of the substrate, and coupling discrepancies in the resonators. The filter exhibited effective stop band rejection, with the initial two spurious resonances occurring at approximately $2.88f_0$ and $3.12f_0$, instead of around $2f_0$. The performance metric is presented in Table 17.

Table 17. Findings of [23]

Size (mm^2)	IL	RL	BW
30 x 20	2.5 dB	15 dB	98.6MHz

The discussion of Ultra-Wideband (UWB) bandpass filters utilizing tapered resonators is presented in [24]. The frequency range of UWB is 3.1 GHz to 10.6 GHz. Tapered transmission line resonators provide benefits such as reduced dimensions, enhanced bandwidth, and superior stopband properties.

The design emphasizes two primary categories of tapered resonators: Exponential Tapered Transmission Line (ETTL), characterized by an exponential variation of impedance along its length, and Linear Tapered Transmission Line (LTTL), defined by a linear variation of impedance along its length. ETTL and LTTL resonators substitute conventional resonators in the design of the UWB BPF. Various taper ratios are employed to regulate bandwidth and stopband characteristics. A higher taper ratio results in a wider bandwidth and improved stopband suppression. The configuration comprises four short-circuited stubs, each separated by uniform transmission lines of identical characteristics. Tapered stubs measure less than fifty percent of the length of the connecting lines. The UWB bandpass filter is implemented on a Rogers RT5880 substrate with a relative permittivity of 2.2 and a thickness of 0.78 mm. The primary metric is presented in Table 18.

Table 18. Performance metric of [24]

fc	Size (mm^2)	IL	RL
6.8 GHz	30 x 20	2.5 dB	15 dB

[25] Introduces a novel category of multilayered ultra-broadband BPF utilizing high impedance slotline resonators, which demonstrate superior radiation loss reduction and enhanced stopband performance.

The proposed resonator substitutes a single short-circuited high-impedance slotline section with two shunt-connected folded low-impedance slotline sections. Thus, it reduces unwanted radiation losses, improves in-band and upper-stopband performance, and enhances impedance matching with microstrip circuits. An ultra-broadband microstrip-to-microstrip vertical transition is designed to integrate the slotline resonators into a multilayered bandpass filter. The transition is modelled using coupled microstrip and slotline resonators. A 7-pole ultra-broadband bandpass filter featuring a Chebyshev equiripple response has been designed utilizing Rogers 4003C substrate, which has a dielectric constant of 2.2 and a thickness of 0.81 mm. The performance metric is presented in Table 19.

Table 19. Performance metric of [25]

fc	Size (mm^2)	IL	RL
2 GHz	21 x 10	1.3 dB	13 dB

[26] presents a microstrip BPF, specifically designed for Bluetooth and Wireless Local Area Network (WLAN) applications. The filter utilizes a polygonal open-loop resonator, optimizing compactness and passband performance while ensuring low insertion loss and effective selectivity. The proposed filter employs two polygonal open-loop resonators, each consisting of 11 segments of varying lengths. This structure permits length variations without expanding the occupied area, in contrast to traditional open-loop resonators. The filter utilizes Rogers RO 3010 substrate, characterized by a relative permittivity of 10.2 and a height of 1.5 mm, at a center frequency of 2.4 GHz. The performance metric is presented in Table 20 below.

Table 20. Results of [26]

BW	Size (mm^2)	IL	RL
230MHz	8 x 16	1.2 dB	25 dB

The limitations of filters utilizing planar resonators are presented in Table 21.

Table 21. Limitations of planar resonator filters

Factor	Limitations
Bandwidth Suitability	Planar resonator filters, including parallel-coupled line filters and dual-mode resonators, are intended for narrowband applications. 5G applications necessitate wide bandwidths, a challenge for planar resonators that often leads to increased loss.
Insertion Loss	Planar resonators exhibit increased insertion loss attributed to conductor and dielectric losses, particularly at frequencies exceeding 3 GHz. 5G bands necessitate minimal insertion loss to optimize RF front-end performance.
Harmonic Suppression	Planar resonators generate undesirable spurious harmonics that impair performance. Additional filtering structures are required to attenuate harmonics, which complicates the design and enlarges the filter's dimensions.

2.6. Filters for mm-Wave Wireless Communication

[27] presents the design of a novel bandpass filter specifically developed for 5G mm-Wave wireless communications. The filter is designed using a microstrip topology.

