Kufa Journal of Engineering
Vol. 16, No. 3, July 2025, P.P. 199-250
Article history: Received 20 September 2024, last revised 22 October 2024, accepted 2 November 2024

MICROWAVE PHOTONIC FILTERS BASED ON STIMULATED BRILLOUIN SCATTERING: A REVIEW

Zainab AL-Zaidi[1] and Adnan Sabbar[2]

[1] M.Sc. Student at Dep. of Electrical Eng., Faculty of Eng., University of Kufa, Iraq. Email: zainabh.alzaidi@student.uokufa.edu.iq

[2] Assist. Prof. at Dep. of Electrical Eng., Faculty of Eng., University of Kufa, Iraq. Faculty of Information Technology, Imam Ja'afar Al-Sadiq University, Al-Najaf Al-Ashraf, Iraq. Email: adnan.sabbar@uokufa.edu.iq

https://doi.org/10.30572/2018/KJE/160313

ABSTRACT

Microwave photonic filters (MPFs) based on stimulated Brillouin scattering (SBS) and their applications in various microwave systems are extensively reviewed. This work summarizes the state of the art, emphasizing new methods, experimental proofs, and optimized passband properties of SBS-based MPFs. Important topics include frequency-tuning-range-extended MPFs, switchable MPFs, high-selectivity rectangular filters, and bandwidth-reconfigurable MPFs, addressing significant issues in traditional filters. Photonic technology in microwave photonics (MWP) enables processing of broadband, high-frequency microwave signals with excellent selectivity, stability, and adjustable passband properties. Applications span optical wireless communication, optical signal processing, radio over fiber (RoF) systems, satellite communications, optical sensors, and instrumentation. This review offers valuable insights into the advancements and potential impact of SBS-based MPFs in microwave systems.

KEYWORDS

Microwave photonics, Microwave photonics filter, Ultra-narrow bandwidth large tuning range, Photonic technologies, Stimulated Brillouin scattering.

1. INTRODUCTION

Microwave photonic filters play a crucial role in optical fiber communication systems due to their ability to process radio frequency (RF) signals in the optical domain. These filters offer several significant advantages over traditional electronic filters, including higher bandwidth, immunity to electromagnetic interference, and the ability to handle high-frequency signals efficiently(Yao, 2009),(Seeds and Williams, 2006). MPFs are used in different military and civil applications(Li and Zhu, 2016),(Borges, Muniz and Sodre Junior, 2017),(Waterhouse and Novack, 2015),(Capmany and Novak, 2007),(Yao, 2022)(Alrubei and Dmitrievich, 2023). Fig.1 shows a simplified diagram of a normal MWP link (Marpaung, Yao and Capmany, 2019).

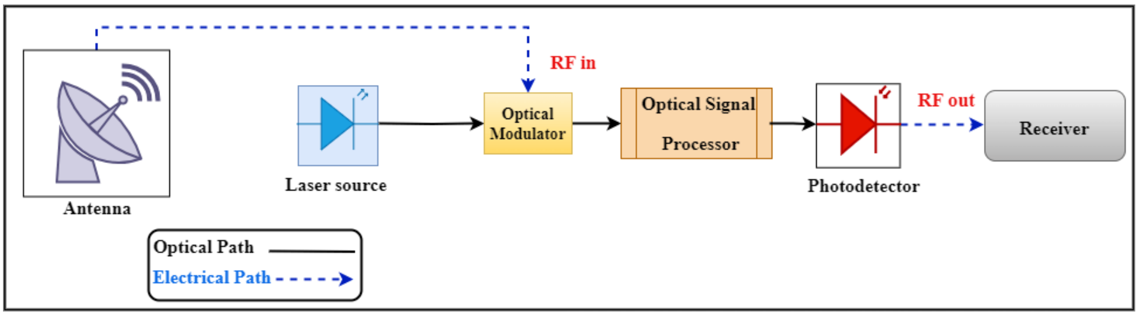

Fig. 1. Illustration depicting the schematic diagram of the microwave photonic link

One main difference between MWP technology and other microwave methods is that MWP technology uses optical domain processing of microwave signals, which lets photonic innovations be used (Seeds and Williams, 2006), featuring exceptional resistance to electromagnetic interference, a wide bandwidth, and extremely low loss. Fig.2 shows the differences between an MPF and a conventional electronic filter (Cny, Ortega, *et al.*, 2005). The conventional microwave filter relies on the RF circuit to handle the incoming RF signal from the RF antenna. Optical devices in the optical domain process the RF signal, which is different from conventional electronic filters. The huge bandwidth allows for direct processing of wideband RF signals at high frequencies. The tunability of MPF is likewise quite good and the potential for reconfiguration (Wang *et al.*, 2014). Various uses can benefit from adjusting the bandwidth and center frequency due to this flexibility (Preussler *et al.*, 2016). Changing the MPF frequency response shape from bandpass to band-stop is also possible (Yu *et al.*, 2010). Additionally, optical signals are very resistant to electromagnetic interference when delivered through optical waveguides or optical fibers (Capmany, Member, *et al.*, 2005). MPF greatly impacts the area of MWP. One application where MPF shines is in optical oscillators (OEOs), which may attain minimal phase noise and broadband tunability (Jiang *et al.*, 2013). Integrated photonic technology also improves the measured bandwidth and accuracy of microwave frequency measurements (Liu *et al.*, 2015). The ability to program MPF allows for the processing of signals in real time and makes it easier to create reconfigurable systems (Liao *et al.*, 2014). MPF has demonstrated significant promise in contemporary communication systems.

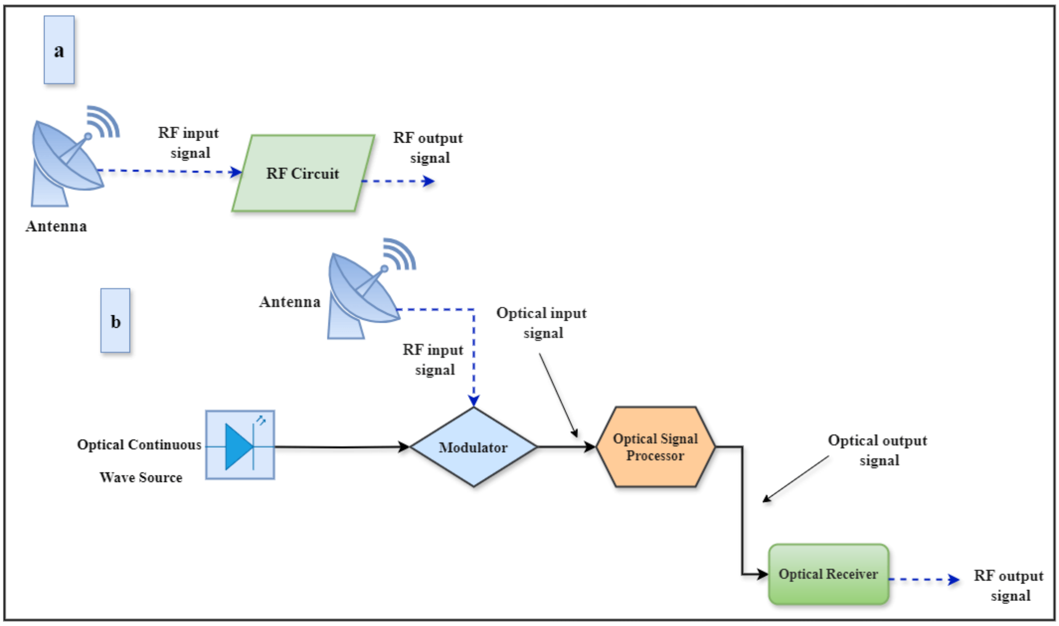

Fig. 2. Comparative analysis of conventional Radio Frequency (RF) filters versus MPF. (a) Diagram illustrating the structure of a conventional microwave filter. (b) Diagram illustrating the structure of the MPF.

The nonlinear effect known as SBS is renowned for its exceptional proficiency in phase conjugation, pulse compression, beam shaping (both temporal and spatial), Brillouin-enhanced four wave mixing, slow light, and beam combining (Hon, 1982),(Omatsu *et al.*, 2012). SBS phase conjugate mirrors (SBS-PCMs) can correct beam distortion induced by optical components in the system, enhancing the performance and brightness of high-power lasers. These applications, such as LIDAR, space communication, and laser fusion, require beams of very high quality, making high-power lasers suitable for their use (Brignon and Huignard, 2004),(Fisher, 2012). Currently, there is ongoing development of distributed optical fiber sensors that utilize Brillouin amplification. These sensors aim to achieve high precision and high-resolution sensing of temperature and stress in the field of engineering (Shimizu *et al.*, 1993),(Bao and Chen, 2012). Using SBS, which is a good way to shorten optical pulses from 10 ns to hundreds of picoseconds, is another possible way to make an ignitor-shock spike for inertial confinement fusion (Perkins *et al.*, 2009),(Schmitt *et al.*, 2010). Furthermore, SBS-based serial laser beam combinations enable significantly higher laser powers than a single-gain medium, all without requiring individual beam phase control (Wang *et al.*, 2007),(Wang *et al.*, 2009). Serial laser beam combination offers the most flexible way to generate a huge pulse output compared to other approaches like polarized combination or multi-wavelength combination. Although SBS has many positive uses, it is also a harmful phenomenon that reduces the maximum power and transmission rate of communication fibers and fiber amplifiers (Smith, 1972),(Brilliant, 2002). As a result, researchers and experts have developed numerous strategies to reduce SBS (Lee and Agrawal, 2003),(Kovalev and Harrison, 2006). When an incident wave interacts with a medium, it can cause various scattering processes, such as Rayleigh scattering, Brillouin scattering, or Raman scattering (Boyd, 2007)(Hameed, 2019). Spontaneous scattering occurs when the intensity of light is low. Nevertheless, once the incoming intensity surpasses a specific threshold, stimulated scattering will occur, characterized by a robust interaction between light fields and matter. Strong laser light interacts with materials in gaseous, liquid, solid, or plasma states, allowing for the observation of the SBS phenomenon, a third-order nonlinear optical effect. SBS occurs when a strong incident light wave interacts with elastic acoustic waves within a material. Hence, the inherent characteristics of a medium exert a substantial influence on SBS performance. Researchers have utilized numerous SBS media to investigate the optimal settings in a diverse range of studies.

2. MICROWAVE PHOTONIC FILTERS THAT UTILIZE STIMULATED BRILLOUIN SCATTERING

In recent years, considerable interest has been devoted to the innovative and interdisciplinary field of MPFs with SBS. By fusing conventional microwave methodologies with photonic technology, this innovation presents an extensive array of potential implementations across diverse sectors. Researchers have extensively devoted their efforts to applying SBS in MPFs, prompting an investigation into its capabilities for generating, transmitting, processing, and manipulating microwave signals. Numerous studies have made contributions to the development of the MPF with SBS over the years. Researchers have centered their efforts on improving the performance, selectivity, and tunability of MPFs, thereby broadening their range of potential technological applications. Looking at the research that has been done in this area over time can teach us a lot about how MPFs have changed over time and how SBS affects their abilities. At this juncture, the research articles detailing previous years investigations will be examined in order to scrutinize the advancements and novel developments pertaining to the MPF with SBS.

A high-performance MPF can be created by utilizing SBS in a silicon nanowire as shown in Fig. 3. The goal of the research was to show that microwave signals can be processed on a chip and to make the first RF photonic filter that works with complementary metal-oxide-semiconductor (CMOS) technology. By utilizing a distinctive cancellation method, they effectively utilized the moderate SBS amplification in silicon to create a high-performing

MPNF. This filter achieved a narrowband and greatly attenuated electrical notch response. The device demonstrated an impressive 48 dB reduction in unwanted frequencies, a bandwidth of 98 MHz with a 3 dB decrease in signal strength, and the capacity to adjust frequencies from 14 to 20 GHz. It achieved this with only 0.98 dB of on-chip SBS gain. This advancement has the potential to revolutionize on-chip microwave signal processing for high-speed communication systems and radar. It provides efficient and cost-effective RF photonic filters that are compatible with CMOS technology (Casas-Bedoya *et al.*, 2015). Notable strengths encompass an innovative methodology, the creation of high-performing devices, and the use of revolutionary techniques in on-chip microwave signal processing and RF photonic filters. However, challenges related to the complexity of the setup, low gain, and fabrication intricacies need to be addressed to achieve practical and widespread implementation.

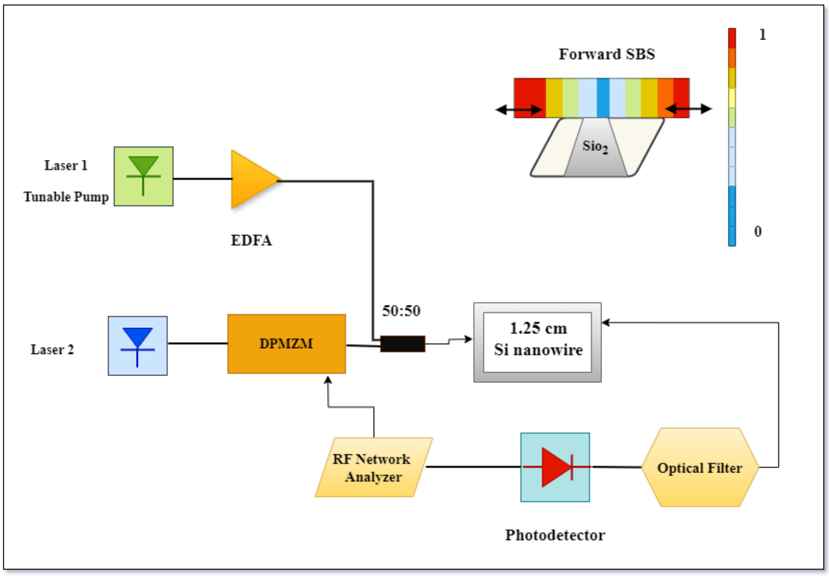

Fig. 3. Experimental setup for the notch filter. DPMZM: Dual-Parallel Mach–Zehnder Modulator, EDFA: Erbium-Doped Fiber Amplifier. The top right shows the simulated transversal acoustic displacement, or forward SBS, from a silicon nanowire (Casas-Bedoya et al., 2015)

The filter of Fig.4 discussed the signal distortions in a bandpass MPF based on SBS. They aimed to understand and mitigate nonlinear aberrations in the filter's passband response. Through theoretical analysis and simulations, they explored filter performance in small-signal and gain-saturation zones, considering factors like gain coefficient, pulse width, and pulse peak power. Results showed linear signal gain in the small-signal zone but slowed growth in the gain-saturation region, unaffected by gain coefficient. Signal gain and broadening factors remained consistent at low peak power but decreased at high power due to saturation. Extended pulses were optimal, especially in the pump-un-depletion zone. The study emphasized saturation's impact on linearity, crucial for real-world MWP systems. These findings are significant for telecommunications, radar, and sensing applications, highlighting the need to mitigate nonlinear distortions in filter responses (Guo et al., 2016). The high frequency selectivity, wide tuning range, and detailed analyses of signal distortions are notable strengths. However, challenges related to the complexity of the experimental setup, environmental sensitivity, and gain saturation effects need to be addressed for practical and widespread implementation of these filters.

