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Review Article

A Comprehensive Survey on Microwave Photonic Filter: Design Techniques and Implementations

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Abstract

Microwave photonic filters (MPFs) have been suggested as one solution to high-speed tunable wideband radio-frequency (RF) signal processing possessing unique characteristics relative to their all-electronic counterparts (or equivalents), both in bandwidth and tunability and insensitivity to electromagnetic interference. The article is a review of MPF design technologies and applications, and also contains relevant techniques in thermal, electrical and optical tuning as well as new methods founded on stimulated Brillouin scattering, optical frequency combs, and micro-ring resonators. The survey focuses on programmable optical processors, including liquid-crystal-on-silicon designs, arrayed waveguide gratings, and cascaded resonator designs, as arbitrary filters synthesis. Critical consideration is done on performance metrics which include bandwidth, selectivity, out-of-band rejection and tuning range, energy efficiency and other practical factors like stability in the environment and complexity of fabrication. The latest advances in reconfiguration with the help of artificial intelligence and machine learning are presented, and their significance in the optimization of adaptive and predictive filters is also highlighted. The paper also discusses the current constraints such as integration, power consumption, and environmental sensitivity and has provided directions of future achievability of compact, low-power and ultrafast and highly flexible MPFs to next-generation RF communication, radio-over-fiber, and cognitive radio systems. The survey should be used as a source of reference to the researchers and engineers who seek to improve the development, testing, and real-life application of the state of art technologies in the field of microwave photonic filtering.

Keywords
Microwave Photonics, Optical Filters, Reconfigurable Filters, Integrated Photonics, Ring Resonator

I. INTRODUCTION

Microwave photonics (MWP) during the past two decades has evolved into a vital cross-disciplinary field that combines the power of microwave (RF) engineering and optical (photonics) technologies to satisfy the ever-growing stringent needs of high-frequency, wide-bandwidth, and reconfigurable signal-processing systems. As communication networks reach into millimeter-wave frequencies and beyond, radar and electronic-warfare systems require tunable and agile front-end filtering, and distributed antenna systems require low-loss RF transport of signal over optical fiber, the limitations of dedicated electronic filters become increasingly severe [1]. Electronic filters are frequency-bandwidth limited, scale poorly, experience increasing loss at higher frequency, are sensitive to electromagnetic interference, and possess limited agility. In contrast, photonic devices offer ultra-wide bandwidth, immunity to electromagnetic interference, low attenuation in long ranges (using optical fiber), and the potential for wide-tuning and rapid reconfiguration. This introduces the field of microwave photonic filters (MPFs) optical devices that perform RF-filtering functions by converting microwave signals to the optical domain, processing them using photonic devices, and back-converting them to the RF domain [2].

The principal benefit of an MPF is that it can exploit the large time-bandwidth product of optics: fiber or waveguide delay lines can achieve long delays without the large size of equivalent RF delay networks; High-Q filtering with compact form is achieved by optical resonators or Bragg gratings; and tuning in the wavelength, optical switching, or programmable spectral shaping allow dynamically tunable filter responses [3]. Thus, MPFs have been proposed and demonstrated for many demanding applications: next-generation wireless communication (5G/6G and beyond), microwave photonic radar, radio-over-fiber (RoF) networks, distributed antenna systems, and high-resolution sensing platforms. For example, these filters enable functionalities such as rapidly tunable band pass/notch filters, multi-band filters, true-time-delay beam-forming front-ends, and phase-shaping networks all that have the potential to surpass purely electronic realizations. Recent publications review the increasing interest in MPFs and their integration into photonic-integrated circuits (PICs) owing to system size, weight, power (SWaP) constraint and deployment in aerospace/defense and miniaturized wireless nodes [4].

In RF front-ends, filtering is mandatory in selecting the favored signal band, suppression of interferences/spurs, receiver protection against strong out-of-band signals, and determination of the spectral response for optimal dynamic-range and noise-figure performance. As frequencies increase and systems increase their instantaneous bandwidths, conventional microwave filter methods are faced with practical limits: it becomes harder to design High-Q resonators; coupling and parasitic gain control; size and expense grow; and tuning agility is typically limited [5]. Photonics for the first time introduces a paradigm: by modulating an optical carrier with the RF signal, transferring the RF frequency components into optical spectral components, employing a photonic filter (which can be reconfigurable in wavelength or delay), and then photo detecting the output, an efficient RF filter is realized, whose center frequency, bandwidth, and shape are controlled by the optical-domain processing. This rule of mapping is the foundation for many MPF architectures and provides design flexibility that is not readily achievable in electronics [6].

Over the years, there has been a very wide taxonomy of MPF architectures including multi-tap tapped-delay structures based upon fiber or waveguide delay, to resonator-based filters (rings, MZIs, FBGs), to more exotic solutions such as stimulated Brillouin scattering (SBS) filters or optical frequency-comb shaped filters. Each category offers distinct compromises in tuning range, resolution (filter bandwidth), dynamic range, insertion loss, and implementation complexity [7]. For example, tapped-delay (FIR) structures offer programmable arbitrary filter profiles by weighted and delayed optical taps but with limited spurious pass-bands and delay-length scaling; narrowband and compact resonator-based filters typically require thermal/electrical tuning and suffer larger losses; SBS-based filters offer ultra-narrow linewidths and high selectivity but suffer from power, complexity and integration challenges. MPF integration onto photonic chips is now an active area of priority, employing silicon, silicon-nitride, InP or hybrid material platforms for miniaturization, reduction of cost and improvement of robustness. More recent examples include chip-scale Brillouin-based filters with MHz resolution and on-chip modulators and photodetectors [8].

Notwithstanding spectacular progress, MPFs are yet to overcome a number of obstacles before they get the mainstream commercial approval. The trade-off between tuning speed and tuning range, and bandwidth-selectivity (Q-factor), are not trivially determined. They include the insertion loss, Opto-electrical noise, polarization dependency, thermal drift and packaging/integration loss that continues to impose performance penalties upon ideal models [9]. Precisely, SFDR and maintenance of linearity of the optical link are crucial issues in the process of converting optical filtering to RF filtering operations. Moreover, photonic integration as promising as it appears to be involves shortening the coupling loss, heater power dissipation, and waveguide dispersion in addition to having many taps or channels. This provides the field with plenty of linearity to gain the innovation of material, architectural, control, and co-design of the photonic and RF subunits [6].

This survey paper will provide an integrated response to microwave photonic filter design methods, including the background theory, classification of the architectures, technologies that enable solution, current developments and future projections. We start with the characterization of physical mapping physical-RF domain, a list of the basic filter topologies, performance compromise and implementation issues, and practical implementation components and integration platforms. We also emphasize state of the art demo at high bandwidth, low line, configurable and integrated. Lastly, we emphasize some of the current challenges and areas of future research, including AI-assisted filter synthesis, reconfigurable photonic processors, real-time-delay beam-forming integration, and chip-scale filters to future wireless and radar front-ends. It is our intention that by introducing this roadmap, both new researchers who are already breaking new grounds in this area and practitioners who may wish to implement MPFs in actual RF systems can look up to this roadmap.

The uniqueness of this book review compared with other reviews focusing on microwave photonic filters is that it makes several special contributions. Firstly, it makes use of theme grouping techniques from the MPF technologies that have better clarity and understanding on the classifications and structures. Secondly, instead of just highlighting other reviews on the field, the book review will carry out a critical trade-off analysis that compares the strengths and weaknesses and overall performances of various MPF technologies. Thirdly, instead of just highlighting various MPF technologies and their requirements, it also provides analyses and comparisons that carry out assessments on various parameters such as bandwidth, Q-factor, and other parameters such as out-of-band and insertion loss on various designs and technologies within the MPF field. Fourthly, it also provides indications on various gaps and future research ideas and recommendations within the field of MPF.