The primary structural components consist of a rectangular loop resonator, which is the principal resonating structure that enhances electromagnetic coupling, facilitating a broad bandwidth and improved insertion loss. A stepped impedance line stub is introduced at the center of the resonator to regulate the filter's passband frequency and bandwidth. Two symmetrical stubs are incorporated on either side of the main structure to enhance stopband rejection and adjust the distribution of the electromagnetic field. The filter is constructed on a Rogers RT/Duroid 5880 substrate, characterized by a relative permittivity of 2.2 and a thickness of 0.64 mm, at a center frequency of 24.2 GHz. The primary metric is presented in Table 22.

Table 22. Findings in [27]

FBW	Size (mm^2)	IL	RL
7%	13 x 13	1.1 dB	15 dB

[28] discusses the design of a mm-Wave microstrip BPF that employs folded half-wavelength resonators and a Dual-Mode Ring Resonator (DMRR). Three primary sections comprise the filter structure. The filter's principal frequency-selective component is the dual-mode ring resonator. The filter's bandwidth is increased, and the passband symmetry is improved by folded $\lambda/2$ resonators. Each resonator is a $\lambda/4$ structure at the center frequency and is symmetrically positioned on both sides of the ring resonator. They are connected to the DMRR via parallel-coupled lines. The input and output terminals are connected by parallel-coupled microstrip feed lines.

BPF is implemented on Rogers RT/Duroid 5880 substrates with ε_r = 2.2 and a thickness of 0.25mm at two frequencies: 34 GHz and 40 GHz. Table 2-23 below denotes the performance metric.

Table 23. Findings in [28]

FBW	Size (mm^2)	IL	RL
8%	14x 10	2.25 dB	14 dB

[29] presents a filter that is based on SIR and a coupled line. Three sections comprise the filter structure. Parallel-coupled lines are employed at both the input and output terminals to facilitate the transfer of energy from the source to the filter and from the filter to the load. The filter structure employs two-shunt SIRs. The upper resonator is composed of a centrally loaded ring resonator remnant. Two sections with distinct impedances compose the lower resonator. Two open-ended stepped-impedance segments are symmetrically arranged in a shunt configuration. Rogers RT/Duroid 5880 substrate with ε_r = 2.2 and a thickness of 0.25mm is used to implement the filter at 33.5 GHz. Table 24 provides a summary of the primary metric.

Table 24. Results of [29]

FBW	Size (mm^2)	IL	RL
4%	20 x 12	1.2 dB	16 dB

[30] Introduces a multilayer Ka-band BPF utilizing SIW technology. The filter comprises five superimposed layers, with cavities, coupling irises, and input/output signal transmission transitions. Layers 1 and 5 serve as enclosures to contain electromagnetic waves within the structure. It consists of Rogers RT/Duroid 6002 with a relative permittivity of 2.98 and a thickness of 0.508 mm. Layer 2 contains cavities C_1 and C_4, which establish the lower-frequency resonance modes, and includes the input/output feed transition to the waveguide. Layer 3 incorporates vertical coupling irises to facilitate the passage of electromagnetic energy between layers. Layer 4 encompasses cavities C_2 and C_3, which resonate at distinct frequency points, aiding in regulating the filter's bandwidth and selectivity. The filter employs both electric and magnetic coupling to attain the requisite frequency response. The filter was fabricated using a multilayer PCB process with laser micromachining to create air-filled cavities. The principal metric is presented in Table 25.

Table 25. Results of [30]

FBW	Size (mm^3)	IL	RL
10%	7.04 x 17 x 3	1.36 dB	11 dB

In [31] discusses a new 38-GHz SIW BPF utilizing a DGS in its metallic layer. Filter architecture comprises four essential components. The SIW serves as the primary waveguiding structure. E-shaped DGSs are inscribed into the upper metallic layer of the SIW, altering the electromagnetic field distribution and generating notch bands that regulate undesirable harmonics. This enhances out-of-band rejection by incorporating transmission zeros in the upper stopband. The face-to-face E-shaped DGS integrates SIR for accurate bandwidth regulation and E-shaped slots for enhanced notch filtering.

The manufacturing process adheres to conventional PCB methodologies. SIW is processed into Rogers RT/Duroid 5880. Metallic via holes are perforated and coated. DGS is inscribed on the upper layer to augment resonance. The performance parameters at f_c = 38.2 GHz are presented in Table 26.