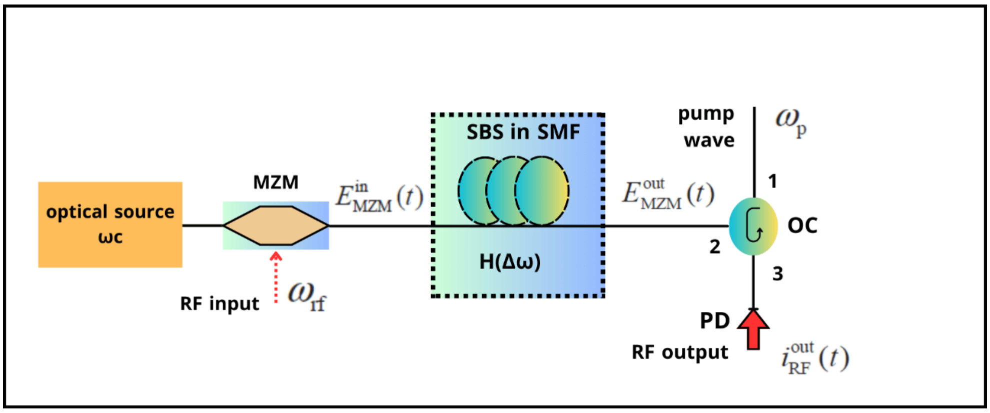

Fig. 4. A standardized schematic diagram of an MPF reference model based on SBS technology. SMF: Single-Mode Fiber, PD: Photodetector, MZM: Mach-Zehnder Modulator, OC: Optical Circulator (Guo et al., 2016)

Building on the insights from the earlier research on signal distortions, a breakthrough was achieved with the development of a low-power SBS-MPF that combines extremely high selectivity with the ability to be reconfigured. This innovative filter can tune over a range of 30 GHz. The researchers optimized the phase and amplitude of sidebands in a chalcogenide (ChG) glass waveguide with centimeter-scale dimensions, enhancing the energy efficiency significantly. Fig. 5 shows such filter where the experiment demonstrated a band-stop MPF that showcases exceptional selectivity. Operating at a low pump power range of 8–12 mW, the MPF achieves an SBS gain of only 1-4 dB. It utilizes dual-sideband modulation to enable precise cancellation of RF signals. The significance of this study is highlighted by its exceptional selectivity, low power consumption, and potential for seamless integration into RF systems and high-speed communication networks handling large data rates (Marpaung *et al.*, 2015). The strengths of this technology are underscored by its innovative approach, high energy efficiency, broad frequency tuning range, and detailed comparison with other existing technologies. Nevertheless, certain obstacles, such as the intricacies of fabrication, sensitivity to environmental factors, and restricted gain, must be overcome to realize the practical and broad adoption of these filters.

A highly selective MPF method utilizing SBS can be created effectively. In Fig.6, the setup developed an optimal rectangular filter through experimental confirmation using a fiber-based method. Experimental results have verified that the filter outperforms previous ones, obtaining a selectivity of 45 dB for a 2-GHz bandwidth with feedback compensation and a 3 dB bandwidth of less than 1.4 dB ripple for bandwidths ranging from 500 MHz to 3 GHz. It worked to cut down on unwanted sidebands, making the change between the passband and stopband clear. There was only a small loss of signal (less than 1.4 dB), but there was a big difference in power levels (from 18.2 dBm to 23.2 dBm). This study focuses on meeting the need for high-performance MPFs in communication, radar systems, sensing, and instrumentation (Lilin Yi, Wei Wei, 2015).

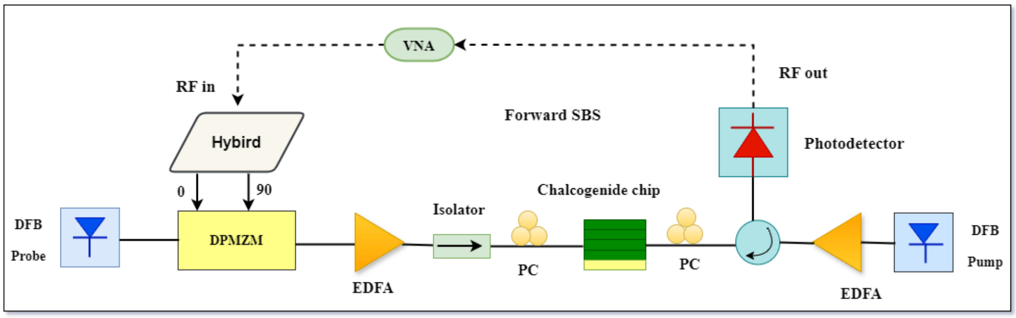

Fig.5. The experimental setup for evaluating the performance of MPFs includes a pump-probe design. including DFB: Distributed Feedback laser, Hybrid: 90° RF hybrid coupler, PC: Polarization Controller, VNA: Vector Network Analyzer (Marpaung *et al.*, 2015)

This research has an important strength, which is experimental verification, a thorough comparative analysis, and a lucid presentation, all of which contribute to the progress of MPF. However, the complexity of implementing such MPF can increase setup difficulty and cost. Additionally, the filter's performance is optimized for a specific bandwidth range (500 MHz to 3 GHz), which may limit versatility. Environmental sensitivity and integration challenges with existing systems could also impact its practical use.

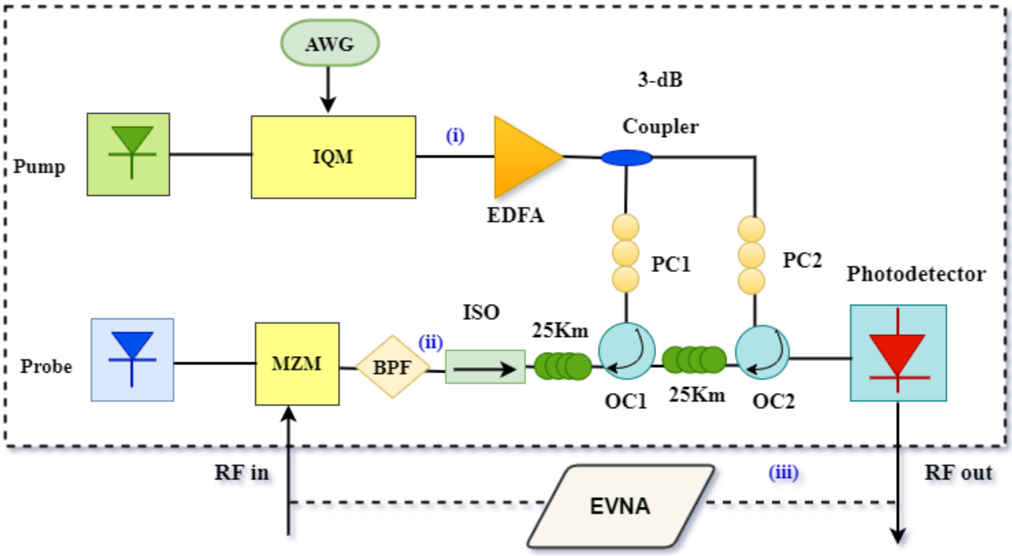

Fig.6. Rectangular MPF experimental setup. EVNA: Electrical Vector Network Analyze, AWG: Arbitrary Waveform Generator, ISO: Isolator, IQM: I &Q Modulator, BPF: Bandpass Filter (Lilin Yi, Wei Wei, 2015)

Some other designs proposed a new method to improve the adjustability of MPFs by employing two SBS pumps. For example, the setup in Fig.7 lets the optical carrier frequency and phase shift be changed on their own, which led to the creation of a two-tap complex coefficient MPF with a frequency response that could be changed over the whole free spectral range (FSR). The experimental results of this setup showed that the operation bandwidth is limitless and that continuous tweaking is available from 1 to 18 GHz. This innovation surpasses existing constraints and has extensive applications in communication systems, radar, and signal processing. Notable strengths encompass a creative approach, empirical verification, and the ability to significantly influence a range of MWP applications (Wang *et al.*, 2015).

This experimental setup presents a highly selective and low-power MPF based on SBS with high selectivity, wide tuning range, and experimental validation. However, the complexity of the experimental setup, sensitivity to environmental factors, and noise issues pose challenges that need to be addressed for practical and widespread implementation.

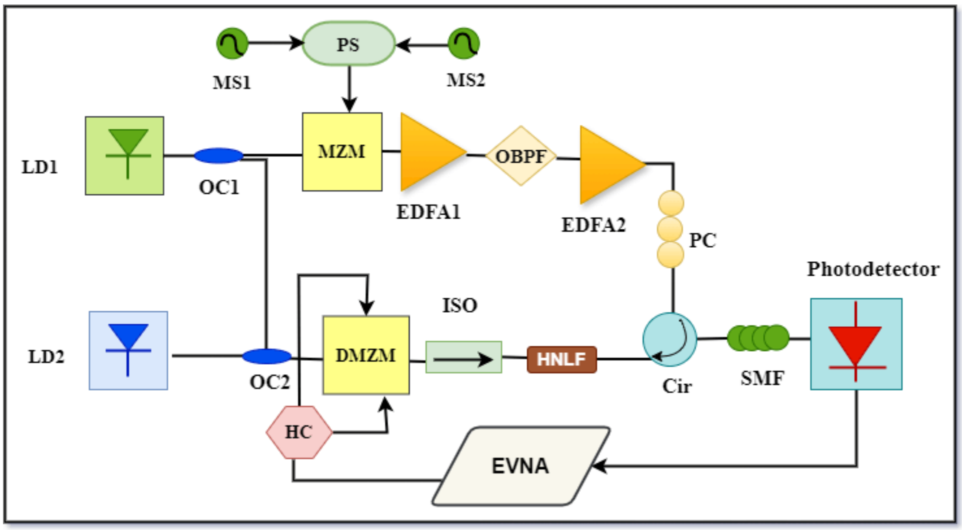

Fig. 7. Experimental apparatus. LD1, LD2: Laser Diode, OC1, OC2: Optical Coupler, DMZM: Dual-drive Mach-Zehnder Modulator, MS: Microwave Source, PS: Power Splitter, OBPF: Optical Bandpass Filter, HNLF: Highly Nonlinear Fiber, Cir: Circulator, HC: Hybrid Coupler (Wang *et al.*, 2015)

A new method for flexible bandwidth reconfiguration in MPFs is illustrated in Fig.8, employing an innovative methodology that utilizes SBS to manipulate the Brillouin gain spectrum by narrowing and expanding it during the SBS process. This gain spectrum processing results in a substantial bandwidth reconfiguration, achieving roughly a 60% reduction and a significant increase of hundreds of times compared to scenarios without this processing. This discovery is highly significant for potential applications in signal processing, communication systems, and radar, providing an autonomous solution for versatile filter applications. (Xiao et al., 2015).The strengths of this method include its innovative approach, comprehensive examination, tangible importance, and promising impact on MPF improvements, but also it has some drawbacks such as complexity, Sensitivity to Environmental Factors, dependence on High-Quality Optical Components, insertion loss, and noise.

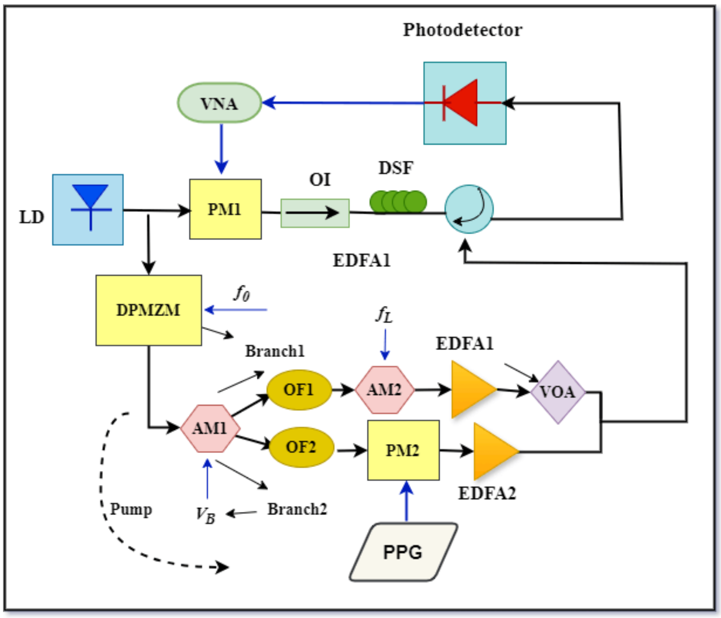

Fig. 8. Diagram illustrating the structure of the proposed filter. PM: Phase Modulator, OI: Optical Isolator, DSF: Dispersion-Shifted Fiber, AM: Amplitude Modulator, VOA: Variable Optical Attenuator, PPG: Pulse Pattern Generator, OF: Optical Filter (Xiao *et al.*, 2015)

An innovative method has been proposed for creating reconfigurable microwave band-stop filters, designed to deliver a square response with a width of 300 MHz, as shown in Fig.9. This methodology successfully overcame the limitations of previous approaches, achieving notable advancements. By electrically adjusting the pump, we managed to tune the bandwidth between 100 and 300 MHz, and significantly reduced on-chip Brillouin loss—achieving an impressive 20 dB reduction in SBS optical filter dispersion, corresponding to about 1.5 dB (Aryanfar *et al.*, 2016). The research is distinguished by its novelty, wide tuning frequency range, precise customization of on-chip SBS loss profiles, and potential impacts on radar, electronic warfare, radio astronomy, optical communication systems, and wireless communications. Besides that, it still shares the same disadvantages highlighted in previous research, including a complex design, heightened sensitivity to environmental factors, in addition to the issue of limited bandwidth.