II. FUNDAMENTAL PRINCIPLES OF MICROWAVE PHOTONIC FILTERING

One of the most important functional blocks in present day microwave photonic systems is Microwave Photonic Filters (MPFs). They are used to travel high frequency RF or microwave signals by converting the manipulation of the signal to the optical domain. The peculiarity of MPFs is that they can reach the characteristics of ultra-wide bandwidth, low loss, and high re-configurability performances unavailable when using traditional electronic filters. Photonic filtering allows the optimization of radio frequency (RF) information to facilitate efficient signal processing in communication systems, radar systems, and systems in

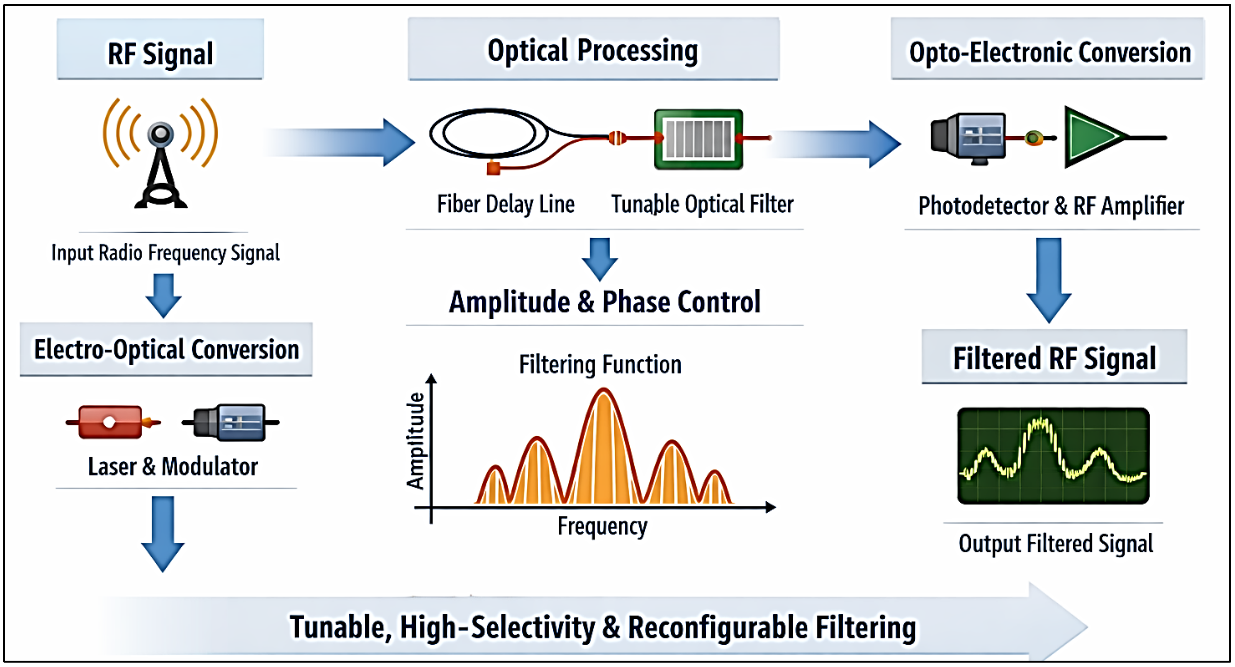


Fig. 1. Fundamental principles of MPF

sensing systems operating over frequencies ranging between a few gigahertz (GHz) to a few terahertz (THz) [6].

The basic idea of MPFs is optical-to-RF mapping, in which the optical spectrum is controlled to achieve desired RF frequency response. The response of the filter can be influenced not only by the optical elements provided in a system as lasers, modulators, optical filters, and photodetectors, but also by their interconnections and coherence. Depending on the architecture, MPFs may imitate finite impulse response filtering (FIR), infinite impulse response filtering (IIR), or one of the two combined. These underlying principles are discussed in the following subsections [10]. Fig.1 shows block diagram illustrating the fundamental principles of microwave photonic filtering.

In recent times, Microwave Photonic Filters (MPFs) have been shown to be a competitive technology to the conventional electronic filters, mainly due to their ability to overcome the underlying constraints in the areas of bandwidth, tunability, and loss associated with purely electronic approaches, particularly in the high RF frequencies. As opposed to the RF electronic filters, MPFs rely on the extensive bandwidth and low propagation loss of the optical components in handling signals in a wideband of frequencies, although in the process, they tend to be more complex and prone to optical effects like laser phase noise and non-linearity. As a result, the MPF architecture options come with their trade-offs.

Various MPF systems have different strengths, and their suitability depends on their application requirements. FIR structured MPFs, which require multi-tap delay line circuitries, allow for better stability as well as reconfigurable capabilities and are well suited for adaptive and programmable filters. However, their applications require multiple paths or wavelengths, thereby complicating system implementation and leading to higher losses with increased numbers of taps or wavelengths employed. Similarly, IIR-structured MPFs, which require optical resonators and/or feedback, have sharper selectivity, and their implementation is efficient in terms of spectral use, although their stability is relatively compromised due to environmental and/or fabrication uncertainties, in particular for longer-term stability requirements. They combine flexibility with selectivity but with complex systems and control.

A. Optical-to-RF Mapping Principle

The operation of a microwave photonic filter may be described with the aid of the principle of optical-to-RF mapping. In case a CW laser having an optical frequency (Ω) is intensity- or phase-modulated by an RF signal with frequency (ω_0), sidebands at optical frequencies ($\omega_0 \pm \Omega$) are created. Optical sidebands experience amplitude and phase changes depending on the transfer function of the optical filter, $H_{opt}(\omega)$ When the optical signal is detected by a photodiode, the sideband beating against the optical carrier generates an RF signal with the envelope of the optical filter response. Mathematically, this can be expressed as

$$H_{RF}(\Omega) \propto H_{opt}(\omega_0 + \Omega) \qquad (1)$$

where:

- $H_{RF}(\Omega)$: is the RF transfer function,
- $H_{opt}(\omega_0 + \Omega)$: optical transfer function at the frequency of the optical carrier shifted by the modulation frequency, and ω_0 and Ω are the angular optical carrier and modulation frequencies.

Therefore, defining the optical filter attributes of delay, resonance or phase shift allows the RF response of the designer to be defined in terms of center frequency, bandwidth and filter form. This mapping scheme forms the foundation for extremely reconfigurable as well as wideband

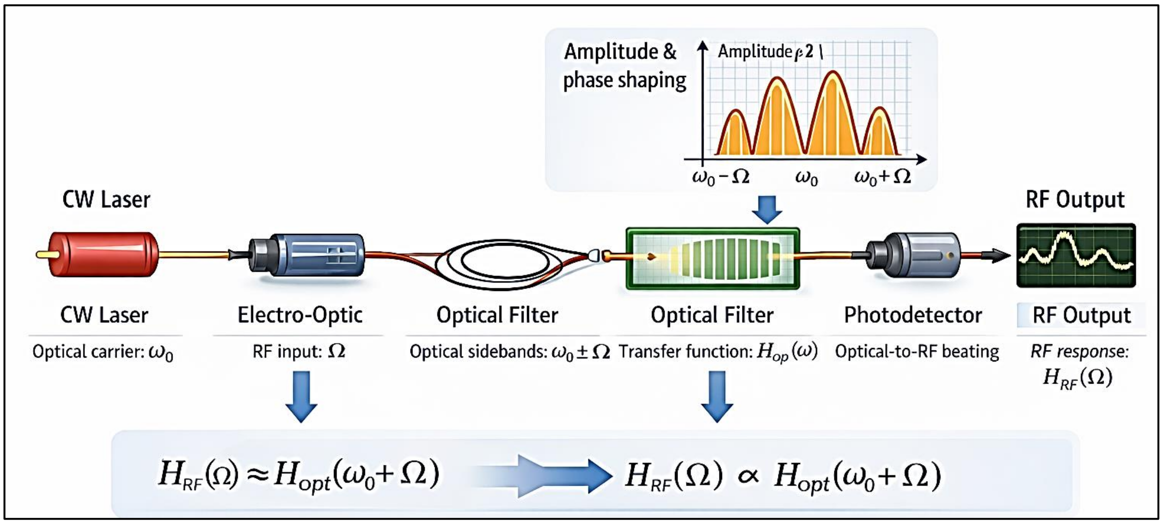


Fig.2. Optical-to-RF mapping principle in MPF

filtering that is free from the constraints of electronic components. Fig.2 shows Optical-to-RF mapping principle in microwave photonic filtering.