Table 26. Results of [31]

FBW	Size (mm^2)	IL	RL
8%	5.6 x 2.64	1.7 dB	12 dB

Discussed in [32] is a 28-GHz SIW BPF that includes semicircle modules. SIW serves as the primary waveguiding structure, as previously mentioned in [31]. Semicircle slots are inserted in the upper metallic layer of the SIW. The openings alter the electromagnetic field distribution within the SIW cavity, resulting in two primary effects. fe and f_m are the two primary resonant frequencies that are produced. The weak interaction with slots results in minimal effect on f_e, whereas f_m is significantly influenced, resulting in a downward frequency shift. The coupling coefficient increases as f_m decreases and f_e remains constant. Standard PCB techniques were implemented for via hole drilling and SIW machining. Copper layers were designed to incorporate semicircle slot structures.

The Rogers RT/Duroid 5880 is employed, with a height of 0.127mm and an eigenvalue of 2.2. At 28GHz center frequency, the transmission and reflection losses are 2dB and 15dB, respectively. The filter's dimensions are 4.55 mm x 4.47 mm.

In [33], the dual-mode SIW with dumbbell-shaped DGS is examined. There are three primary components of the filter structure. The principal resonator is the SIW cavity, as discussed in [30]. The first passband (28.3 GHz) is unalterable, while the second passband (38.5 GHz) is adjustable. The second passband is the sole area of the SIW cavity that is influenced by its length, which enables reconfigurability. Input/output coupling is achieved using 50Ω microstrip lines. Standard PCB techniques were implemented for via hole drilling and SIW machining. The DGS slots were engraved in a dumbbell shape using chemical etching and photolithography.

The Rogers RT/Duroid 5880 is employed, with a height of 0.25 mm and an ε_r of 2.2. The RL, IL, and FBW are 16dB, 1dB, and 2% at f_c 28.3 GHz, 28dB, 1dB, and 3% at f_c = 38.5 GHz, respectively. The filter's total surface area measures 10 x 7 mm^2.

[34] Introduces a BPF utilizing the hybrid resonator method tailored for 5G mm-Wave applications. The design of the resonator integrates lumped capacitors with distributed microstrip lines, successfully attaining an ideal equilibrium between compactness and functionality. The placement of lumped capacitors beneath the ground plane contributes to improved miniaturization and electrical coupling. The distributed microstrip lines are positioned above the ground plane, facilitating resonance and coupling between resonators. Optimized 50Ω microstrip feed lines guarantee minimal reflection loss and effective impedance matching.

The filter utilizes a Ferro A6-M LTCC substrate characterized by a relative permittivity of 5.7 and a thickness of 10µm. Several layers of Ferro A6-M LTCC have been meticulously stacked and aligned. Laser drilling is utilized to create via holes, while electroless copper plating is employed to establish electrical connections. Patterns for conductors in microstrip and lumped elements are printed onto various layers. The performance parameters are presented in Table 27. The BPF developed at 28GHz utilizing traditional microstrip technology is examined in [35]. The filter structure is composed of three resonators, including two hairpin resonators and one zigzag resonator.

The hairpin resonator reduces the overall filter size by folding the resonator structure, enhances inter-resonator coupling, and aids in confining the electromagnetic fields within the PCB. The zigzag resonator is composed of two segments that are grounded via tape to improve inter-resonator coupling. It improves bandwidth and stopband rejection. The coupled feed transmission line employs a tapered microstrip configuration to ensure seamless impedance matching.

Table 27. Results of [34]

Parameter	Filter-1	Filter-2
Transmission Loss	1.3 dB	1.1 dB
Return Loss	15 dB	15 dB
FBW	18%	18%
Size (mm^2)	0.79 x 0.94	0.86 x 1.22

The filter is constructed on a Rogers 4003C substrate with a relative permittivity of 3.55 and a thickness of 0.20 mm. The parameters of the output are organized in Table 28.

Table 28. Results of [35]

IL	RL	FBW	Size (mm^2)
4 dB	~10 dB	7 %	14.85 x 15.96

The discussion focuses on a highpass filter utilizing CSRR for applications in the Ka band, as detailed in [36]. The filter employs a microstrip transmission line designed with an optimized width to achieve 50Ω impedance matching. The parallel-coupled lines significantly enhance electric field coupling, leading to improved filter selectivity and better impedance matching. Rectangular open-circuited stubs are strategically positioned at both ends of the microstrip transmission line to enhance coupling, thereby improving impedance matching. The CSRR serves as a crucial element in the design of the proposed high pass filter. This introduces a negative permittivity effect, which alters the transition between left and right-handed materials. The intersection of the LH and RH bands enhances the high pass response, leading to an expanded passband. The cutoff frequency is modified by altering the dimensions and placement of the CSRR. It is inscribed directly on the ground plane, located beneath the microstrip transmission line, and meticulously aligned with the inter-digital coupled structure. The effects of negative permittivity from CSRR interact with the electric field of the microstrip, modifying the transmission characteristics and thereby regulating the transition between stopband and passband through the creation of a high-impedance surface.