An on-chip reconfigurable bandpass and band-stop MPFs utilizing SBS was created as depicted in Fig.10. The design produced an impressive on-chip SBS gain (>40 dB) by using CHG waveguides. The filters exhibited substantial bandwidth adjustment, frequency versatility, and exceptional selectivity through meticulous SBS gain customization using electrical combing. The bandpass filter exhibited a tuning range spanning from 30 MHz to 440 MHz, with a center frequency ranging from 3 GHz to 30 GHz. Band-stop filters demonstrated adjustable bandwidths ranging from 75 MHz to 300 MHz and variable center frequencies up to 30 GHz. These advancements in the process of creating, adjusting, and choosing specific properties indicate potential uses in the fields of microwave signal manipulation and radar technology (Choudhary *et al.*, 2016). A significant progress is presented in this work for enhancing fabrication procedures and illustrating the filter's performance, which contributes to the development of small, cost-effective, and high-performance MWP devices. Nonetheless, issues such as the intricate experimental setup, insertion loss, and the need for precise phase matching must be resolved to facilitate the practical and widespread deployment of these filters.

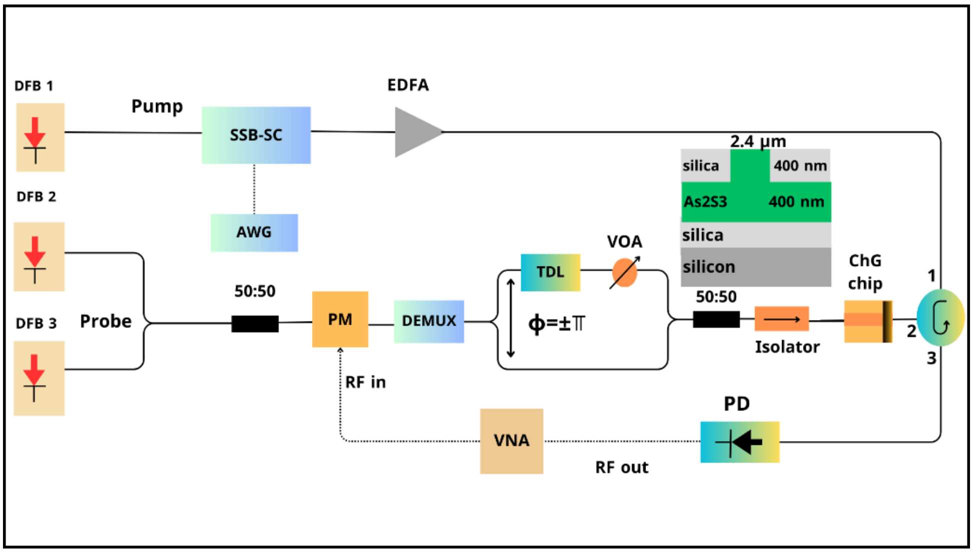

Fig. 9. Diagram illustrating the structure of the SBS-based MPF. SSB-SC: Single-Sideband Suppressed-Carrier, TDL: Tunable Delay Line, CHG chip: Chalcogenide photonic chip, DEMUX: Demultiplexer, RF: Radio Frequency (Aryanfar *et al.*, 2016)

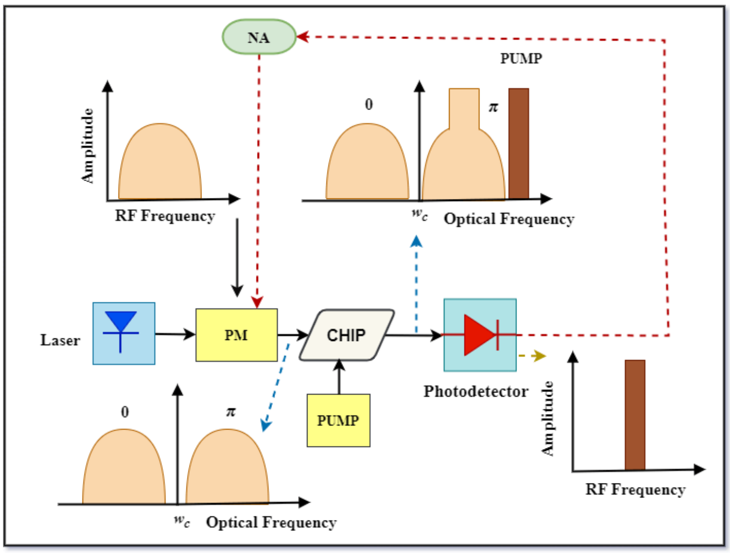

Fig. 10. Function of the bandpass filter via principle. The SBS chip creates a highly selective bandpass filter by processing an RF signal that has been modulated into the optical domain. NA: Network Analyzer (Choudhary *et al.*, 2016)

Fig.11 Introduced a groundbreaking chip-based photonic Brillouin filter for RF spectrum analysis. This innovation successfully overcame the inherent trade-off between range and accuracy. Utilizing a CHG glass waveguide, it precisely calculated RFs up to 38 GHz with an impressive error margin of only 1 MHz. The system incorporated SBS for precise measurement of microwave frequencies over a large range. It enables the separate estimation of numerous tones with a minimum spacing of 50 MHz. Significantly, the system exhibited a 1 MHz deviation in estimation throughout a wide frequency range of 9–38 GHz. The comparative analysis emphasized the distinctive benefits of the SBS-on-chip Instantaneous Frequency Measurement (IFM) system. It can measure frequencies up to 20 GHz and is very accurate up to 400 kHz. This is possible with the amplitude comparison function (ACF) method and narrow-band filters. This advancement shows potential for military applications that necessitate rapid and accurate assessment of numerous radio frequency signal frequencies (Jiang *et al.*, 2016). The high precision, wide measurement range, and experimental validation are notable strengths. However, challenges related to the power requirements, environmental sensitivity, and dependence on high-quality optical components need to be addressed for practical and widespread implementation of these systems.

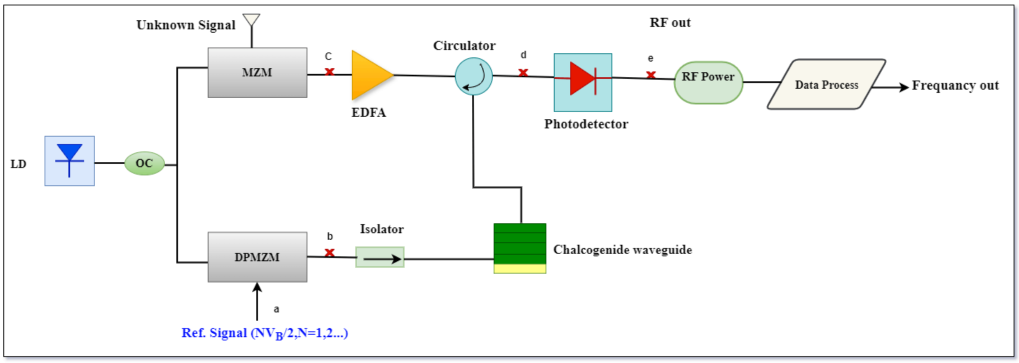

Fig. 11. The experimental configuration (Jiang *et al.*, 2016)

In Fig.12, the setup presented a dual-band bandpass adjustable MPF utilizing SBS. The research aimed to overcome the limits of conventional filters by introducing a technology that achieves a high level of resolution and effectively rejects out-of-band signals. By utilizing SBS, the researchers created a dual-band filter with two individually tunable passbands spanning from 1 GHz to 19 GHz. The experimental results showed that the system achieved a high resolution of less than 30 MHz bandwidth. It also displayed a significant out-of-band rejection of approximately 40 dB at an optical pump power of 25 mW. The system successfully utilized sideband amplification generated by SBS to convert phase-modulation (PM) to amplitude modulation (AM) (Li *et al.*, 2016). The proposed filter, designed for wireless communication applications, provides versatility, a wide frequency range, and robust electromagnetic interference (EMI) suppression. The research's merits reside in the amalgamation of theoretical analysis with experimental demonstration, highlighting the filter's practical significance and potential impact across various domains. However, issues such as the complexity of the experimental setup, sensitivity to pump power, and reliance on stable laser sources must be addressed to enable practical and broad adoption of this technology.

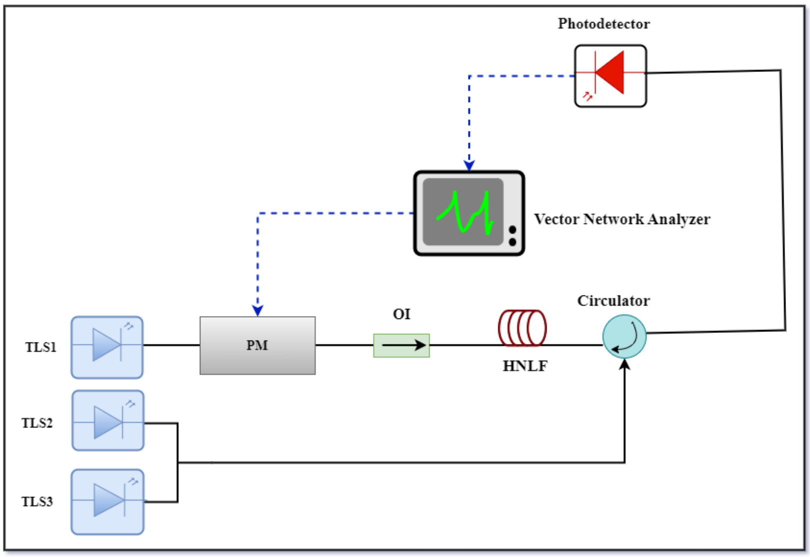

Fig. 12. Configuration for the Dual-Band Bandpass MPF Experiment. TLS: Tunable Laser Source (Li *et al.*, 2016)

Addressing the challenge of enhancing the steepness of the filter slope in Brillouin-based MPF, as depicted in Fig.13, researchers achieved significant improvements by incorporating Brillouin gain and loss reactions to phase-modulated (PM) signals. This modification resulted in an impressive passband response of 16.7 dB per octave. Their methodology demonstrated effectiveness while minimizing the introduction of substantial interference, thus preserving the integrity of the signal link with minimal disruption. Importantly, the approach proved its compatibility with integration into compact photonic integrated circuits (PICs) due to its short interaction length and moderate amplification. Despite a modest decrease of 5 dB in the signal-to-noise ratio (SNR), the method's overall features mark it as a noteworthy improvement with potential applications in communication systems, radar, and sensing equipment's (Samaniego and Vidal, 2016). The technique's capacity to produce sharp filter slopes and flat-top responses while minimizing noise degradation stands out as a key achievement. Nevertheless, challenges such as the complexity of the setup, inherent tradeoffs between bandwidth and gain, and issues related to noise degradation must be resolved to facilitate practical and widespread adoption of this technology.

A pioneering polarization-independent rectangular MPF utilizing SBS in optical fiber is shown in Fig.14, researchers effectively attained a high level of selectivity and adjustability, demonstrating a form factor of 20 dB with a low value of 1.056. Using a depolarized frequency-sweeping pump helped the MPF become independent of polarization effects, which solved problems that come with being dependent on polarization. The filter, which had a four-stage structure, exhibited a selectivity of 57 dB over a bandwidth of 2.1 GHz, thereby satisfying the technical specifications (Yi *et al.*, 2016) . This work is important because it demonstrates the successful application of a high-performance MPF that can be adjusted, exhibits a high level of selectivity, and produces less noise. This makes it an attractive technology for RF systems and communication technologies. The strengths encompass originality, strong empirical validation, significant technical advancements, and potential real-world implementations in diverse RF and communication systems. However, challenges related to system complexity, high pump power requirements, measurement limitations, and dependence on specialized components must be addressed to enhance the practical implementation and scalability of the proposed MPF.