The optical-to-RF mapping principle explains how and why microwave photonic filters may offer better performance than their electronic counterparts. At the same time, it also indicates significant trade-offs in optical filter design. Utilizing an optical transfer function $(H_{opt}(\omega_0)$ it is easy to control and manage the RF response in terms of an appropriate center frequency, bandwidth, and/or selectivity. Such wideband and highly flexible RF filtering may not be feasible through electronic technology. Comparing it with direct electronic filtering, it has lesser optical loss and is resistant to electromagnetic interference, making it highly suitable for high-frequency and broadband filtering. In addition to that, it entirely relies on high-quality mapping of the RF response. Resonance-based optical filters are highly selective in RF response but are temperature and variation sensitive. Another delay-based optical filter is more stable and precise but needs longer optical paths and added hardware. In this way, the flexibility of optical-to-RF mapping may have practical implications depending on design complexity and robustness.

B. Key Building Blocks of Microwave Photonic Filters

An N-F type microwave photonic filter is a set of highly critical optical and optoelectronic devices operating in synergistic mode for RF-to-optical and optical-RF conversion, spectrum shaping and signal reconstruction. The key building blocks and their typical features are summarized in the following table. Table (1) indicate the main constituents and performance metrics of the microwave photonic filter systems.

Each component contributes uniquely to filter performance.

- **Laser coherence** ensures stable interference between optical tones.
- **Modulator linearity** determines signal fidelity and distortion levels.
- **Optical filter characteristics** dictate the filter's selectivity and re-configurability.
- **Photodetector bandwidth** sets the upper frequency limit of the RF response.
- **Optical amplifiers** extend the system's dynamic range but must be used carefully to control noise.

Recent developments in integrated photonics platforms like silicon (Si), silicon nitride (SiN), indium phosphide (InP), and lithium niobate ($LiNbO_3$) enable small and energy-efficient solutions for implementations of the devices on a single chip. Integration promotes thermal stability, reduces size, and unlocks programmable photonic filtering structures. Table I. provides a summary of the core parts of MPF and the impact of their performance characteristics on filter responses. Although coherent light sources with a low linewidth ensure low noise and stable RF outputs, a fully coherent light source could cause higher vulnerability to phase noise and increase the overall cost of the MPF system. Similarly, although a high linear modulator with a broad bandwidth is required for accurate and linear RF transfer with negligible distortion in the RF output, a low insertion loss and low chirp modulator operation at speeds higher than 40 GHz still remains a technological challenge. Optical filters are the most important and distinguishing components, since they directly determine RF selectivity and reconfigurability. Resonator filters enable high Q values and size reduction, but exhibit limited tunability and sensitivity to the environment, while delay line and AWG filters enable excellent robustness and bandwidth agility, but exhibit larger size and reduced spectral resolution. Photodetectors further constrain system performance by bandwidth and noise constraints, and high-speed photodetectors enable system operation up to millimeter-wave and sub-THz bands, but typically suffer from sensitivity at the expense of responsivity. Finally, optical amplifiers, such as EDFAs and SOAs, counteract signal attenuation, but induce ASE and non-linear effects, which may impair RF dynamic range and thus overall MPF performance. Efficient MPF system design, therefore, implies system-wide, multi-dimensional optimization of these components, beyond optimizing RF bandwidth, noise, or tunability, and size individually and independently.

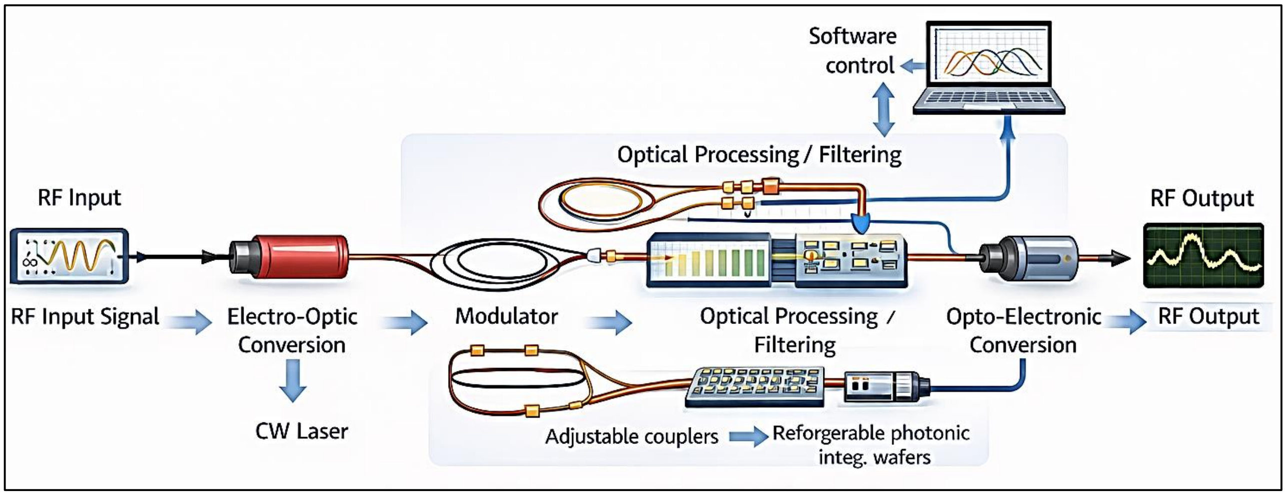


Fig. 3. Generic MPF link

TABLE I.
KEY COMPONENTS AND PERFORMANCE PARAMETERS OF MPF

Component	Function	Key Performance Parameters
Optical Source (Laser)	Provides a stable optical carrier for modulation.	Linewidth (<100 kHz), coherence length, tunability, relative intensity noise (RIN).
Modulator (MZM, EOM, IM, PM)	Converts RF signal into optical intensity or phase modulation.	Linearity, insertion loss, chirp parameter, bandwidth (>40 GHz).
Optical Filter (FBG, Ring Resonator, Delay Line, AWG)	Controls amplitude and phase of optical sidebands, shaping the RF response.	Free spectral range (FSR), quality factor (Q), tunability, polarization dependence.
Photodetector (PIN, APD, High-Speed PD)	Converts processed optical signal back into RF domain.	Responsivity, dark current, bandwidth (>60 GHz), noise equivalent power (NEP).
Amplifiers (EDFA, SOA)	Compensate optical losses and boost signal strength.	Gain flatness, noise figure, saturation power, wavelength range.

C. *Main Filter Types in Microwave Photonics*

Microwave photonic filters can be grouped according to their impulse response characteristics: Finite Impulse Response (FIR), Infinite Impulse Response (IIR), and Hybrid or Programmable Filters [11]**.** Fig.3 shows the conceptual architecture of the generic Microwave Photonic Filter (MPF) link. From the figure, the overall link functionality involves RF-to-optical modulation, optical signal processing and filtering, and finally optical-to-RF conversion. As a consequence of the filtering function being carried out in the optical domain and the corresponding response being transformed back to the RF domain by photo detection, the MPFs are able to provide a wideband, tunable, and reconfigurable frequency response that cannot be achieved electronically.

1) *Finite Impulse Response (FIR) MPFs*

FIR MPFs are typically implemented using multi-tap delay lines, where the optical signal is divided into several paths, each with a different delay and weighting. In the photo detection, these delayed replicas interfere to create a synthesized RF frequency response [12]:

$$H_{RF}(\Omega) = \sum_{k=0}^{N-1} a_k\, e^{-j\Omega k\tau} \qquad (2)$$

where (a_k) is the weight of the k^{th} tap τ is the delay difference, and (N) is the total number of taps.