The filter utilizes an Arlon 5880 substrate with a dielectric constant 2.2 and a height of 0.8mm, optimized for a center frequency of 34.1GHz. The parameters of the output are organized in Table 29.

Table 29. Findings of [36]

IL	RL	FBW	Size (mm^2)
1.5 dB	~15 dB	5%	10 x 6

Table 30 summarizes the limits of filters in mm-Wave applications.

2.7. Filters based on Split Ring and Complementary Split Ring Resonators

The design of an SRR-based BPF centered at 2.4 GHz is presented in reference [37]. The SRR structure consists of two concentric rings: the outer and inner rings. Key characteristics include the ring gap, inter-ring gap, ring length, and ring width.

The filter, in conjunction with SRR, incorporates a coupling element defined by parameters such as strip length, strip width, and strip gap. A transmission line-based feed line is utilized for interfacing the filter with external circuits. The influence of ring parameters on filter response is presented in Table 31. The filter design incorporates three SRR elements configured in a sequential arrangement, with inter-element distances optimized for performance.

Table 30. Limits of the filters in mm-wave

Factor	Limitations
Insertion Loss	Increased insertion loss can negatively impact signal strength and power efficiency. LTCC and SIW filters exhibit reduced insertion loss; however, this advantage comes with heightened fabrication complexity.
Fabrication Complexity and Cost	SIW and LTCC filters necessitate multilayer fabrication, resulting in high costs and manufacturing complexity.
Size Constraints	Certain designs necessitate a larger area, complicating the integration with compact 5G devices.
Stopband Performance and Spurious Responses	Certain designs exhibit a constrained FBW, limiting their capacity to accommodate broadband 5G applications.
Bandwidth Limitations	Certain filters exhibit inadequate stopband rejection, resulting in undesirable signal leakage.

The filter is constructed using Rogers RT/Duroid 6010/6010LM substrate, which has a relative permittivity of 10.2 and a height of 1.9 mm. The performance parameters of the filter, which covers an area of 25 x 19 mm², are detailed in Table 32.

A parallel-coupled microstrip filter that integrates SRR and CSRR, designed for operation at 1GHz, is presented in [38]. The fundamental configuration of the filter consists of a parallel-coupled microstrip line, which delineates the passband characteristics.

Two-step impedance stubs are symmetrically positioned around the center of the parallel-coupled microstrip resonator. The fundamental architecture exhibits issues with spurious harmonics and inadequate stopband rejection. These challenges can be addressed through the incorporation of SRR, CSRR, and stepped impedance stubs. The addition of stepped impedance stubs has resulted in improved selectivity. The implementation of SRR and CSRR has resulted in a notable improvement in insertion loss, demonstrating excellent stopband rejection from 1.22 GHz to 5 GHz, effectively eliminating spurious harmonics.

The resonator is constructed on a FR-4 substrate with a permittivity of 4.4 and a height of 1.6 mm. The performance parameters of the filter, which covers an area of 30 x 18 mm², are summarized in Table 33.

Table 31. Effect of ring parameters on frequency response

Parameter	Effect
Ring Length	Increasing the ring length shifts the centre frequency downward. The RL, IL and BW remain relatively stable with slight variations.
Ring Width	Increasing the ring width shifts the centre frequency upward. The RL and IL remain relatively stable with slight variations. However, the BW varies from 50MHz to 100MHz.
Ring Gap	Increasing the ring gap shifts the centre frequency higher. RL relatively improves while IL is stable. The BW increases from 75MHz to 100MHz.
Inter-Ring Gap	Increasing the inter-ring gap shifts the center frequency higher. IL and RL improve, while the BW remains relatively stable.

Table 32. Findings of [37]

f_c	IL	RL	FBW
2.4GHz	2.5 dB	16 dB	5%

Table 33. Findings of [38]

f_c	IL	RL	FBW
1.0 GHz	1.1 dB	~16 dB	21 %

In [39] outlines the design of a narrowband BPF tailored for X-band applications, utilizing a circular-shaped SRR featuring two concentric rings. The microstrip feedline serves as the connection between the SRR and the external circuit. The filter design undergoes optimization through systematic modifications of key parameters of the SRR, aimed at enhancing the filter's response regarding return loss, insertion loss, and center frequency accuracy. Modifying the ring gap results in an upward shift of the center frequency when increased, and a downward shift when decreased. Increased ring widths lead to an upward frequency shift, whereas decreased ring widths result in a downward frequency shift. The alteration of spacing between the rings does not influence the frequency.