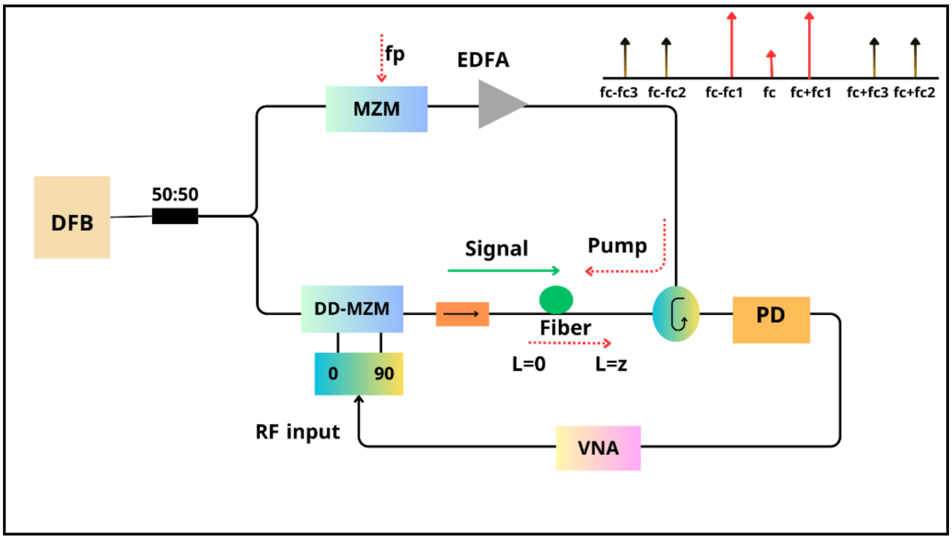

Fig. 13. Schematic representation of the experimental configuration. DD-MZM: Dual-Drive MZM (Samaniego and Vidal, 2016)

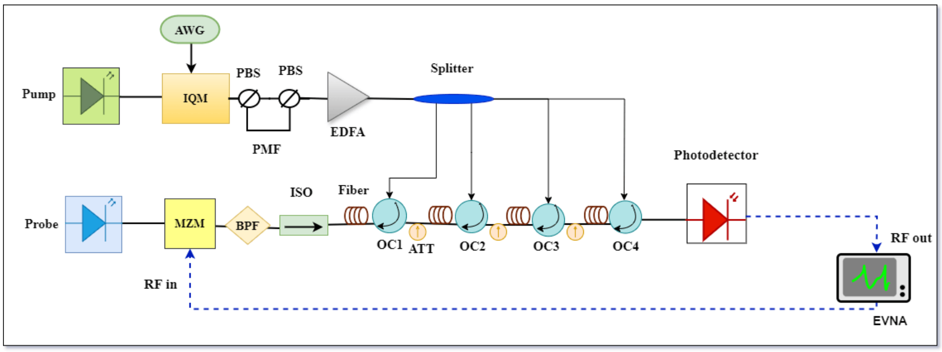

Fig. 14. Design of a pump-splitting four-stage SBS for polarization-independent MPF experiments. ATT: Attenuator, PBS: Polarization Beam Splitter, PMF: Photonic Microwave Filter (Yi *et al.*, 2016)

A new type of MPF that has the ability to reduce noise and adjust its bandwidth is shown in Fig. 15. This MPF is based on the losses caused by SBS in optical fiber. Instead of using normal

SBS gain-based filters, they used SBS losses to get narrow-banded aperiodic bandpass characteristics. The filter exhibited the capacity to adjust its frequency range from 500 MHz to 10 GHz by effectively reducing unwanted signals using symmetric SBS losses. The main accomplishment was the successful implementation of a filtering technique that achieved almost complete noise reduction with a noise pedestal of only 5 dB, in contrast to SBS gain-based filters. This filter is useful in dense wavelength-division-multiplexed (WDM) networks because it has a large independent bandwidth, a center frequency that can be changed, a response that is the same across the spectrum, and very little noise (Feng, Preussler and Schneider, 2017). The study stands out because it uses a well-known technology, a precise experimental setup, and a full comparison with SBS gain-based filters, which shows that the proposed method is better at handling noise. However, to advance the practical implementation and scalability of the proposed filter, it is essential to overcome challenges such as the experimental complexity, limited selectivity, constraints on central frequency bandwidth, and vulnerability to environmental interferences.

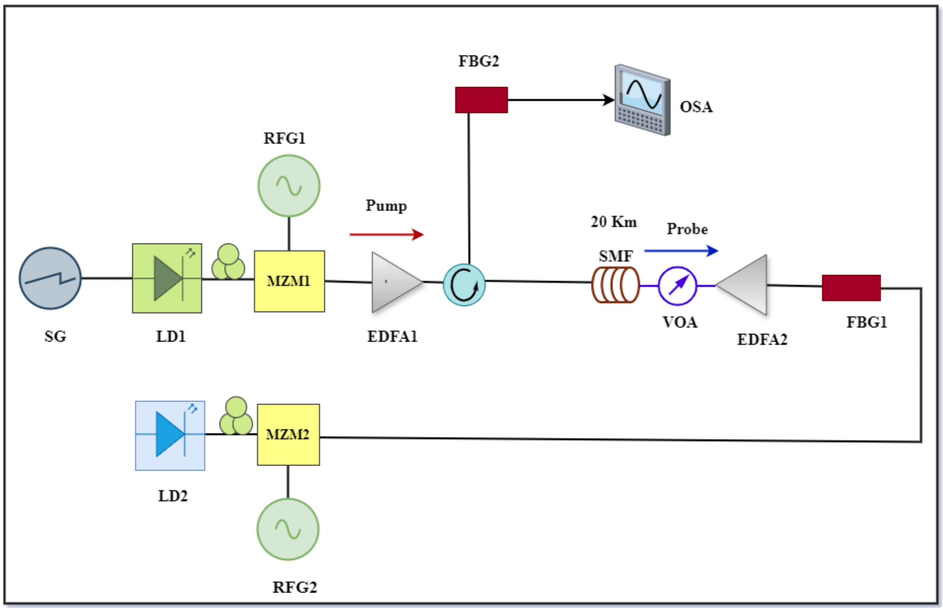

Fig. 15. The experimental configuration. SG: Signal Generator, RFG: Radio Frequency Generator, FBG: Fiber Bragg Grating, OSA: Optical Spectrum Analyzer (Feng, Preussler and Schneider, 2017)

An extremely narrow dual-passband MPF that operates based on SBS can be created as directed in Fig.16. The filter demonstrated a very restricted frequency range of 20.1 MHz, an exceptional ability to reject signals outside of this range with a ratio reaching 35 dB, and a bandwidth shape factor of 2.5 (20 dB to 3 dB). By manipulating the RF oscillation frequency supplied to the electro-optic modulation (EOM), the dual-passband MPF enables tunability between passbands using SBS and EOM. The paper presented an elaborate theoretical framework that accounted for both Brillouin gains and losses. Experimental verification validated the filter's exceptional selectivity and narrow dual-passband response. An innovative filtering method is presented in this study, which can be applied in radar systems, satellite communications, and optical signal processing (Hu et al., 2017). This work offers advantages in terms of originality, theoretical modeling, experimental verification, adjustability, and potential enhancements for advanced multi-band wireless communication systems. Nonetheless, to improve the practical applicability and scalability of the proposed filter, it is crucial to address challenges such as the high-power requirements, reliance on high-quality components, measurement limitations, and elevated noise figure.

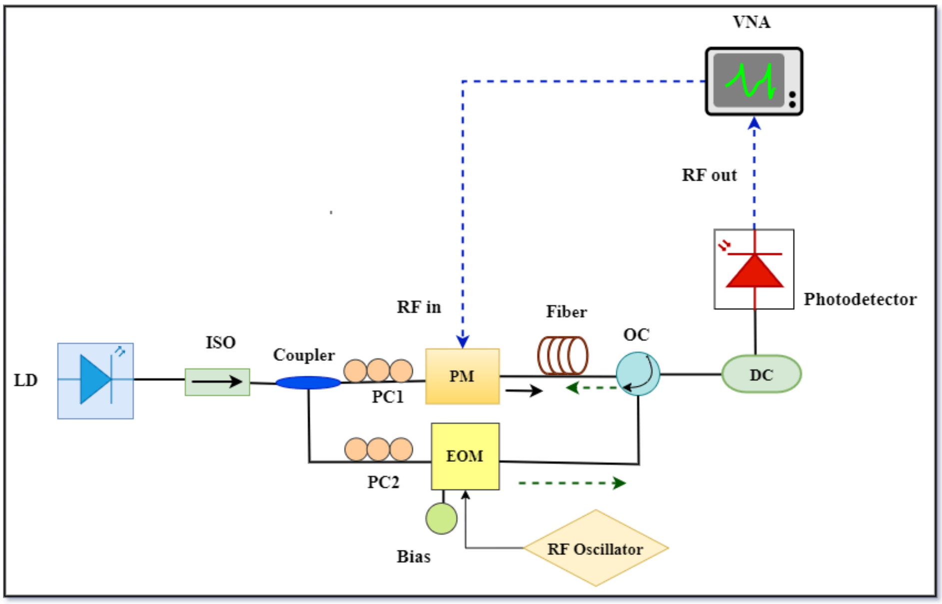

Fig. 16. The suggested dual-passband filter's schematic diagram, along with its operating principle and diagram. DC: Dispersion Compensator, EOM: Electro-Optic Modulator (Hu et al., 2017)

An innovative approach for multiphoton fluorescence MPF utilizing SBS and dispersion-induced phase mismatching in optical fibers has been introduced as shown in Fig.17. Their method tackled the task of developing a flexible and adjustable filter for precise optical signal processing and adaptable switching in fast optical transmission systems. By employing the PM detection approach, they enhanced the selectivity of SBS and the efficiency of pump power. The experimental results showed that the SBS response had a selectivity of 26.08 dB and a pump power of 2.28 dBm. Researchers achieved this by changing the laser wavelength and incorporating a time delay compensation (TDC) module (Shi et al., 2017). The research is noteworthy due to its pioneering methodology, validated tests, and prospective applications in improving optical transmission systems and MWP. However, to improve the practical applicability and scalability of the proposed filter, it is essential to address challenges such as the complexity of the experimental setups, high power requirements, measurement limitations, and the impact of environmental dispersion effects.

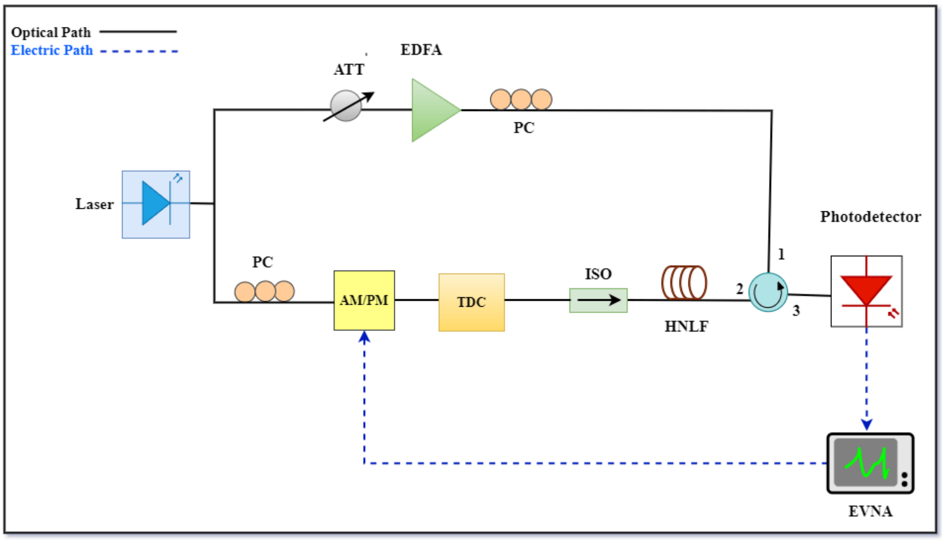

Fig. 17. Experimental apparatus for measuring SBS selectivity. TDC: Time Delay Compensation, AM: Amplitude Modulation (Shi *et al.*, 2017)

The designed MPF of Fig.18 discussed the restricted range of frequency tuning in MPFs that rely on SBS. The researchers suggested and empirically validated a single-passband MPF with a broad adjustable frequency range through the optimization of crucial SBS characteristics. The study introduced a theoretical framework and empirically confirmed the effectiveness of the MPF. The MPF was able to tune from 0 to 40 GHz by carefully adjusting things like pump power, the length of the highly nonlinear fiber, and the polarization states. The main-to-secondary sidelobe ratio was 55 dB, and the bandwidth at half-maximum was 16 MHz. This MPF has successfully addressed past restrictions and is now capable of performing highly selective filtering across a wide range of frequencies. It can be used in various applications such as radar, mobile telephony, phased array antennas, radio-across-fiber systems, optical communication, sensing, and instrumentation (Tang *et al.*, 2017). The strengths points of this work are its good methodology, methodical optimization, exceptional performance, and ability to address shortcomings in previous SBS-based systems. However, the sensitivity to polarization, and dependency on high-quality components are challenges that need to be addressed for practical and widespread implementation.

A cost-effective and versatile approach for MPFs utilizing a directly modulated laser (DML) can be designed. Fig.19 shows such MPF that employing a DML, which had a simpler structure and used fewer digital-to-analog converter (DAC) resources than an in-phase and quadrature (I&Q) modulator (IQM) technique, was used to accurately and freely change MPF shapes. Experimental validation successfully demonstrated the viability of rectangular MPFs (500 MHz to 2 GHz) and various filter shapes, including truncated Gaussian, super Gaussian, and triangle filters, using a 500 Mb/s signal. The DML-based approach showcased its adaptability and promise for use in telecommunications, radar, and sensing (Wei *et al.*, 2017). The MPF in this research offers key strengths like adaptability, comparable efficacy, empirical verification, and potential cost-efficiency for high-performance photonic systems. However, optimizing performance requires managing thermal effects, ensuring feedback accuracy, maintaining DML stability, and addressing modulation current limitations.