The periodicity of the frequency response is inversely proportional to the delay spacing. By adjusting (a_k) and (τ), one can achieve tunable passbands, stopbands, or multi-band filters. FIR MPFs are inherently stable and straightforward to reconfigure, making them suitable for adaptive systems such as beamforming**,** radar pulse shaping**,** and multi-channel communications [13]**.**

2) *Infinite Impulse Response (IIR) MPFs*

Infinite Impulse Response Microwave Photonic Filters utilize optical feedback loops or resonant structures to create recursive signal behavior analogous to electronic IIR filters. A common implementation employs micro-ring resonators**,** Fabry–Pérot cavities, or fiber loops, providing sharp resonance peaks and narrowband selectivity. Their general transfer function is [14]:

$$H_{RF}(\Omega) = \frac{b_0 + b_1 e^{-j\Omega\tau}}{1 - a_1 e^{-j\Omega\tau}} \qquad (3)$$

These filters achieve high Q-factors, narrow linewidths, and compact footprints. However, their performance depends critically on optical feedback stability and noise sensitivity, which may require active control techniques such as thermo-optic or electro-optic tuning [15].

3) *Hybrid and Programmable Architectures*

Hybrid MPFs combine FIR's multi-tap versatility with IIR's selectivity-enhanced resonance. Hybrid architectures may include delay lines and subsequent resonators or cascaded photonic networks that enable multiple filter functions in one architecture. Modern programmable photonic processors integrate dozens of adjustable couplers and phase shifters to implement arbitrary filter responses through digital control interfaces. Reconfigurable systems enable the foundation for software-defined microwave photonics to enable dynamic spectrum allocation, adaptive interference cancellation, and AI-optimized optical filtering responses [6].

4) *Generic MPF Link*

The conceptual architecture of a generic MPF can also be illustrated as shown in Fig. 4.

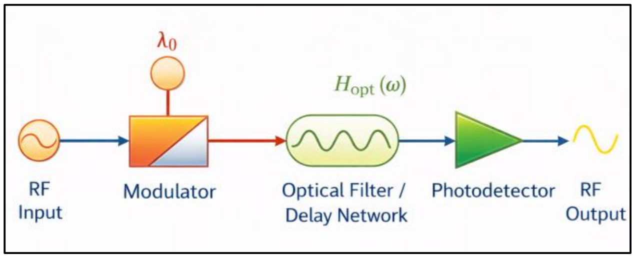


Fig. 4. Generic microwave photonic filter link

Microwave photonic filtering is a revolutionary high-frequency signal processing solution, bridging the gap between photonics and RF electronics. Its principle of optical-to-RF mapping allows unparalleled control over frequency response by handling light. Dependent on system architecture, MPFs can achieve tunable, reconfigurable, and even programmable operation with very wide frequency ranges. With ongoing advances in integrated photonics, low-loss modulators, and high-speed detectors, the next generation of MPFs can achieve full integration, miniaturization, and smart adaptability paving the way for 6G networks, radar imaging, quantum communication, and cognitive radio systems [16].

Comparative analyses of FIR, IIR, and hybrid MPF topologies demonstrate that there is no “one-size-fits-all” winner, and each of them finds its niche depending on the specific operational conditions and requirements of the target application. FIR MPFs, in particular, shine with the natural stability, linear phase response, and simple reconfiguration capability, since the properties of the filters can be straightforwardly adjusted through the set of weighting coefficients and the corresponding delays. These properties of the filters make them highly beneficial for use in adaptive beamforming systems, multi-band sensors, and other real-time systems that demand rapid, dynamic, and flexible operations. Nonetheless, there is the fundamental disadvantage that requires the use of the large number of taps to enable the filters to possess the required level of sharp cut-off selectivity, which brings about the increased optical complexity and insertion losses, thereby raising the system footprint. In opposition to that, the IIR MPFs possess high efficiency, sharp cut-off selectivity, and entirely compact designs realized using the minimal set of components, which makes them highly attractive candidates due to the elevated quality factors and the compact sizes, while involving the increased sensitivity to the temperatures, the component tolerances, and the noise coupled from the feedback paths, which, again, requires active stabilization to overcome the adverse effects. Hybrid MPFs, which combine the best qualities from the FIR and the IIR platforms, seek to provide highly dynamic, flexible, and multifunctional support to the dynamic environments, incorporating the beneficial qualities from the other platforms while bringing the disadvantages of additional control complexity to balance the system adaptability, scalability, and functionality, which is an essential step towards the emergence of intelligent photonic systems, where the system adaptability, functional performance, and scalability cannot be strictly optimal but should be well-adjusted to satisfy the system functionalities depending on the target environment.

D. *Classification of Microwave Photonic Filters*

MPFs may be categorized based on their architecture or working principle, reflecting the various mechanisms by which they operate on and transform microwave signals in the optical domain. Each of the MPF types offers unique advantages in terms of tunability, bandwidth, integrability, and applicability to different uses [17].

Table II offers a summary of the primary types of MPFs, example technologies, and their features. The classification extends from traditional architectures such as finite impulse response (FIR) filters using fiber delay lines, to advanced resonator-based and stimulated Brillouin scattering (SBS) filters, enabling ultra-narrowband operation. Fiber Bragg grating (FBG)-based filters enable a compact and stable approach to fixed or thermally tunable frequency selection, while frequency-comb-based filters enable fully programmable and reconfigurable filter responses that are suitable for high-speed communication systems [1].

Recent advances in integrated photonics with materials such as silicon (Si), silicon nitride (SiN), indium phosphide (InP), and lithium niobate ($LiNbO_3$) have made possible very compact, low-loss, and CMOS-compatible MPF realizations with large-scale integration and low-cost production potential. Alternatively, coherent or phase-based filtering techniques make use of coherent detection and fine-grained phase control to provide advanced and adaptive filtering capability with enhanced performance [18].

Not only does this classification also point to the technological diversity of microwave photonic filters, but also suggests that the trend of this field currently is towards miniaturization, reconfigurability and integration. Both are targeted at both the extreme narrowband spectral filtering requirements to the broadband arbitrary waveform processing, and provide a wide variety of design trade-offs to modern RF and microwave photonic systems [19].

TABLE II.
CLASSIFICATION OF MICROWAVE PHOTONIC FILTERS BASED ON ARCHITECTURE AND OPERATING PRINCIPLE [1]

Category	Example Technology	Key Features
FIR (Tapped Delay Line)	Fiber delay lines, integrated waveguides	Multi-tap, reconfigurable
Resonator-Based	Ring resonators, MZI, Fabry–Perot	Compact, tunable, narrowband
SBS-Based Filters	Stimulated Brillouin Scattering	Ultra-narrow bandwidth
FBG-Based Filters	Fiber Bragg Grating	Fixed or thermally tunable
Frequency-Comb-Based	Optical comb shaping	Programmable arbitrary filter shapes
Integrated Photonics	Si, SiN, InP, LiNbO3	Compact, CMOS-compatible
Coherent / Phase Filters	Coherent detection systems	Phase control, complex filtering

Table II offers a systematic breakdown of microwave photonic filter technology, explaining how system design considerations and physical concepts cause a clear impact on system performance. FIR tapped delay line filters are always preferable in broadband and adaptive processing due to simplicity in reconfigurability. On the other hand, multiple delay stages cause higher area and loss, especially in fiber implementations. Thus, there is a requirement to shift to integrated waveguides. Resonator-based microwave photonic filters, such as ring resonators and Mach Zehnder interferometers, remedy the area loss in terms of small area requirements. Nevertheless, inherent narrowband characteristics and problems with temperature drift cause constraints in terms of long-term stability.