The filter has a total area of 25 x 22 mm² and is constructed on a Roger RT/Duroid 5880 substrate with a relative permittivity of 2.2 and a thickness of 0.5 mm. The primary metric of the filter is presented in Table 34.

Table 34. Findings of [39]

f_c	IL	RL	FBW
9.0GHz	3.7dB	15dB	1%

In [40] analyses the EC between two identical SRRs and a CSRR. A dual-band BPF is designed in the first configuration utilizing twin SRRs, which are positioned with a minimal coupling gap between them. The SRR gaps are oriented in the outward direction. The frequency response reveals that the two pass bands at 5.02 GHz and 8.92 GHz exhibit a lack of sharp transition between them, suggesting weak coupling. In the second configuration, the alignment of the gaps facing each other resulted in enhanced coupling, which facilitated an increase in bandwidth from 230 MHz to 320 MHz in the lower band. In the third configuration, the inclusion of CSRR resulted in a significant enhancement of the coupling between the twin SRRs, thereby improving the overall performance of the filter. The CSRR implemented a notch filtering effect, successfully removing undesired signals within and outside the passband. The filter demonstrated more pronounced transitions. The enhancement in the critical parameters is detailed in Table 35.

The performance metric of the filter, which occupies an area of 16 x 24 mm², is designed on a Rogers RO4003 substrate with a relative permittivity of 3.55 and a thickness of 0.85 mm, and is indicated in Table 36.

A microstrip BPF incorporating a circular SRR is presented in reference [41]. Microstrip feed lines, engineered for 50Ω impedance matching, are utilized to excite the SRR and enable signal transmission. The SRR serves as the primary resonating structure within the filter, comprising two concentric circular rings that are positioned with gaps to induce capacitive effects. Electromagnetic waves interact with the SRR, resulting in the induction of charge oscillations. The gaps function as capacitors, facilitating the storage and release of electromagnetic energy at a designated frequency. The inductance of the rings and the capacitance of the gaps create an LC circuit, which establishes the resonant frequency.

Table 35. Comparison between different filter configurations

Parameter	Configuration -1	Configuration -2	Configuration -3
Lower band fc	5.02GHz	No shift	No shift
Upper band fc	8.92 GHz	No shift	No shift
Lower BW	230MHz	Unchanged	Unchanged
Upper BW	280MHz	Increased	Increased
Selectivity	Weak	Moderate	Improved
Stop band rejection	Weak	Moderate	Improved

Table 36. Performance metric of [40]

Parameter	Lower Band	Upper Band
IL	6.22dB	5.23dB
RL	12.67dB	18.78dB
FBW	6 %	3%

The filter is designed on a Rogers RT/Duroid 6010 substrate with a relative permittivity of 11.4 and a height of 1.9mm. Table 37 summarizes the quality metrics.

Table 37. Performance metric of [41]

f_c	IL	RL	FBW	Size (mm^2)
2.4GHz	1.3 dB	18.8 dB	5%	25 x 25

The influence of different dielectric constants and substrate height is critical in establishing the resonant frequency, bandwidth, and overall performance of the Square Shaped Double Split Ring Resonator (S-DSRR), discussed in [42].

The influence of substrate permittivity and thickness on the resonant frequency and bandwidth is presented in Table 38. In contrast, the influence of substrate thickness on transmission loss and electromagnetic coupling is presented in Table 39.

The discussion on the parallel-coupled line BPF that integrates double CSRRs can be found in [43]. Two etched ring resonators are positioned on the ground plane. Microstrip-based parallel coupled lines serve the purpose of signal coupling and transmission. The design of the filter was optimized through the variation of key parameters that influence frequency response, BW, and IL, as detailed in Table 40.

The filter is constructed using a Rogers RT/Duroid 5880 substrate with a relative permittivity of 2.2 and a thickness of 0.5 mm. Table 41 summarizes the quality metrics.

In [44] presents the design of a band-stop microstrip filter utilizing SRR metamaterial. This study examines the impact of varying the number of SRRs embedded in the microstrip substrate on essential performance parameters. The application of one SRR results in an attenuation of ~ 4.4 dB, leading to a narrower bandwidth.

Increasing the count to 3 results in an attenuation of ~ 19 dB and a broader bandwidth, while raising the count to 6 yields an attenuation of around 30 dB and further broadens the bandwidth. Each SRR interacts with the incident electromagnetic wave, and the presence of multiple SRRs enhances the resonance effect. This enhances energy absorption, thereby improving stopband rejection.