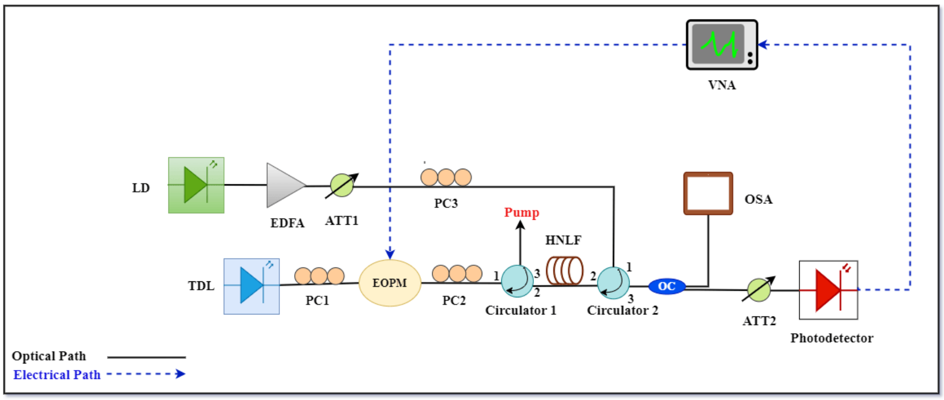

Fig. 18. An MPF proposal utilizing SBS and PM. TLD: Tunable Laser Diode, EOPM: Electro-Optic Phase Modulator (Tang *et al.*, 2017)

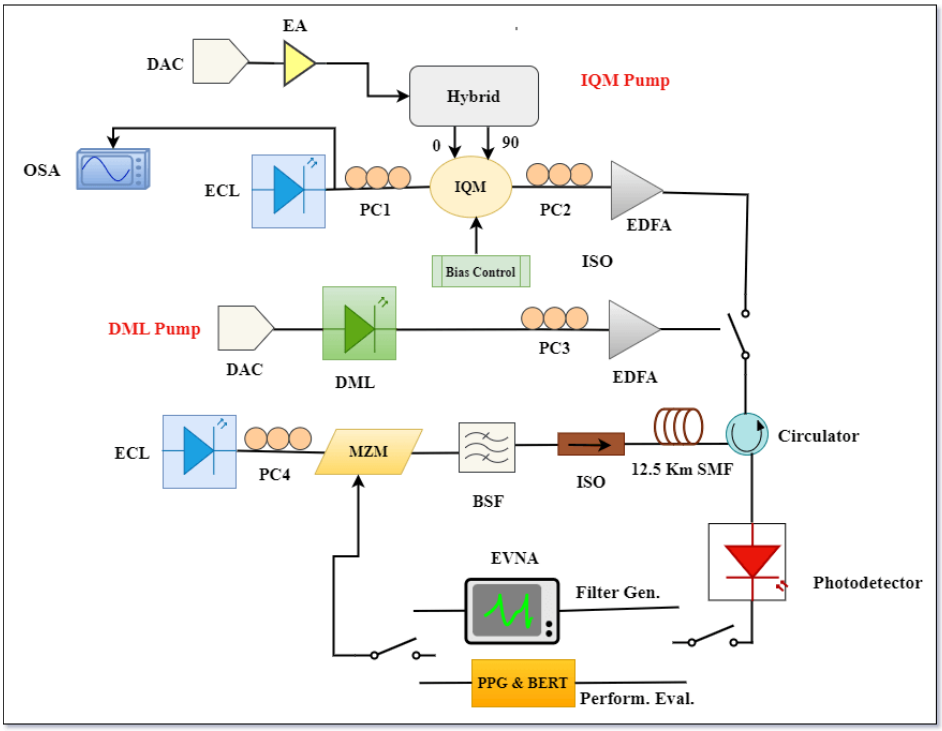

Fig. 19. Experimental configuration for the generation and evaluation of arbitrary-shaped filters utilizing the DML and IQM methodologies. ECL: External Cavity Laser, DAC: Digital-to-Analog Converter, DML: Directly Modulated Laser, PPG&BERT: Pulse Pattern Generator & Bit Error Rate Tester, IQM: In-phase and Quadrature (I&Q) Modulator, EA: Electrical Amplifier(Wei *et al.*, 2017)

The problem of gain saturation in SBS-based MPFs has been addressed in Fig. 20, where a two-stage SBS-MPF are suggested with utilizing a pump-splitting method to enhance gain for varying input powers. This method greatly enhanced the range of input values and the ability to distinguish between different inputs while maintaining a high level of linearity. The researchers produced an input dynamic range of over 40 dB and a selectivity of over 49 dB by using steady-state wave equations. The filter's bandwidth can be adjusted from 50 MHz to 200 MHz. The filter maintained a low passband ripple of less than 1.3 dB and a shape factor of 1.2, with a 20-dB difference between the passband and stopband for a 200-MHz filter. The research presents an innovative method for microwave signal processing applications, providing adaptability in radar systems, wireless networks, and high-performance situations (Zhang et al., 2017). The MPF of this research has good innovative methodology, rigorous experimental verification, and thorough performance assessment, significantly contributing to MWP. But the complexity of the system is considered a weak point in the design, in addition to, polarization control requirement, and in-band noise must be addressed for practical implementation of the proposed filter.

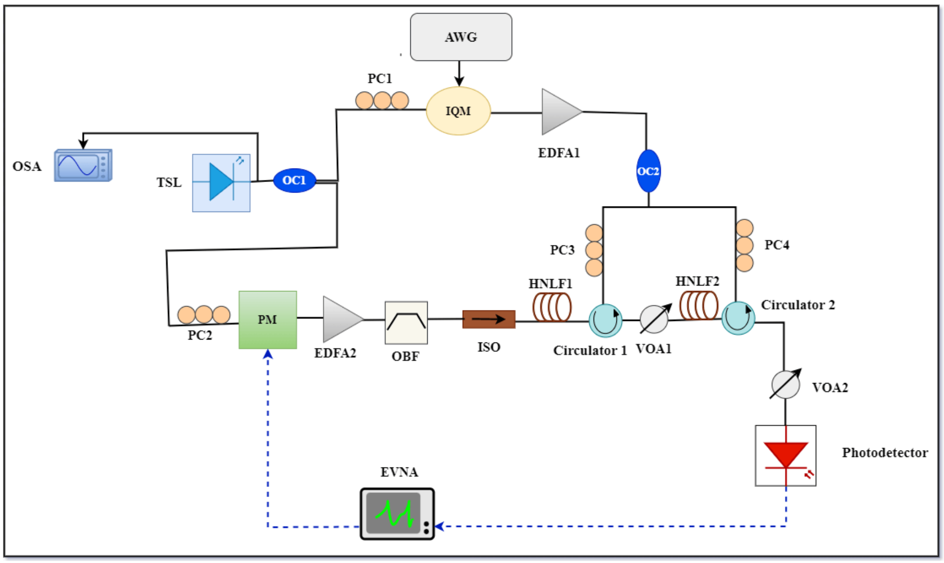

Fig. 20. The suggested dual-stage SBS-based MPFs experimental setup for measuring its frequency response. OBF: Optical Bandpass Filter, TSL: Tunable Laser Source (Zhang *et al.*, 2017)

A reconfigurable MPF using SBS can be created too. Such filter as shown in Fig.21 exhibited three alternative configurations: a single broadened response, two passbands with varying bandwidths, or a multiband filter. The researchers utilized a programmable single-sideband suppression carrier signal to accurately place optical lines and create customizable passbands. This adaptable filter allows for the direct and simultaneous manipulation of different microwave signal types, providing a valuable solution for diverse signal processing applications. The research presents a novel methodology, substantiated by experimental evidence, that has the potential to significantly influence microwave signal processing, communication systems, radar technology, and wireless communication. This study improves comprehension by investigating the correlation between bandwidth and modulation data patterns (Zhang et al., 2018) . The ability to switch between different passband configurations and the use of cost-effective components are notable strengths. However, challenges related to modulation sensitivity and dependence on high-quality components need to be addressed for practical and widespread implementation.

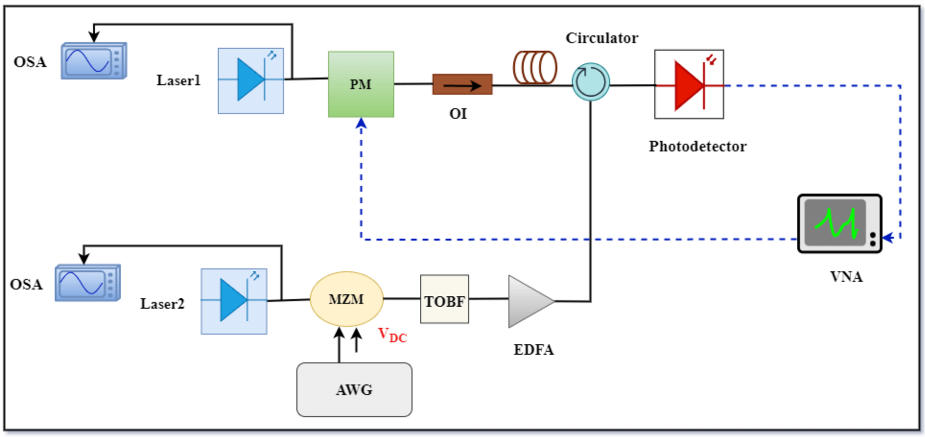

Fig. 21. Schematic of the suggested filter. TOBF: Tunable Optical Bandpass Filter (Zhang *et al.*, 2018)

In order to study the effect of the dispersion on the filter performance, the setup in Fig.22 examines the influence of dispersion on SBS-based MPNFs. Negative consequences are discovered including a shift in the center frequency of the notch by 8.3 MHz and a decrease in stopband rejection by 21 dB. The proposed setup suggested and showcased dispersion compensation strategies, offering insights into the intricate relationship between RF notch power and dispersion. This work makes a substantial contribution to enhancing the performance of MPNF, specifically in the context of MWP and optical communication systems (Feng, Preussler and Schneider, 2018). The strengths of this approach include its comprehensiveness, practical applicability, empirical validation, potential for broad impact, and clear communication of results. Nonetheless, challenges such as sensitivity to precise dispersion compensation, saturation effects, tuning accuracy limitations, and additional component-induced dispersion need to be addressed to improve its practical and widespread implementation.

A highly efficient and adjustable single-passband MPF utilizing SBS and a fiber ring resonator (FRR) is introduced in Fig.23. This discovery met the need for high-quality MPFs with a narrow frequency range. These are needed for tasks like making microwave signals that are very pure and running high-performance MWP radar systems. The MPF demonstrated a remarkably tight 3 dB bandwidth of 825 ± 125 kHz across a broad tuning range of 2–16 GHz. It attained a maximum Q-factor of 17778 at 16 GHz. It was particularly selective, had excellent out-of-band suppression (>25 dB), and was easy to design. This was a big step forward in MPFs that can be used in a wide range of high-frequency signal processing tasks (Wen *et al.*, 2018) . The research is exceptional because of its extensive adjustability, uncomplicated structure, and successful experimental verification. These combined strengths significantly enhance the MPF performance. On other hand, the sensitivity to environmental conditions, reliance on high-quality components, modulation bandwidth limitations, and amplitude mismatch can limit its performance quality.

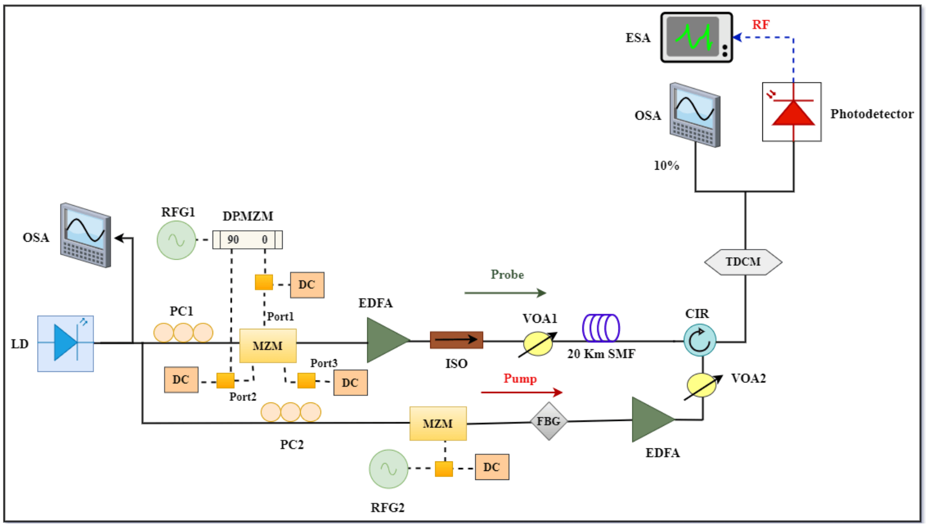

Fig. 22. Experimental apparatus. FBG: Fiber Bragg Grating, TDCM: Tunable Dispersion Compensation Module, CIR: Circulator, ESA: Electric Spectrum Analyzer (Feng, Preussler and Schneider, 2018)

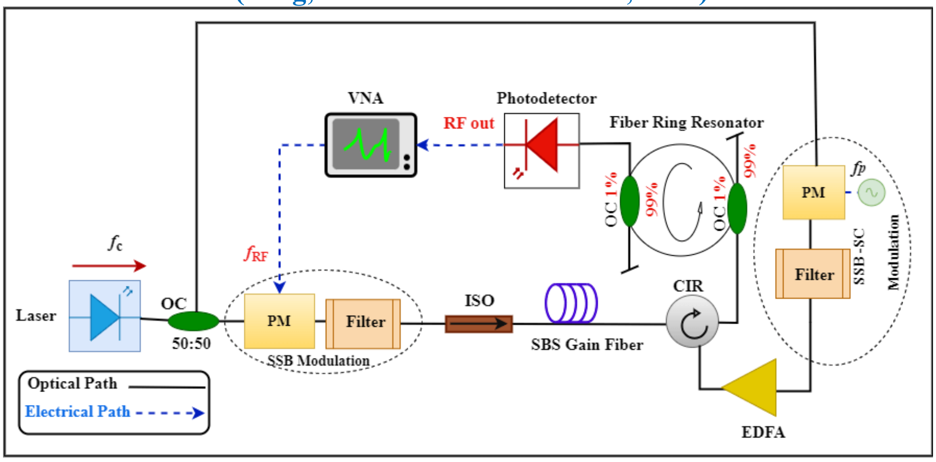

Fig. 23. The MPF experiment design. SSB-SC: Single-Sideband Suppressed-Carrier (Wen *et al.*, 2018)

A high-performance MPFs that rely on SBS loss responses is well studied in Fig.24. The researchers addressed the issue of noise-free passband responses in practical microwave applications by combining a highly efficient analog photonic connection with low-noise SBS-based filters. The researchers developed an agile multi-bandpass filter with impressive characteristics, including a low noise figure of 18.9 dB, a spurious-free dynamic range (SFDR) of 106 dB·Hz^(2/3), and an insertion loss of -13.9 dB. The main discovery highlights the need for combining the optimized analog photonic link with low-noise SBS-based filters to create high-performance, adjustable, and adaptable SBS-based MPFs with a maximum of 10 passbands. The research presented a notable breakthrough by integrating superior link performance, filter functionality, and a condensed monolithic photonic chip (Mahendra et al., 2018). This work excels in its practical experimental approach, in-depth analysis of key variables, and the promising microchip proposal for future MWP subsystems in wireless communication and defense. Yet, the experimental setup's complexity, reliance on high-quality components, and performance trade-offs must be resolved for broader practical implementation.