The SBS-enabled MPFs stand apart due to the unique capability to perform ultra-narrow bandwidth filtering that is hard to implement using other photonic approaches. In the context of academic study, their utility is immense for interference cancellation and metrology applications, but the need for high optical pump power and sophisticated control system arrangements narrows their applicability to low-power or economical systems. FBG filters demonstrate exceptional spectral accuracy and insusceptibility to noise but cannot meet the dynamic adaptability needed for cutting-edge adaptive RF communication systems. The frequency comb-based MPFs come close to achieving fully dynamic filtering but currently pose active areas of study in the realm of complexity and the availability of reliable comb sources for such systems.

Finally, integrated photonics and coherent or phase-sensitive filtering techniques point towards the way forward for MPFs. Integration on such platforms as silicon, silicon nitride, and lithium niobate is compatible and scalable, but loss, nonlinearity, and efficiency of tuning still need to be traded off. Coherent MPFs, on the other hand, provide phase and amplitude manipulation capabilities like those of complex-valued filters, but these need tight synchronization and high stabilization of the system itself. The current trend is, on the one hand, to seek ways of integrating these different techniques together instead of pursuing MPF on its own.

III. ENABLING TECHNOLOGIES

Enabling technologies in the form of building blocks play an important role in ensuring the performance of the microwave photonic filters. These technologies set bandwidth, noise figure, dynamic range, linearity and configurability. The optical sources (lasers), electro-optic modulators, optical filters, photodetectors, optical amplifiers and photonic integration platforms are the most important components of an MPF system. They constitute the backbone of any MPF system: they determine the end result in terms of frequency response, stability, and even integrability capability [20].

A. Lasers

The lasers but more correctly the optical carriers convert the microwave signal to the optical frequency domain. The most desirable laser in MPFs would be that which is of narrowline, low phase noise, high optical power, and wavelength tenability. The narrow-linewidth lasers (including external-cavity lasers and distributed feedback lasers) are important because the lasers produce less phase noise and higher signal-to-noise ratio (SNR) in the RF-frequency. Tunable lasers allow to tune the optical carrier wavelength, which facilitates configurability and frequency agility of the MPF response [21]. The recent years have seen the introduction of optical frequency combs as a paradigm-shifting source of MPFs. Various frequency combs offer several or more coherent lines separated by a fixed frequency, and so multi-tap filters with spacing between taps can be generated, and amplitudes are controllable. They can be generated by the mode-locked laser or electro-optic modulation or the micro resonator-based Kerr combs. Further integration and programmability of MPF systems was also achieved through integrated comb sources, leading to arbitrary synthesis of filters and high-resolution signal processing [22].

B. Modulators

Electro-optic modulators (EOMs) are those that modulate the microwave signal onto the optical carrier. Of the types, Mach–Zehnder modulators (MZMs) are most prevalent because of their linear operation, high-bandwidth performance, and compatibility with both phase as well as intensity modulation schemes. Dual-parallel Mach–Zehnder modulators (DPMZMs) provide single-sideband (SSB) or suppressed-carrier modulation, which is essential to avoid RF-image interference and high-fidelity map optical and RF spectra [23]. Phase modulators are used in phase coherence or frequency modulation-dependent systems such as coherent MPFs or dispersive mapping systems. The performance of modulators is dependent on key parameters such as half-wave voltage (Vπ), insertion loss, bandwidth, and chirp. Lithium Niobate ($LiNbO_3$) modulators are the current industry standard due to their linearity and electro-optic efficiency, and silicon-based and thin-film $LiNbO_3$ modulators offer integration and scalability advantages [24].

C. Optical Filters

The optical filter is the core of an MPF since its spectral response determines the microwave filter characteristics directly. Common optical filters are micro-ring resonators (MRRs), Mach–Zehnder interferometers (MZIs), fiber Bragg gratings (FBGs), and photonic crystal filters. FBGs are wavelength-selectively reflective and can be utilized to achieve narrowband filtering with tenability via thermal or strain control [25]. Micro-ring resonators are small, integrable, and High-Q for filtering, which is best suited to chip-scale MPFs with fine thermal or electro-optic tuning. MZIs and AWGs (arrayed waveguide gratings) support multi-channel filtering and spectral shaping in order to create programmable filter responses. Photonic crystals provide strong confinement and sharp spectral selectivity and are beneficial in the realization of ultra-compact filters. Selection of optical filters depends on the desired frequency response (notch, band pass, or multi-band), integration level, and tenability [26].

D. Photodetectors

Photodetectors (PDs) convert the processed optical signal to the electrical (microwave) domain. The two main types are PIN photodiodes and avalanche photodiodes (APDs). PIN photodiodes are preferred in high-linearity and high-speed applications due to their high bandwidth (tens of GHz) and low noise. APDs provide internal gain through avalanche multiplication, which enhances sensitivity at the cost of higher noise and lower linearity. In MPFs, high-speed photodiodes with large saturation current are required to preserve the integrity of the RF signal and achieve high SFDR. UTC-PDs have recently been developed with bandwidths greater than 100 GHz, enabling ultrafast RF–optical–RF conversion for 5G, radar, and optical sampling applications [27].

E. Optical Amplifiers

Optical amplifiers compensate for loss in modulation, filtering, and propagation. The most common ones are erbium-doped fiber amplifiers (EDFAs) and semiconductor optical amplifiers (SOAs). EDFAs offer high gain (20–40 dB) and low noise in the 1550 nm window and are thus ideally suited for MPFs made from fiber. SOAs can, however, be built on photonic chips and offer integration and fast gain dynamics. However, SOAs pose higher noise figures and nonlinear distortion, with proper bias control required. Optical amplifiers play dual roles in SBS-based MPFs in amplifying pump power and enhancing nonlinear interaction intensity. Low-noise and broadband integrated amplifiers are required for the implementation of high-performance, fully integrated MPFs [28].

F. Integration Platforms

Drive on photonic integration has brought an earthquake in the development of MPF. Other materials including silicon (Si), silicon nitride (SiN), lithium niobate (LiNbO 3), indium phosphide (InP) and polymer-based materials have its own merits. Silicon photonics is also scalable and compatible with CMOS but has high propagation loss and inefficient electro-optic characteristics. SiN has low loss and is highly transparent, which is optimal in passive filtering and delay lines. A material of relevance in recent years is LiNbO3-on- insulator (LNOI), which offers a high electro-optic coefficient together with low-loss waveguide to make efficient and fast modulation of the material possible [29]. InP provides the monolithic integration of laser, modulator and detector, whereas polymer photonics provides tunability, cheapness and flexibility. The denser type of integration, which is the integrating of multiple materials in a single chip, the so called hybrid form of integration, is becoming more significant to provide optimal performance in MPFs, at the cost of low loss, high modulation efficiency, and miniaturization [30].

Microwave photonic filters are being made more integrated, smaller and on a better performance level through enablement. The technology that includes narrow-linewidth laser, high-speed modulator, tunable optical filter, low-noise photodetector and on-chip amplifier is being built on scalable material platforms that are taking MPFs out of the laboratory and into useful sub-systems of communication and sensing in next-generation. Ongoing technologies in hybrid material incorporation, low-power-tuning as well as enhanced control algorithms (including AI-assisted calibration) can potentially violate existing boundaries, and establish new horizons, in programmable and adaptive microwave photonic signal processing [31]. Table III shows summary of enabling technologies for microwave photonic filters. It explains how microwave photonic filter performance is intrinsically limited and facilitated by the development of underlying technologies, where each technology features both advantages and challenges. The laser, requiring a low linewidth and high coherence, is necessary for stable optical to RF mapping, while optical frequency combs are uniquely suited to multi-tap and programmable filtering; while very useful, they entail costs and thermal sensitivities. The performance of electro-optic and optoelectrical devices, especially $LiNbO_3$- and LNOI-based MZMs, provides very high-speed, highly linear modulation to support MPFs across a wide bandwidth; however, both bias instability and high drive voltage constitute viable challenges, particularly for low-power applications. Optical filters embody basic spectral processing; however, there remains a trade-off between miniaturization and tuning capabilities, where highly integrated filters fraught with increased losses and changed reconfiguration capabilities come to fore. Photodetectors establish the highest frequencies of the generated RF; while UTC-PDs make possible their extension into the mm-wave and sub-THz bands, saturation and noise limit present-linearity. Optical amplifiers compensate link losses, but ASE noise, NL distortion, and other impairments degrade post-amplification RF fidelity. Final integrated platforms hold promises of both scalability and miniaturization; however, coupling losses, as well as processing intricacies, suggest a clear path towards materials and device engineering. In terms of technology, further MPF development is needed today to execute a more integrated cross-material approach.