Table 38. Effect of substrate permittivity and height on frequency and bandwidth

Parameter	Resonant Frequency	Bandwidth
Substrate Permittivity	An increase in the ε_r results in a higher effective capacitance of the SRR, which in turn lowers the resonant frequency. Conversely, a decrease in the ε_r reduces capacitance, causing the resonant frequency to shift higher.	The increase in the ε_r results in a higher effective capacitance of the SRR, which leads to a narrowing of the BW. Conversely, a decrease in the ε_r results in reduced capacitance, thereby widening the BW.
Substrate Height	Increasing the substrate height results in a slight increase in effective capacitance, which in turn leads to a decrease in resonant frequency. Conversely, decreasing the substrate height reduces the capacitance, causing the resonant frequency to shift higher.	Increased substrate thickness results in a broader bandwidth due to the accommodation of additional fringing fields, which improves the coupling between resonators. Thinner substrates lead to a reduction in bandwidth due to the tighter confinement of electromagnetic energy.

Table 39. Effect of substrate thickness on insertion loss and electromagnetic coupling

Insertion Loss	Electromagnetic Coupling
Thicker substrates result in elevated losses, leading to an increase in insertion loss. Thinner substrates enhance energy confinement, leading to a reduction in insertion loss.	Increased substrate thickness improves electromagnetic coupling between SRRs because of enhanced fringing fields. Reduced substrate thickness results in diminished coupling, thereby constraining the interaction strength.

The filter is constructed on a Rogers RT/Duroid 5880 substrate with a relative permittivity of 2.2, a height of 0.794 mm, and occupies an area of 32 mm x 5 mm. The filter demonstrates enhanced rejection at lower frequencies, achieving approximately 39dB at 3.21GHz, which decreases by about 12dB at higher frequencies, specifically 9.98GHz. Higher frequencies necessitate SRRs with smaller radii to achieve optimal rejection. At 3.21 GHz, the widest BW of 450 MHz was observed, allowing strong rejection over a broader range. However, at 5.64 GHz and 9.98 GHz, the BW is narrower by 140MHz, meaning the rejection is more frequency specific.

The design of a BPF employing SRR for operation at 2.4 GHz, 4.5 GHz, and 5.2 GHz is presented in [45]. Three rectangular-shaped SRR unit cells are employed, with each cell corresponding to one of the three resonant frequencies. The microstrip transmission line serves as the primary signal pathway. The etched slot at the center of the transmission line enhances frequency selectivity. The parametric analysis of SRR dimensions facilitated the optimization of impedance reflection and transmission loss. The increase in width enhanced the RL, while the increase in length enhanced the IL.

Table 40. Impact of different parameters on BPF frequency response

Parameter	Effect on Frequency Response
CSRR Gap Distance	Tighter gap results in a wider BW but increases IL; a weaker gap leads to a narrower BW.
Feed Stub Length	A longer stub enhances coupling; however, it may also lead to the introduction of spurious resonances.
Feed Line Spacing	Reducing the spacing enhances impedance matching.

Table 41. Quality metrics of filter in [43]

f_c	IL	RL	FBW	Size (mm^2)
3.6 GHz	1.6 dB	~17 dB	5%	27 x 14

The filter, measuring 26 x 18 mm², is constructed on a FR-4 substrate characterized by a dielectric constant of 4.3 and a thickness of 1.6 mm. The quality metrics are presented in Table 42. [46] Details the design and optimization of a metamaterial-based cut-band filter utilizing SRR arrays. This study examines the impact of various SRR configurations on the bandwidth and rejection level of the filter. The filter design utilizes SRR arrays coupled to a microstrip transmission line on FR-4, which has a thickness of 1.6 mm and a relative permittivity of 4.4.

Table 42. Quality metrics of filter in [45]

Frequency	IL	RL	BW
2.4 GHz	1.0 dB	~18 dB	170MHz
4.5 GHz	1.4 dB	~18 dB	240MHz
5.2 GHz	2.1 dB	~16 dB	390MHz

The initial filter design comprises seven SRRs, each measuring 5 mm, positioned at intervals of 5.5 mm along the microstrip line. Augmenting the quantity of SRRs enhances the rejection level while maintaining the narrowband response. Various combinations of SRRs of differing sizes were evaluated to expand the stopband. In the initial configuration, the two outermost SRRs measure 4.5 mm and 5.5 mm, respectively, while the central SRRs maintain a size of 5 mm. Bandwidth has improved; however, the rejection level is still constrained to 12dB.