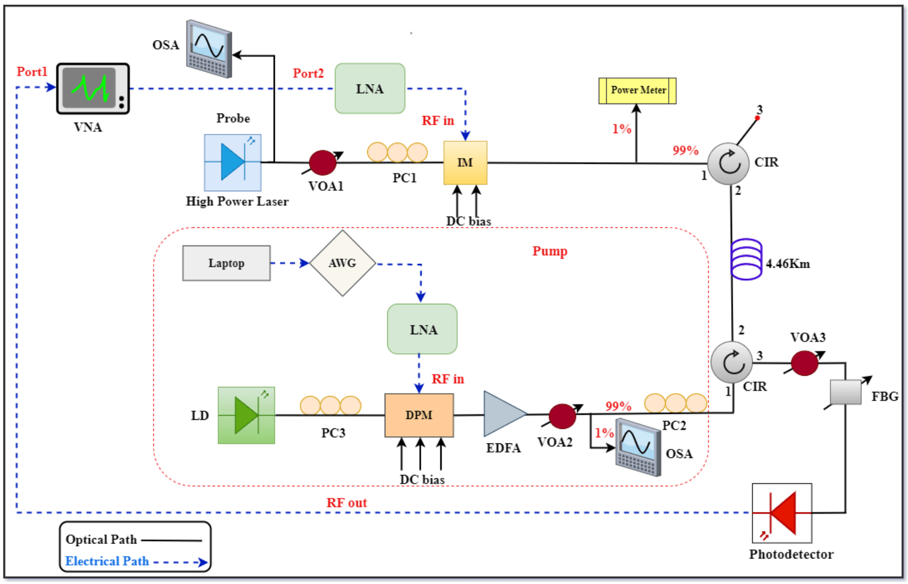

Fig. 24. Block diagram of the experimental setup for an SBS loss-based filter. Top-half of the setup is the probe. The bottom side of the figure shows the pump of the filter setup , LNA: Low Noise Amplifier, IM: Intensity Modulator (Mahendra *et al.*, 2018)

Fig.25 Presented a new MPF that incorporates SBS to achieve adjustable bandwidth. By utilizing a binary phase shift keying (BPSK) signal to modulate a dual-drive Mach-Zehnder modulator (DDMZM), the filter achieved a 196 MHz 3-dB bandwidth. This generated a 5-line optical comb for the SBS filter, resulting in a passband that was virtually rectangular and had good resolution. The SBS filter exhibited adjustable resolution and strong suppression of unwanted frequencies (20 dBm) with minimal pump power (<4 dBm) and a broad frequency tuning range (0–20 GHz) (Gong et al., 2019). The research is strong because it carefully looks at current filters, uses a targeted problem-solving approach, successfully implements SBS, is backed up by experiments, and looks into how it can be used in telecommunications, radar, and electronic warfare systems. This makes the research stand out as unique and important. However, to enable practical and widespread implementation, it is crucial to address challenges such as the complexity of the experimental setup, amplitude fluctuations, and modulation bandwidth limitations.

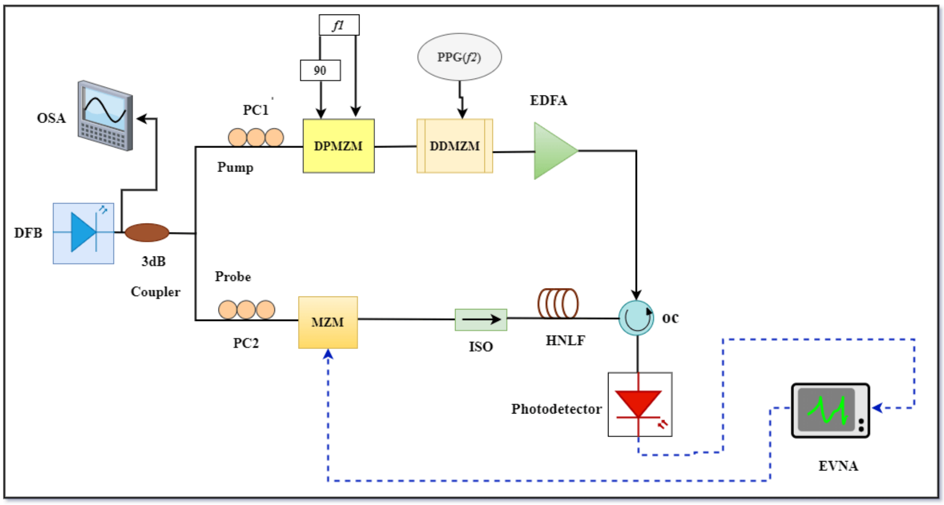

Fig. 25. Schematic diagram of the experimental setup (Gong *et al.*, 2019)

A switchable MPF that operates by exploiting the polarization dependency of SBS is presented in Fig.26. The MPF provides versatility by altering bandpass and notch filter configurations by manipulating the polarization orientation of the pump and signal light. The results of the experiments showed a bandpass reaction with a 3-dB range of 112 MHz and a notch reaction with a 3-dB range of 21 MHz. This proved that the suggested method worked. The research emphasized the benefits of MPFs, such as their wide bandwidth, low weight, adaptable tunability, rapid reconfigurability, and resistance to EMI. Various communication systems, such as wireless communication, radar, and optical fiber communication, have utilized the versatile switchable MPF (Gu et al., 2019). The study has notable strengths such as a thorough analysis, empirical verification, lucid exposition, and citations to pertinent literature, hence enhancing the comprehension and advancement of MPFs. However, challenges related to the sensitivity to polarization states, environmental factors, limited tuning range, and dependence on high-quality components need to be addressed to ensure practical and widespread implementation.

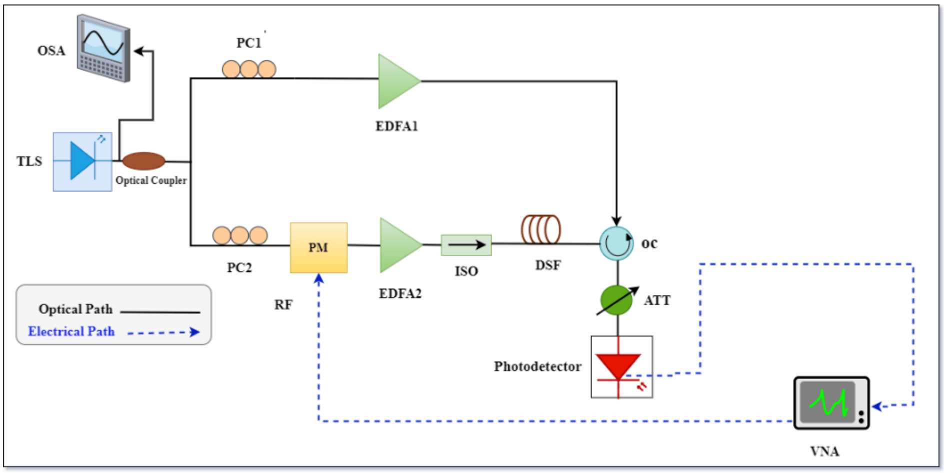

Fig. 26. The suggested switchable MPF schematic (Gu *et al.*, 2019)

A novel approach to creating a flat-top bandpass MPF with adjustable bandwidth is illustrated in Fig. 27. The way involved the combination of SBS and FWM methods with a Semiconductor Optical Amplifier (SOA). SBS and four-wave mixing (FWM) methods with a semiconductor optical amplifier (SOA). This made an optical spectrum with a flat-top profile. By manipulating the polarization state of the pump light and the optical signal injected into the SOA, FWM was effectively controlled, enabling precise adjustment of the passband's Full Width at Half Maximum (FWHM) bandwidth. The research showcased exceptional adaptability, attaining FWHM bandwidths ranging from 18 MHz to 52 MHz while maintaining a continuously low ripple amplitude within the passband (less than 0.5 dB). Their concept was proven to be resilient through experimental validation using practical demonstrations. This design provides a feasible solution for flat-top bandpass MPFs with adjustable bandwidth. The potential applications of this study included telecommunications, radar systems, wireless communication, and signal processing (H. Tang et al., 2019). The filter's tunable bandwidth, flat-top response, high selectivity, low power consumption, and effective use of SBS and FWM techniques make it a promising solution for high-resolution microwave signal processing. However, the complexity of the experimental setup, sensitivity to environmental factors and amplitude fluctuations are challenges that need to be addressed for practical and widespread implementation.

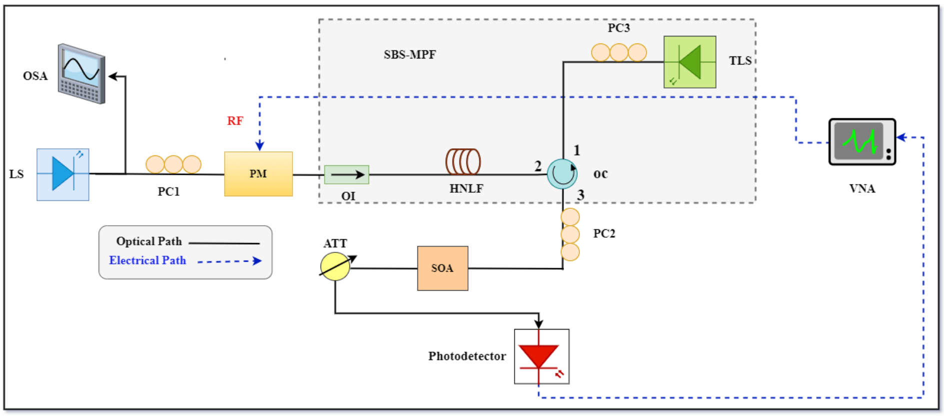

Fig. 27. This is a schematic of the proposed Opto-Electronic Oscillator (OEO) that uses a frequency-stabilization feedback loop and an ultra-high-Q silicon micro-ring resonator. SOA: Semiconductor Optical Amplifier, LS: Laser Source(H. Tang et al., 2019)

The issue of low skirt selectivity in SBS-based MPFs is discussed in the setup of Fig.28. The new method used the polarization sensitivity of Brillouin gain in birefringent fibers to make an experiment work. The result was a significant filter slope of 8.3 dB/oct and an amazing out-of-band rejection ratio of about 40 dB. This improvement is essential for overcoming the typically gradual fading of the Lorentzian tail in natural Brillouin responses. A streamlined design for SBS-based MPFs is presented in this study, which can be utilized in MWP, communication systems, and radar technology. This research makes a substantial contribution to enhancing the performance of high-quality microwave filters (Samaniego and Vidal, 2019). This study offers a filter with enhanced selectivity, high out-of-band rejection, and simple tuning, but faces challenges with setup complexity, environmental sensitivity, component quality, frequency range limitations, and amplitude fluctuations.

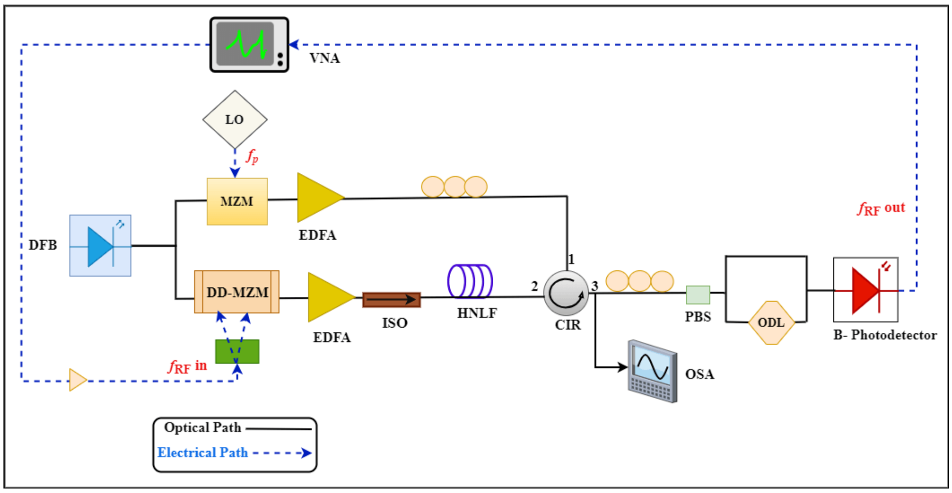

Fig. 28. Block diagram of the experimental setup. Where, ODL: Optical Delay Line, B-Photodetector: Balanced Photodetector, LO: Local Oscillator (Samaniego and Vidal, 2019)

An extensive investigation on chip-based Brillouin bandpass MPFs is performed with the help of Fig.29. The study compared several filter topologies. Researchers carefully looked at different options and found that the bandpass filter that uses SBS loss resonance in an intensity-modulated (IM) link configuration had the best qualities. These include a passband that is free from noise and has the lowest level of noise when compared to other strategies. The study tells us a lot about how well chip-based Brillouin bandpass MPFs work overall, showing us the best filter architecture with the best properties. This discovery has great importance in the progression of MWP and has extensive implications for the development of advanced RF systems, including communication networks, radar systems, sensing applications, and signal processing (Xie *et al.*, 2019). In summary, the study makes a valuable contribution by employing a thorough methodology, demonstrating practical significance, identifying an optimal filter scheme, and potentially enhancing RF technologies. However, challenges related to noise, implementation complexity, and the need for advanced integration technologies must be addressed for broader practical applications.

Fig. 30 introduced an innovative approach for creating a highly adjustable single-bandpass MPF using dual-fiber SBS. The dual-fiber structure employed a tunable laser, optical carrier splitting, and PM to achieve an effective MPF at a frequency of 21.4 GHz. The filter has a 3-dB bandwidth of 38 MHz and an out-of-band rejection ratio of more than 30 dB. The MPF exhibited a broad frequency range tuning capability of 40 GHz, making it appropriate for applications such as radar, RoF, and mobile communications. The main discovery of the research was the achievement of a highly adjustable single-bandpass MPF, which presents a favorable solution for advanced and adjustable filters in wideband signal processing applications (Yan *et al.*, 2019). The proposed MPF design features an innovative methodology and high performance with potential practical applications, but challenges such as environmental sensitivity and amplitude fluctuations need to be addressed to ensure the filter's effectiveness.