Microwave photonic filters are based on the concept of optical-to-RF mapping, wherein the optical spectrum is modulated to produce the required RF spectrum. FIR filters employ multi-tap delay line structures, wherein the RF filter characteristic is generated through the interference of delayed waves, while IIR filters utilize concepts of feedback or resonance to provide a narrow bandwidth selectivity. These different concepts are merged in a single design. Critical performance parameters define filter performance:

1. Bandwidth: It defines the RF frequencies that are passed or attenuated.
2. Q-factor: Indicates the measure of selectivity, which is the ratio of the center frequency to the bandwidth.
3. Insertion Loss: Measures the amount of signal degradation that occurs during the optical to RF conversion.
4. Link Gain: This is the efficiency of the signal process from RF through optical to RF.
5. Noise Figure: Represents the noise added to this RF link.
6. SFDR (Spurious Free Dynamic Range): It specifies the dynamic range in which the filter can operate without distortion. It is also known as linear operation range.

All these specifications are interconnected; for example, having ultra-narrow bandwidth may cause an increase in insertion loss. Knowledge of these specifications is of significant value in designing MPFs with high performance and stability.

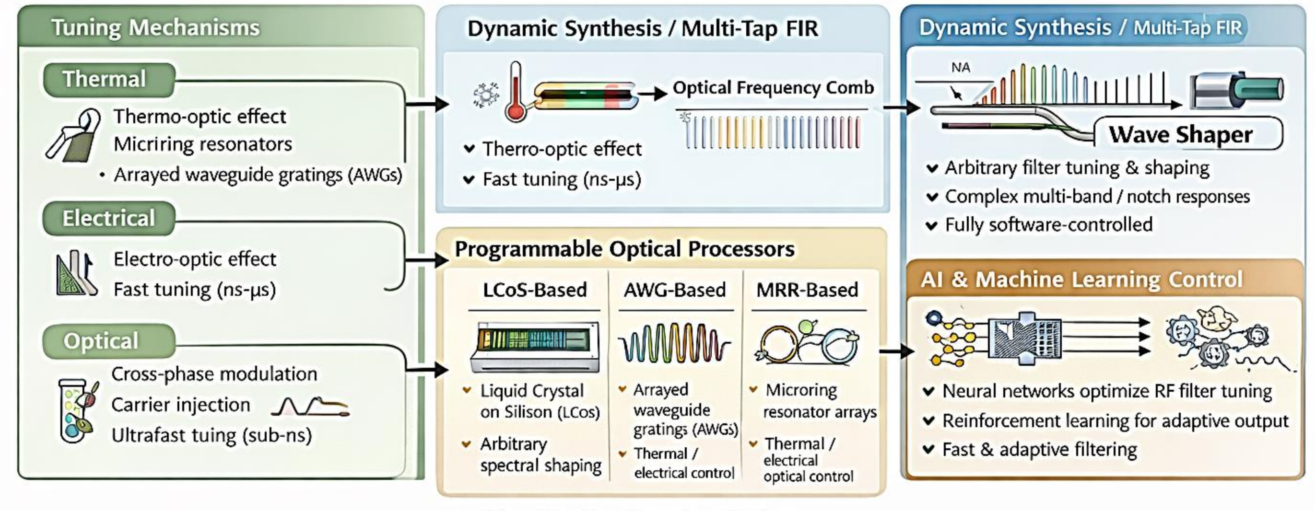
TABLE III.
SUMMARY OF ENABLING TECHNOLOGIES FOR MICROWAVE PHOTONIC FILTERS [32]

Component	Technologies	Key Features	Advantages	Limitations
Lasers	DFB, ECL, tunable laser, optical frequency comb	Narrow linewidth, tunability	High coherence, stability, multi-tap generation (comb)	Cost, thermal drift
Modulators	MZM, DPMZM, PM ($LiNbO_3$, Si, LNOI)	Intensity or phase modulation	High speed, linearity, SSB generation	Bias drift, Vπ power requirement
Optical Filters	FBG, MRR, MZI, AWG, photonic crystal	Wavelength-selective filtering	Compact, tunable, programmable	Limited tuning range, loss
Photodetectors	PIN PD, APD, UTC-PD	Optical-to-RF conversion	High bandwidth, low noise	Saturation current, noise in APDs
Amplifiers	EDFA, SOA	Optical gain	Compensate losses, boost signal	ASE noise, nonlinearity (SOA)
Integration Platforms	Si, SiN, $LiNbO_3$, InP, polymer	Material-based PIC technologies	Compact, scalable, hybrid integration possible	Coupling loss, fabrication complexity

IV. RECONFIGURABLE AND PROGRAMMABLE MPFS

Reconfigurable and programmable microwave photonic filters shown in Fig.5 are a new generation of devices that dynamically manipulate radio-frequency (RF) signals with the help of optics. Their tunability is perhaps the most significant feature, making their response modifiable by thermally, electrically, or optically actuated mechanisms. Thermal tuning relies on the thermo-optic effect, where the refractive index of the waveguides or resonators varies with temperature [33]. This method is widely applied in microring resonators (MRRs) and arrayed waveguide gratings (AWGs) and provides high resolution and continuous wavelength control of the resonance wavelengths. Thermal tuning is relatively slow, typically between microseconds and milliseconds, and power-hungry [34]. Electrical tuning takes advantage of the electro-optic effect, e.g., Pockels or Kerr effects, to modify the phase or amplitude of optical signals. thus is suitable for real-time adaptive filtering algorithms. Optical tuning mechanisms like cross-phase modulation, carrier injection, and two-photon absorption allow ultrafast reconfiguration at sub-nanosecond speeds, ideal for high-speed signal processing in dynamic RF environments. The choice of tuning mechanism thus involves a trade-off between speed, power dissipation, and tuning resolution [35].

Dynamic synthesis of filter is commonly achieved with the help of optical frequency combs (OFCs) and reconfigurable wave shapers. Optical frequency combs produce a large set of evenly spaced spectral lines, which may be independently weighted in amplitude and phase to generate multi-tap finite impulse response (FIR) filters in the RF domain [36]. Wave shapers such as the Finisar Wave shaper, a commercial product, offer line-by-line amplitude and phase control and allow the implementation of an arbitrary filter shape. The combination makes it easy to precisely tune the center frequency, bandwidth, and passband of RF filters, and can handle complex multi-band or notch responses. The flexibility of this technique makes it possible for MPFs to possess very extensive sets of filter functions in a single optical configuration, and reconfiguration is achieved entirely by software [37]. This



Classification Based on Performance

	Thermal	FOt; Salv	Optical + wave shaper	Prognmable Processors + AI	
● Thermal	●●	●●●	●●●●●	●●●●	●●●●●●
● Electrical	●●●	●●●● High	●●●●● Mad – Higl	●●●●●	●●●●●● Low
● Optical Comb + Wave shaper	●●●● Fast	●●●●	●●●●● Fast	●●●●●	●●●●●● Very high
● Programmable Processors + AI	●●●●	●●●●	●●●●● Fast	●●●●●	●●●● Lninite

Fig.5. Architecture and key mechanisms of reconfigurable and programmable MPFs

method allows very high-speed reconfiguration, response times of the nanosecond to microsecond order.