In the second configuration, the size of the SRR increases incrementally from 4.7 mm to 5.3 mm. The rejection performance is superior to that of the initial configuration. Furthermore, a notable enhancement in bandwidth is observed without an increase in filter size. Increasing the number of SRRs per row enhances electromagnetic coupling, thereby improving rejection. The implementation of two rows of 5 mm SRRs results in enhanced coupling and increased rejection depth. Conversely, the addition of a third row reduces the transmission level to 35 dB, thereby improving cut-band filtering.

3. Results and Discussion

This review highlights the evolving landscape of BPF design in response to the stringent demands of 5G communication systems. The surveyed literature reveals that filter performance is heavily influenced by design topology, substrate material, and resonator configuration. Key performance parameters such as IL, RL, BW, and form factor vary significantly across different filter technologies.

3.1. Comparative Performance Across Filter Types

Conventional filters, such as lumped element and cavity-based designs, offer simplicity and high-Q performance but face scalability issues. Lumped-element filters exhibit high IL at higher frequencies due to parasitic inductance and capacitance. While low in loss, Cavity filters are bulky and unsuitable for integration in compact 5G RF modules.

SAW and BAW filters are effective in lower frequency bands and are well-suited for narrowband applications. However, their limited bandwidth and challenges in scaling above 3 GHz reduce their viability for wideband 5G applications, especially in the n77 and n78 bands.

Planar and plasmonic filters offer better integration potential, with moderate performance in terms of IL and RL. However, they require complex fabrication and often suffer from spurious resonances and high propagation losses, particularly below 6 GHz.

3.2. Role of Metamaterial-Based Filters

Metamaterial-based filters, particularly those incorporating SRRs and CSRRs, have garnered considerable attention in recent years as viable solutions to the limitations of conventional BPF designs in 5G applications. Unlike traditional structures that rely solely on natural material properties, metamaterials are engineered to exhibit tailored electromagnetic responses, such as negative permittivity (ε) and permeability (μ), which are not found in naturally occurring media. These properties enable unprecedented control over signal propagation, leading to compact, frequency-selective, and highly customizable filter designs.

3.2.1. Miniaturization and Integration

One of the most significant advantages of SRR and CSRR-based designs is the ability to achieve substantial size reduction without sacrificing performance. The resonance in SRRs is achieved through the creation of artificial LC circuits formed by the ring structure's geometry, where the metallic loops act as inductors and the gaps create capacitance. This artificial resonance occurs at sub-wavelength dimensions, allowing filters to operate at desired frequencies using far smaller structures than traditional λ/2 or λ/4 resonators. This makes metamaterial filters highly attractive for 5G front-end modules, where PCB real estate is limited and multi-band integration is essential. Their planar form factors are also compatible with low-cost printed circuit fabrication, supporting mass production and system-on-chip integration.

3.2.2. Frequency Selectivity and Tunability

Metamaterial-based BPFs exhibit excellent frequency selectivity due to the sharp resonant behavior of SRRs and CSRRs. By altering geometrical parameters such as ring size, ring width, inter-ring gap, and substrate characteristics, designers can achieve fine-tuned control over center frequency and bandwidth. This level of flexibility is advantageous for adapting filters to different 5G bands (e.g., n77, n78, and mm-wave bands).

Moreover, these structures can be extended to support reconfigurable or tunable filters by incorporating varactor diodes, MEMS switches, or ferroelectric materials. This enables real-time frequency agility, a key requirement for future dynamic spectrum allocation in 5G and beyond.

3.2.3. Dual and Multi-Band Operation

Another notable capability of SRR/CSRR configurations is their adaptability to dual-band or multi-band operation. By cascading or embedding multiple resonators with varying dimensions on the same substrate, multiple passbands can be created, each tuned to a different frequency. Such architectures can support the coexistence of multiple services, such as 2.4 GHz IoT, 3.5 GHz mid-band 5G, and 5 GHz Wi-Fi in a compact, single-package filter design. For example, as reviewed in reference [45], using three SRR unit cells enabled simultaneous filtering at 2.4 GHz, 4.5 GHz, and 5.2 GHz, with satisfactory insertion and return loss metrics. This ability to customise frequency behavior using a single metamaterial framework is particularly valuable for multi-standard, multi-band wireless devices.

3.2.4. Enhancement of Stopband Performance

The negative refractive index of SRRs and CSRRs introduces transmission zeros and sharp notches that help suppress unwanted harmonics and adjacent-band interference. When integrated with stepped impedance stubs or defected ground structures (DGS), the rejection and selectivity can be further improved. As demonstrated in [38, 40], combining CSRRs with parallel-coupled microstrip resonators significantly improved stopband rejection and spurious suppression without enlarging the footprint, making them suitable for dense 5G network environments prone to interference.