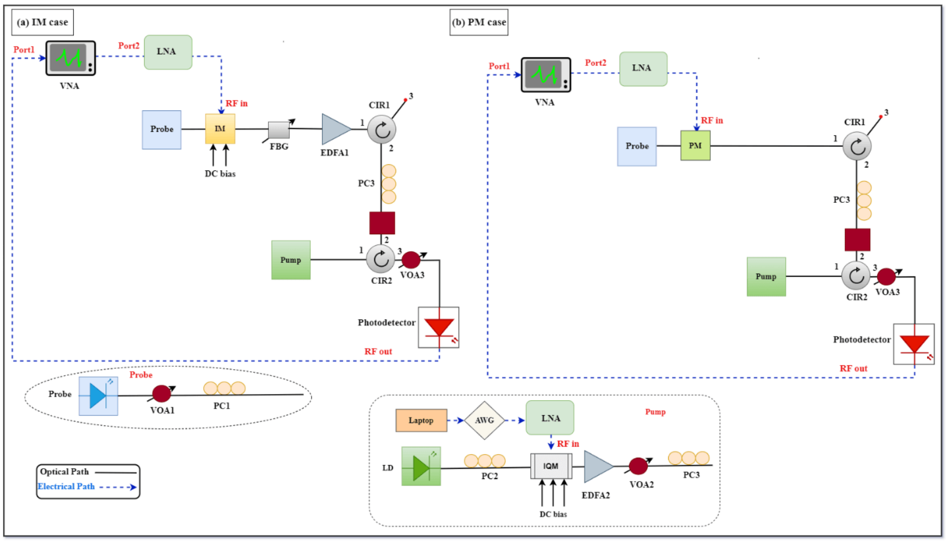

Fig. 29. Schematic diagram of the apparatus used to test bandpass filters. The high-powered laser source is part of the probe's path, DC bias input, LNA: Low Noise Amplifier. The figure's lower half depicts the filter setup's pump (Xie *et al.*, 2019)

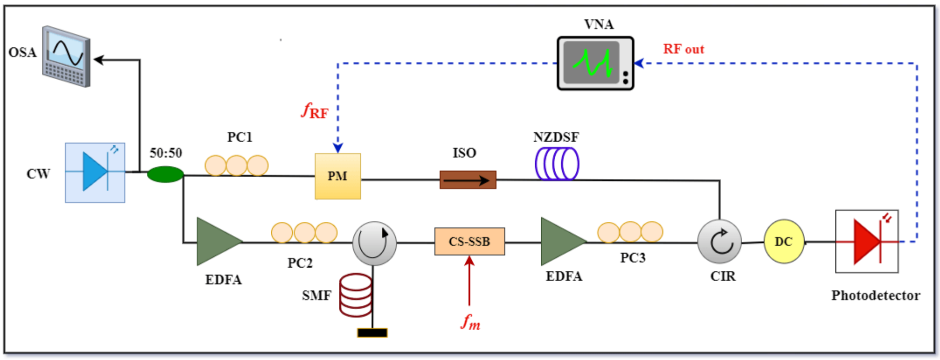

Fig. 30. Illustration of the experimental setup. Where, CS-SSB: Carrier Suppressed Single-Sideband, CW: Continuous Wave, NZDSF: Non-Zero Dispersion Shifted Fiber (Yan *et al.*, 2019)

A new MPF that allows for the independent adjustment of two passbands is shown in Fig.31. The study achieved this by utilizing a two-tone pumped SBS technique. They went beyond what regular dual-passband filters could do by using a dual-parallel Mach-Zehnder modulator (DPMZM) to change a two-tone pump freely and changing frequencies between PM and IM using SBS in a highly nonlinear fiber (HNLF). The experimental findings validated the effectiveness of a dual-passband MPF that exhibits both good selectivity and stability. Furthermore, this MPF offers the advantage of flexible tunability within the frequency range of

0–9.644 GHz. The passbands had a rejection ratio of more than 25 dB outside of the desired frequency range and a bandwidth of less than 55 MHz at the 3 dB point, which showed that the suggested method worked. The main discovery was achieving a dual-passband MPF that can flexibly adjust, offering solutions for reconfigurable microwave systems. The scheme's capacity to customize passband characteristics offers a potential solution for programmable dual-passband MPFs, which find applications in wireless communication, radar systems, electronic warfare, and signal processing (Zeng et al., 2019). This designed MPF presented with successful experimental verification and good stability but the setup complexity and dependency on high-quality optical components are considered the main challenges to the work.

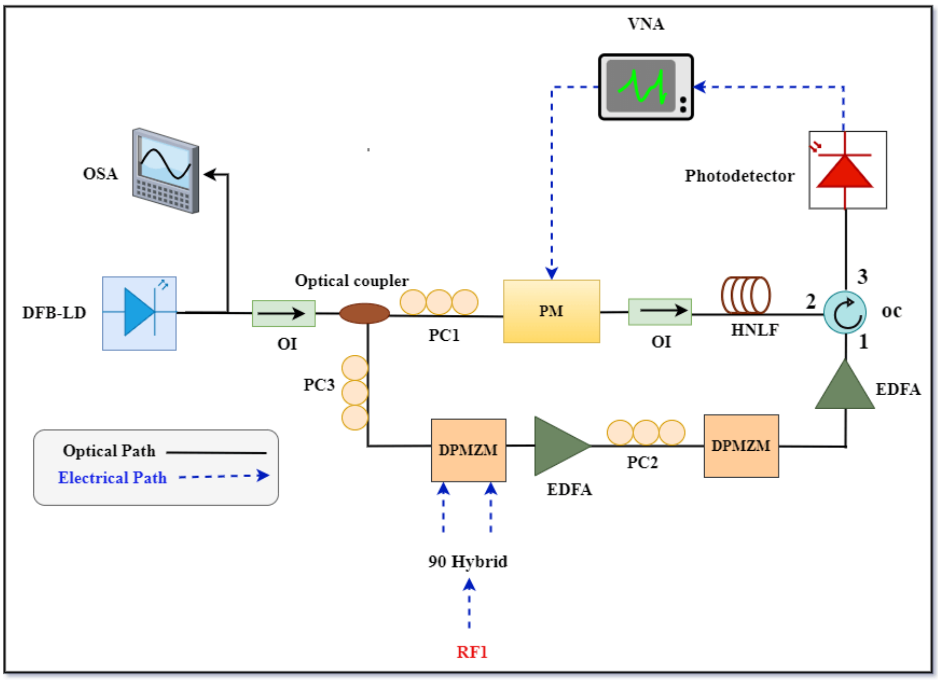

Fig. 31. The operation principle and schematic representation of the arbitrarily tunable dual-passband MPF utilizing SBS phase-to-intensity modulation. DFB-LD: Distributed Feedback Laser Diode (Zeng *et al.*, 2019)

Over the past four years, researchers have increasingly focused on the study, investigation, and in-depth analysis of microwave photonic filters. This growing interest has led to significant advancements, both in the development of innovative techniques and the refinement of analytical methodologies. Moreover, the research has broadened its scope to explore a wide array of practical applications, demonstrating the potential of these filters across different fields. The ongoing efforts in this area reflect a deeper understanding and a more comprehensive approach to overcoming the challenges associated with microwave photonic filter technology. For example, in (Gong et al., 2021), a new bandwidth-reconfigurable MPF utilizing SBS in fiber is presented as in Fig.32. This filter exhibited a 3 dB bandwidth spanning from 20 to 500 MHz, showcasing a broad range of adjustable frequencies and exceptional rejection of signals outside the desired range. The researchers employed vector modulation techniques to minimize passband volatility. The experimental setup consisted of optical and electrical components, resulting in a flexible bandwidth range of 20 to 500 MHz. They measured the passband fluctuation at 110 MHz to be 0.49 dB. The center frequency tuning range spanned from 1 to 20 GHz while retaining an out-of-band rejection ratio that exceeded 40 dB. The SNR was tested at 33.7 decibels, while the error vector magnitude (EVM) was measured at 2.1 percent. The proposed filter, designed for microwave signal processing in satellite communications and radar systems, showcased its novelty, wide range of tuning, low passband fluctuation, high rejection of out-of-band signals, and thorough experimental validation. These characteristics indicate its potential impact in a variety of microwave signal processing applications.

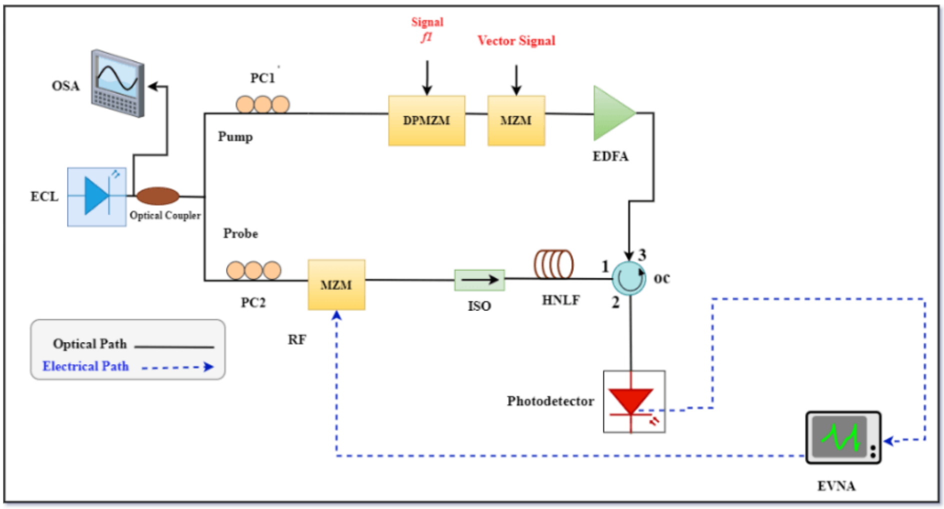

Fig. 32. Setting up the experimental SBS-based MPF. ECL: External Cavity Laser (Gong et al., 2021)

A development of a Tunable Microwave Photonics Gain Filter (TMWPF) utilizing SBS is illustrated in Fig.33. By employing a laser that can be adjusted in frequency, an RF amplifier (RFA), and a Gallium Arsenide (GaAs) I-Q DPMZM modulator, TMWPF obtained an impressive gain of 70 dBm. The study introduced a novel RF mixing technique to expand the bandwidth of SBS, demonstrating accurate manipulation and adaptability with different modulation schemes, particularly when used in conjunction with RFA. The successful RF mixing exhibited a range of bandwidth fluctuations from 20 MHz to 40 MHz. TMWPF, with its 32 GHz RF and 40 GHz optical tuneability, is well-suited for use in advanced communication systems such as 5G, 6G, aerospace, and satellite communication. The research possesses several notable features, such as its originality, rigorous experimentation, thorough comparisons of different components, extensive operating capabilities, and possible applications in sophisticated communication systems and future technologies. These strengths make a substantial contribution to the field of MWP technology (Ali, Haxha and Flint, 2022).

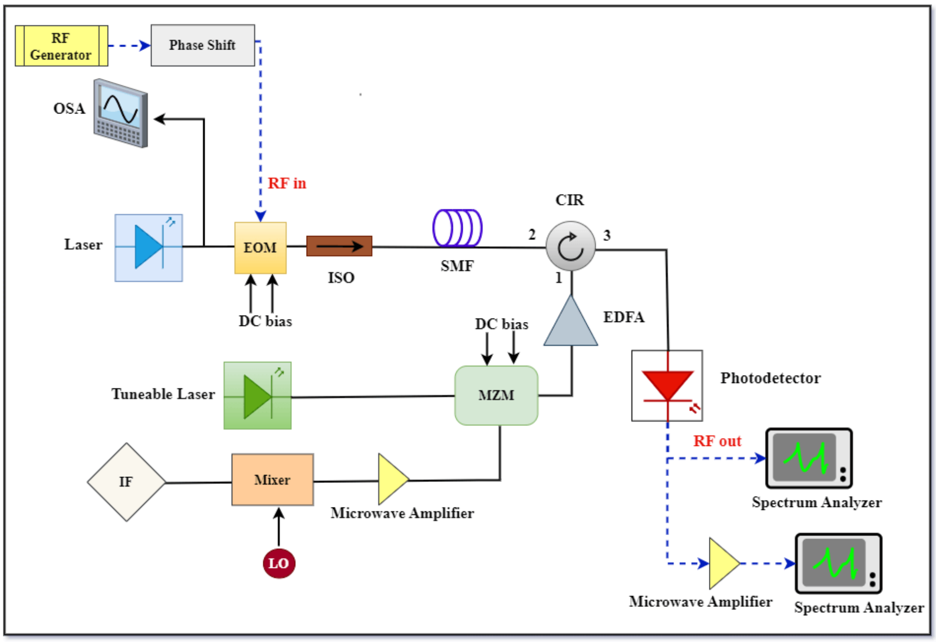

Fig. 33. SBS-based TMWPF. LO: Local Oscillator, IF: Immediate Frequency (Ali, Haxha and Flint, 2022)

In Fig.34, a novel signal processing method formulti-port photonic-phononic emitters-receivers (PPER) devices, utilizing Brillouin interactions to create narrowband, adjustable notch filters on an all-silicon platform is proposed. The PPER demonstrated excellent narrowband performance, achieving bandwidths as low as 2.7 MHz and signal rejection up to 57 dB using forward Brillouin scattering. Integration of PPER in interferometers improved the performance of silicon photonics notch filters, overcoming limitations of existing MPF technology. The all-silicon platform ensures minimal signal loss, immunity to RF interference, and easy integration with current production processes for integrated photonics. This study enhances future radar and communication systems by introducing efficient signal processing at very low frequencies, enabling frequency adjustments, and suggesting applications in advanced systems (Gertler et al., 2022).