Programmable optical processors provide an optical implementation platform with flexibility for these filters as optical complements to digital FPGAs. Liquid Crystal on Silicon Device (LCoS) devices phase- and amplitude-modulate optical spectral components electrically, enabling arbitrary spectral shaping and adaptive RF filtering. Arrayed waveguide gratings (AWGs) can recombine and split wavelength channels, and they are tuned through thermal or electrical control of path lengths, making multi-tap filter implementations and channelized RF processing feasible [38]. Micro-ring resonator arrays allow resonance wavelengths to be tuned individually by thermals, electricity, or optical means, and this makes highly compact and reconfigurable RF filter banks achievable. All these reprogrammable processors promote high flexibility, dynamic control, and microwave photonic system miniaturization [39].

An illustrative example of reprogrammable MPFs is the use of a Finisar Wave Shaper for arbitrary filter synthesis. In this setup, an optical frequency comb is inputted to the Wave shaper, where the individual spectral lines are weighted in amplitude and phase. The weighted optical lines sum after photo detection to produce the RF filter response. With this method, arbitrary filter shapes can be designed with software-driven bandwidth, center frequency, and ripple behavior. It indicates the potential of optical frequency domain manipulation in providing RF signal processing capability that would be difficult or not practical with conventional electronic methods [40].

MPF reconfiguration has increasingly been combined with artificial intelligence and machine learning in recent work. Weighting methods based on neural networks map target RF filter responses onto optimal operating points of optical components directly without manual or iterative tuning. Reinforcement learning techniques have also been employed to dynamically tune microring resonator arrays or Wave shaper parameters for real-time adaptive tuning to maintain desired filter characteristics under changing environmental conditions. AI-assisted MPFs are therefore able to reconfigure quickly and accurately, offering predictive and adaptive functionality beyond normal programmable photonic filters [41].

The various reconfiguration techniques can be classified on the performance of each technique that is according to the speed, resolution, power consumption, flexibility and suitability towards an application. Thermal tuning has high resolution, slow speed response and high power consumption whereas electrical tuning has moderate to high resolution, speed response is very fast. Optical tuning can be reconfigured with high precision in a few tens of seconds and optical frequency combs in combination with wave shapers can be used to generate arbitrary filter profiles with high flexibility [42]. Programmable optical processors such as LCoS, AWGs, and arrays of MRR can be highly flexible in RF processing applications with complexity, and AI or machine learning-control creates new flexibility, making it possible to use smart and predictive filter operation in dynamically changing RF applications. The combination of these characteristics makes reconfigurable and programmable MPFs heterogeneous devices that are difficult to implement using only electronic means and provide high-speed, high-resolution and adaptive filtering [43].

It underlines the main tuning techniques: thermal, electrical, and optical with the respective mechanisms and speed range are illustrated. Dynamic filter synthesis is depicted by optical frequency combs and wave shapers, as well as programmable optical processors like LCoS, AWGs, and micro ring resonator arrays. AI and machine learning-assisted control provides for adaptive RF filter tuning. At the bottom of Fig.5, a classification table compares the performance of each technique in terms of the achieved speed, resolution, power consumption, flexibility, and suitability for RF applications, providing an overview of heterogeneous and software-controlled Microwave Photonic Filtering implementations.

V. LITERATURE SURVEY

Xu et al. (2022) [44] overcame the limited frequency tuning range and limited passband selection of typical MPFs by a dual-polarization dual-parallel Mach-Zehnder modulator (DPolDPMZM). The proposed scheme expanded the frequency tuning range and was energy efficient, yet flexible in operating modes and compact in configuration. Challenges were encountered with dispersion effects, environmental sensitivity, and fine control requirements. Experimental results showed the 1.43 GHz to 19.43 GHz frequency tuning range and effective design of dual-passband MPFs with the same amplitude and a 2 GHz gap in frequency by controlling the RF carrier of a single-tone signal.

Varun and Pant (2022) [45] were interested in averting dispersion issues that impair Brillouin-based bandpass MPFs. They used double-sideband intensity modulation with phase control using a z-cut intensity modulator to provide improved out-of-band rejection and uniform filter performance. Their technique, even with the complexity of the experimental setup and environmental sensitivity, was capable of offering efficient dispersion compensation, greater than 40-dB out-of-band rejection, and system integration compatibility. Modulation of the bias voltage enhanced performance even more, demonstrating the potential of intensity modulators in managing dispersion in microwave photonic systems.

Zhang et al. (2022) [46] sought to address the issue of achieving narrow bandwidth and high-quality factors in MPFs. Using SBS, they created a High-Q tunable narrow bandpass filter. The mechanism was prone to environmental effects and needed extremely precise experimental implementation. The filter created had a 7.8 MHz bandwidth, 24 dB gain, and a high-quality factor of 2412, serving as a benchmark for achieving high selectivity and stability in photonic filters.

Garrett et al. (2023) [47] aimed to develop a highly integrated photonic circuit that integrates all essential electro-optic functionality and megahertz-level spectral resolution for RF connectivity. By integrally integrating waveguides, modulators, and photodetectors onto a silicon photonic chip in a CMOS foundry, they were able to achieve high spectral resolution, excellent out-of-band rejection (51 dB), and 3-dB bandwidth as low as 37MHz. Propagation and insertion losses were limiting factors, indicating the need for RF link optimization in MPF integrated platforms.

Girish et al. (2023) [48] focused on low-power, reconfigurable sub-MHz-accuracy microwave band-stop filters that would suppress interference over an extended range of frequencies. They implemented SBS-based MPFs using advanced RF phase engineering to modulate the upper sideband and control RF interference. Despite being limited by SBS gain and environment sensitivity and requiring precise phase manipulation, the method achieved a form factor below 1.35, high suppression above 15 dB, and the ability to realign the filter from band-pass to band-stop through merely changing phases, showing both flexibility and performance.

Xu et al. (2023) [49] addressed the problem of achieving ultra-narrow bandwidths in filters and high frequency selectivity with a wide range of tuning. They used a Brillouin laser resonator to generate a very selective MPF using the Vernier effect as a method of tunability and stability. Though the technique was environmentally sensitive and required a complicated setup, the filter remained stable in tuning over 0 to 20 GHz with an out-of-band rejection of around 20 dB and a 3-dB bandwidth of at least 114 Hz, showing ultra-high selectivity.

Hou et al. (2023) [50] developed an ultra-narrow bandwidth MPF from a single Brillouin fiber laser with longitudinal mode parity-time symmetry. Their system provided ultra-narrow bandwidth, extended tuning range, high side-mode suppression, and rapid tuning performance. The technique demonstrated a single-passband of 72 Hz with an 18 dB side-mode rejection ratio and center frequency tuning range of 0 to 20 GHz. Challenges included high pump power requirements, environmental sensitivity, and complex experimental setup, highlighting ultra-high-performance MPF trade-offs.

AL-Zaidi and Sabbar (2024) [51] developed a tunable MPF for high-bandwidth, high-frequency use with an SBS-based architecture involving cascaded ring Fabry–Pérot structures and a Brillouin laser resonator. It had high tunability from 0 to 20 GHz, good stability, high out-of-band rejection, and the simplicity of the tuning mechanism enhanced practicality. While environmental deployment may be challenging, the system proved stable performance in simulation and hence possesses potential application to high-end radio-over-fiber systems.

Parihar et al. (2024) [52] stressed creating highly high rejection (100 dB) between passband and stopband in MPFs with increased stability. They employed a one-laser SBS system to create an electromagnetically induced transparency-like phenomenon. The method showed high tunability from 10.8 GHz to 22.8 GHz, maximum delay of 50 ns, and low-power efficient operation (13 dBm), but at the expense of needing accurate phase control and setup complexity.

Zhang et al. (2024) [53] aimed at achieving a tunable MPF with ultra-narrow passband and good out-of-band rejection. Zhang et al. applied vector composite SBS to superpose two Brillouin loss spectra over a central gain profile, narrowing the passband and increasing rejection. The technique achieved 3-dB bandwidth of 5.5 MHz, 20-dB bandwidth of 14.4 MHz, 55 dB out-of-band suppression, frequency tuning of 11 to 20 GHz, and interference cancellation of 56 dB with minimal signal loss of 0.3 dB. The challenge was in having reduced SBS gain and complex polarization and power control.