4. Future Scope

The evolution of BPF technologies is central to meeting the rapidly growing demands of 5G and beyond wireless communication systems. While metamaterial-based filters, especially those employing SRRs and CSRRs, have demonstrated significant advantages in terms of miniaturization, frequency selectivity, and design flexibility, several research directions remain open for further exploration and optimization.

4.1. Development of Reconfigurable and Tunable Filters

As 5G networks continue to adopt dynamic spectrum allocation and carrier aggregation, filters are increasingly needed to adjust their center frequency and bandwidth dynamically. Future research should focus on integrating varactor diodes, PIN diodes, MEMS switches, or ferroelectric materials within SRR and CSRR structures to enable real-time frequency tunability and reconfigurability, while maintaining low insertion loss and stable performance.

4.2. Multi-Band and Wideband Metamaterial Designs

The design of multi-band and UWB filters using composite or nested SRR/CSRR structures presents a promising area of study. Developing innovative geometries such as fractal SRRs, meandered rings, or nested ring arrays can enable compact designs with multiple resonant modes, allowing a single filter to support multiple 5G bands (e.g., n77, n78, and mm-wave allocations). This is particularly critical for modern RF front ends where integration and versatility are prioritized.

4.3. Hybrid Filter Architectures

Combining the strengths of different technologies, such as metamaterials, DGS, SIR, and SIW, can produce hybrid filters with enhanced bandwidth, stopband suppression, and miniaturization. Future studies may focus on exploring the optimal configuration of these hybrid designs to achieve broadband operation with minimal spurious emissions, especially in mm-wave bands where performance degradation is more pronounced.

4.4. AI-Driven Optimization and Modeling

With the complexity of modern filter structures and the multitude of design parameters involved, incorporating artificial intelligence (AI) and machine learning (ML) techniques into the filter design process is a future-forward approach. AI algorithms can assist in predicting optimal geometries, reducing simulation time, and achieving automated performance tuning, which can accelerate development cycles and enhance design accuracy.

4.5. Advanced Substrate and Fabrication Technologies

The choice of substrates significantly influences the performance of high-frequency filters. Future research can explore novel substrate materials (e.g., flexible polymers, nanocomposites, or LTCC/HTCC ceramics) that offer low dielectric losses, mechanical robustness, and compatibility with multilayer integration. Additionally, additive manufacturing (3D printing) and laser micromachining can be leveraged to fabricate complex metamaterial structures with high precision and repeatability, especially for miniaturized mm-wave devices.

4.6. Integration with 6G and IoT Platforms

As the communication ecosystem moves toward 6G and large-scale IoT deployment, the demand for filters that are ultra-compact, energy-efficient, and capable of operating at THz frequencies will become critical. Metamaterial-based designs, with their inherent scalability and customizability, offer a viable foundation for developing next-generation filters for THz-band communication, wearable devices, and edge sensors in pervasive IoT environments.

5. Conclusion

This review comprehensively examines BPF technologies developed to meet the stringent performance demands of 5G communication systems. Through an in-depth analysis of various design methodologies, including lumped element filters, cavity resonators, SAW/BAW devices, planar and plasmonic structures, and advanced metamaterial-inspired architectures, the paper highlights the strengths, limitations, and applicability of each approach across different 5G frequency bands. While traditional filters offer simplicity and proven performance at lower frequencies, their scalability and bandwidth limitations pose significant challenges for high-frequency and compact 5G applications.

In contrast, metamaterial-based filters, particularly those utilizing SRRs and CSRRs, demonstrate promising potential due to their sub-wavelength resonance capabilities, compact form factor, and tunable frequency behavior. These structures offer enhanced control over insertion loss, return loss, and fractional bandwidth, and can be engineered for multi-band operation through geometric optimization. The discussion further underscores that although metamaterial filters are well-suited for sub-6 GHz and low mm-wave 5G applications, challenges such as limited bandwidth, fabrication sensitivity, and higher insertion losses in certain configurations remain open research areas. Moreover, the integration of metamaterials with hybrid topologies, tunable components, and AI-assisted design processes presents a forward-looking approach to filter innovation.

In conclusion, metamaterial-inspired BPFs represent a transformative solution for next-generation wireless communication systems. Their ability to balance compactness, selectivity, and performance makes them strong candidates for future 5G and 6G RF front ends. Continued research and development in this field will be essential to fully unlock their potential and meet the evolving requirements of high-speed, high-capacity communication networks.

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