You et al. (2024) [54] designed a tunable and flexible MPF with two ultra-narrow passbands and high selectivity using a dual-wavelength Brillouin laser resonator with a dual-ring cavity. The system achieved a 3-dB bandwidth of 83 Hz, out-of-band suppression of 28.3–29 dB, tuning ranges of 300 kHz to 20 GHz, and adjustable passband intervals from 2 to 18 GHz. The method required strict experimental control but offered high flexibility and performance for advanced RF filtering applications.

TABLE IV.
RELATED WORKS ANALYSIS

Category	**Reference**	**Technology / Method**	**Key Performance & Features**	**Limitations / Challenges**
Modulator-Based MPFs	Xu et al. (2022) [44]	Dual-Polarization Dual-Parallel MZM (DPolDPMZM)	Frequency tuning 1.43–19.43 GHz, dual-passband with 2 GHz gap, energy efficient, compact	Dispersion effects, environmental sensitivity, precise control required
	Varun & Pant (2022) [45]	Double-sideband intensity modulation with phase control (z-cut IM)	Efficient dispersion compensation, >40 dB out-of-band rejection, integration compatible	Complex experimental setup, environmental sensitivity, bias voltage control required
SBS / Brillouin-Based MPFs	Zhang et al. (2022) [46]	SBS narrowband filter	High-Q, 7.8 MHz bandwidth, 24 dB gain, Q-factor 2412	Environmentally sensitive, requires precise experimental setup
	Girish et al. (2023) [48]	SBS-based band-stop filter with RF phase engineering	Sub-MHz accuracy, high suppression >15 dB, reconfigurable band-pass to band-stop, form factor <1.35	Limited SBS gain, environmental sensitivity, precise phase control required
	Xu et al. (2023) [49]	Brillouin laser resonator with Vernier effect	Ultra-narrow 3-dB BW 114 Hz, stable tuning 0–20 GHz, out-of-band rejection ~20 dB	Environmentally sensitive, complex setup
	Hou et al. (2023) [50]	Single Brillouin fiber laser with PT-symmetry	Ultra-narrow 72 Hz bandwidth, 18 dB side-mode suppression, 0–20 GHz tuning, rapid tuning	High pump power, environmental sensitivity, complex setup
	AL-Zaidi & Sabbar (2024) [51]	SBS with cascaded ring F-P & Brillouin laser	High tunability 0–20 GHz, good stability, high out-of-band rejection, simple tuning	Challenging environmental deployment
	Parihar et al. (2024) [52]	Single-laser SBS with EIT-like effect	High rejection 100 dB, tunable 10.8–22.8 GHz, max delay 50 ns, low power 13 dBm	Requires accurate phase control, complex setup
	Zhang et al. (2024) [53]	Vector composite SBS	3-dB BW 5.5 MHz, 55 dB out-of-band suppression, tunable 11–20 GHz, 56 dB interference cancellation	Reduced SBS gain, complex polarization & power control
	You et al. (2024) [54]	Dual-wavelength Brillouin laser with dual-ring cavity	Two ultra-narrow passbands 3-dB 83 Hz, out-of-band suppression 28–29 dB, tuning 300 kHz–20 GHz, adjustable passband 2–18 GHz	Strict experimental control, complex setup
Integrated Photonics MPFs	Garrett et al. (2023) [47]	Fully integrated silicon photonic chip	CMOS-compatible, 3-dB BW 37 MHz, out-of-band rejection 51 dB, high spectral resolution	Propagation and insertion losses, RF link optimization needed

Table IV gives a comparative overview of the most recent developments and progress reported for microwave photonic filters (MPFs), to give the reader a sense of the variety of approaches, levels of performance achieved, and feasibility limitations being explored within the literature. All of the works discussed and listed are distinguished by their respective underlying technologies or modulations used, filter attributes including bandwidth, tuning, selectivity, or reconfiguration capabilities, and limitations or problems associated with their implementation. By condensing all of this information into a clear comparison matrix for the diverse range of filter architectures explored for microwave photonics, from dual-parallel Mach Zehnder modulators to Brillouin scattering-based and integrated photonic chips, the reader can easily identify how each particular type of filter satisfies specific criteria including tuning range, suppression ratios, and resolutions per unit.

Despite the major progress that has been achieved in the area of microwave photonic filters, there still exist important open challenges that hinder the broad use of such filters. Although the developed designs possess outstanding properties, such as the capability to provide an extremely narrow bandwidth, wide tunability, or high selectivity, this is done at the expense of other parameters, which, in turn, adversely affect scalability, complexity, and power efficiency. Furthermore, the existing discrepancies in benchmarking and evaluating the performance of various designs make it rather difficult to compare and select the most efficient solutions. It is extremely important to acknowledge the existing challenges to direct future research and development efforts towards the development of efficient, low-complexity, and low-power-consuming microwave photonic filters that can be easily integrated into modern RF and photonic systems.

- Environmental Sensitivity: Many of today’s high-performance microwave photonic filters are very sensitive to variations of temperature, vibration, and process variations. This is unfortunate as it affects the reliability of such filters and makes it very difficult for these filters to be used outdoors or in mobile applications.
- System Complexity: Realization of very narrow band widths or high Q values and multi-passband structures can, for example, exhibit very demanding requirements with respect to optical alignment, phase control, and optical pump power handling. These issues result in poor scalability and poor integration capabilities.
- The Choice Between Tunability and Resolution: Those filters which are capable of a broad frequency tuning range always find it difficult to ensure ultra-narrow bands, and vice-versa. There still exists a dearth of solutions available to ensure maximum flexibility, resolution, and stability simultaneously.
- Integration and Scalability Limitations: Although offering advantages of compactness and compatibility with semiconductor technology, usually suffer from high insertion loss and only mediocre spectral resolution and limited tunability. Fully programmable and hybrid architectures have been mostly proposed in research literature.
- Power and Efficiency Constraints: In some high-performance filters, a large optical pump power is often needed in order to sustain the filter's function. This will make energy efficiency a limiting factor in some mobile and distributed applications.
- Out-of-Band Rejection: It is still hard to achieve very high out-of-band attenuation. A lot of available filters provide medium levels of out-of-band attenuation, which can be insufficient in environments rich in radio frequency interference.
- Polarization and Dispersion Management: More complex schemes benefiting from dual-polarization or sideband engineering would need accurate control and compensation of dispersion and control of the polarization state. This would add to the hardware and control complexities of the original WDM-based designs.
- Lack of Standardized Performance Metrics: The fact that there is no reliable benchmark means that it is not possible to directly compare different filter designs based on bandwidth, tuning, rejection, or robustness to the surrounding environment.

VI. CONCLUSION

The Microwave photonic filters have shown this same highly promising potential of wide-band high-speed and reconfigurable signal processing of RF signals, with performance benefits that are hard to obtain in the utilization of purely electronic systems. This review has covered the broad range of MPF design techniques that include thermal, electrical, and optical tuning, and enhanced architectures relying on stimulated Brillouin scattering, microring resonators, optical frequency combs, and programmable optical processors. These methods have different tradeoffs in terms of tuning range, bandwidth, selectivity, reconfiguration speed, and power efficiency. Artificial intelligence and machine learning have been discovered to possess very different potential to facilitate flexible, predictive, and automated reconfiguration of filters that make them profoundly flexible and efficient. In spite of such progress, various challenges exist that include environmental sensitivity, high power consumption, complexity of fabrication, and ultrafast tunability limitations. The future research direction must be aimed at creating smaller, lower power and fully integrated MPFs with better stability, a hybrid tuning technique, advanced photonic integration and intelligent tuning technique. Also, the potential of MPFs can be increased with further research on new approaches to exploiting nonlinear optical effects, the frequency comb, and programmable photonics devices.

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