An innovative and energy-efficient method to address the limits of Brillouin-based bandpass MPFs, specifically targeting issues related to bandwidth and power consumption is discussed in the setup of Fig.35. Their approach successfully implemented wideband reconfigurable filters that exhibit exceptional selectivity and little power consumption. By doing models and experiments, they proved that the phase response is flat, the group delay is zero, the selectivity is above 20 dB, and the bandwidth is more than 700 MHz. The filters demonstrated the ability to adjust their frequency up to 22 GHz, demonstrating their adaptability. The research makes valuable contributions to the fields of optics, photonics, sustainable photonic systems, and advanced MWP filtering technologies. The strengths of this work encompass a unique methodology, thorough experimental verification, remarkable outcomes, adaptability, possibility for incorporation, and energy-efficient breakthroughs in MWP (Raj *et al.*, 2022).

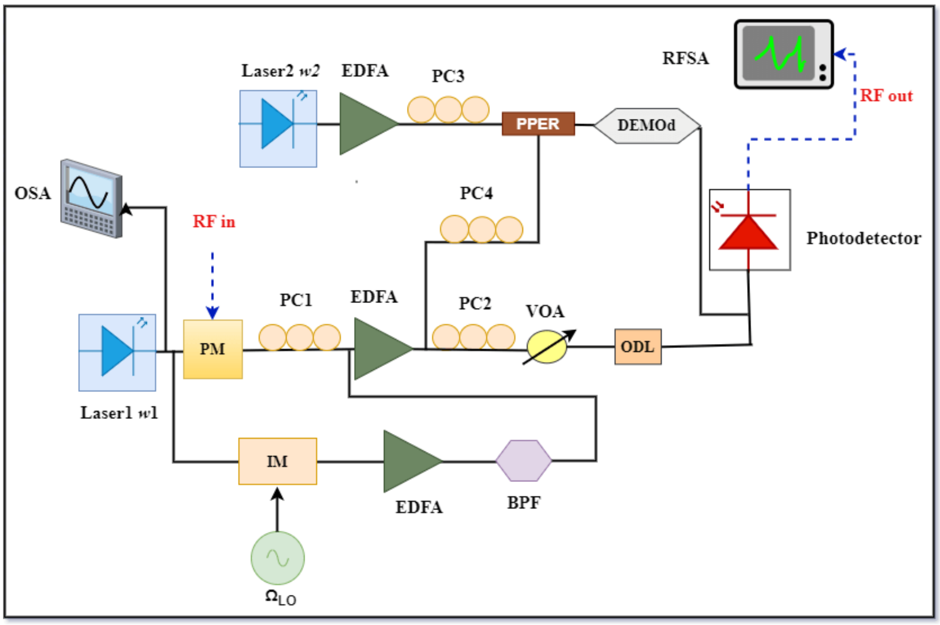

Fig. 34. Tunability of the frequency of a microwave-photonic notch filter. The experimental arrangement employs a diagram to adjust the frequency at which the notch occurs. Employing a Phase Modulator (PM) modifies the RF signal. Combining an Intensity Modulator (IM) with an optical Bandpass Filter (BPF) generates a Local Oscillator (LO) tone. ODL: Optical Delay Line, PPER: multi-port Photonic-Phononic Emitter-Receiver, DeMod: phase Demodulation (bandpass filtering), RFSA: Radio Frequency Spectrum Analyzer(Gertler *et al.*, 2022)

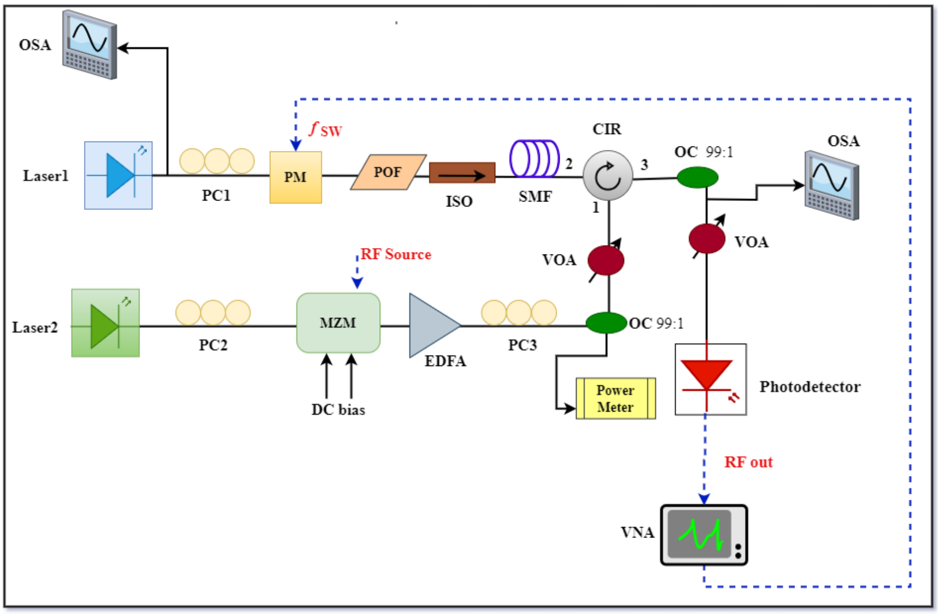

Fig. 35. Experimental configuration for the realization of a reconfigurable bandpass filter with a low-power bandwidth. POF: Programmable Optical Filter, USB: Upper Sideband, LSB: Lower Sideband(Raj *et al.*, 2022)

A method to enhance frequency tuning and passband selection in MPFs using a dual-polarization DPMZM (DPol-DPMZM) is introduced in Fig.36. By leveraging the Brillouin effect and employing a DC-9 GHz single-tone RF carrier, they expanded the tuning range of single-passband MPF to 1.43–19.43 GHz. For dual-passband MPFs, they adjusted the lower DPMZM's DC bias to resolve passband size and frequency range issues, achieving identical properties at 2 GHz intervals. This research demonstrates the effectiveness of small MPFs in frequency tuning and passband selection, promising advancements in radar systems, sensors, microwave signal processing, and telecommunications. The technology's experimental validation, compact structure, and wide range of potential applications signify significant progress in MPF technology (Xu *et al.*, 2022).

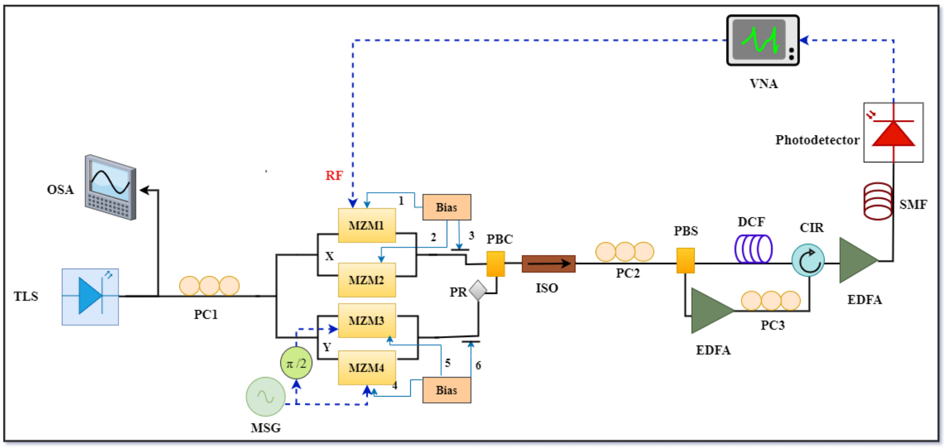

Fig. 36. Design of the suggested MPF schematic. MSG: Microwave Signal Generator, PR: Polarization Rotator, PBC: Polarization Beam Combiner, DCF: Dispersion Compensation Fiber (Xu *et al.*, 2022)

Fig.37 is discussed the reducing of the negative effects caused by dispersion in Brillouin-based bandpass MPFs. The researchers conducted a comparison of double-sideband PM (DSB-PM) and double-sideband IM (DSB-IM) setups. DSB-IM successfully resolved dispersion problems by keeping a consistent filter profile that achieved over 40 dB of out-of-band rejection. IM's ability to provide real-time dispersion compensation enables the development of integrated bandpass MPFs for applications in MWP, 5G systems, and RF signal processing. The research is notable for its originality, empirical verification, practical relevance, lucid exposition, and substantial advancements in the domains of MWP and RF signal processing (Varun and Pant, 2022).

The requirement for narrow-band, high-quality MPFs that are crucial for 5G, radar, and wireless communication are recognized in Fig.38. They employed SBS to fabricate a narrow-band filter characterized by a Q value of 2412. Their pioneering methodology, characterized by a meticulous mathematical framework, enhanced comprehension of SBS technology. The experimental results demonstrated a filter with a bandwidth of 7.8 MHz and a gain response of 24 dB. The research makes significant progress in the field of signal processing in MWP and has the potential to be applied in several areas, such as 5G technology, radar systems, wireless communication, and signal processing for photonics. Notable strengths encompass creativity, meticulous control, empirical confirmation, and extensive technical influence (Zhang *et al.*, 2022).

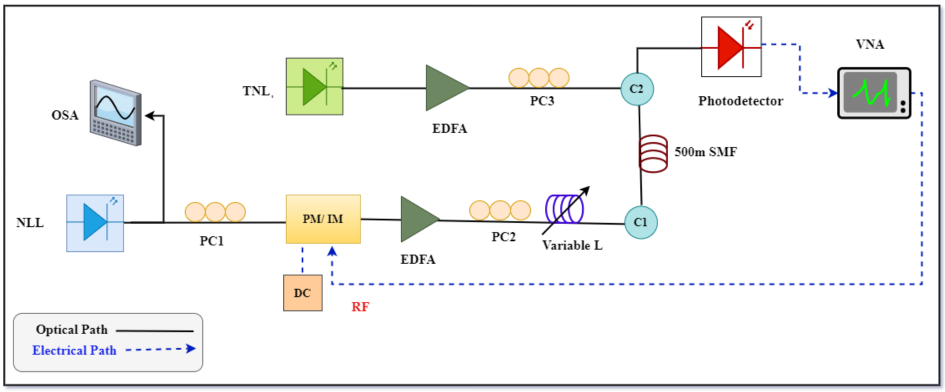

Fig. 37. Representation of the experimental configuration for bandpass MPFs based on DSB-PM and DSB-IM. TNL: Tunable Narrow-linewidth Laser, NLL: Narrow Linewidth Laser (Varun and Pant, 2022)

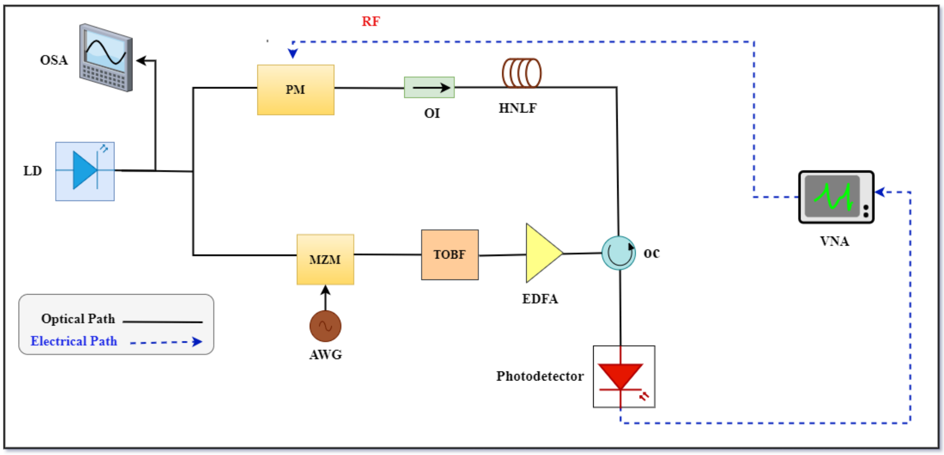

Fig. 38. Diagram illustrating the structure and components of the MPF. TOBF: Tunable Optical Bandpass Filter (Zhang *et al.*, 2022)

A chip-scale MPF measuring 5 mm × 5 mm is illustrated in Fig.39. This MPF had active electro-optic components and achieved a spectral resolution of 37 MHz. The combined Brillouin and active-silicon photonic circuit employed CHG waveguides within a CMOS silicon photonic device. The MPF exhibited excellent spectral resolution and achieved a high level of RF rejection, measuring 51 dB. This resulted in improved performance of the RF connection by utilizing the on-chip EOM. The finding represents a significant advancement in the development of small, high-quality RF photonic filters that are essential for applications such as RF communication systems used in aircraft and spacecraft. The strengths of this product are its originality, effective incorporation of technologies, outstanding filter performance, and the ability to support various RF functionalities. In summary, it signifies a significant advancement towards a high-capacity, fully integrated MWP processor (Garrett *et al.*, 2023).

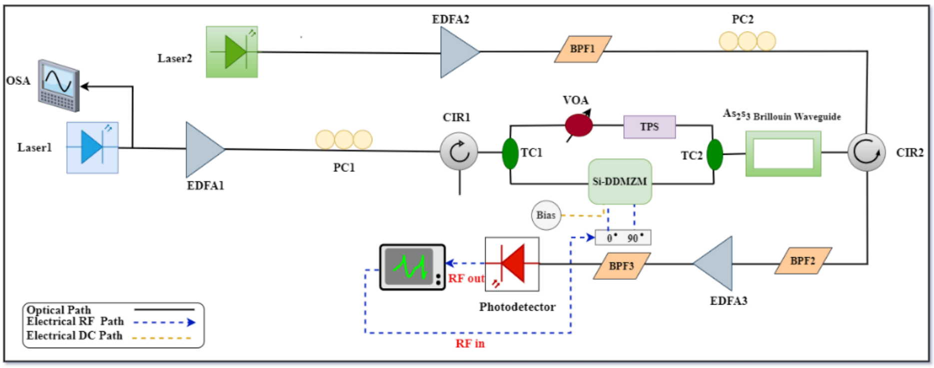

Fig. 39. Schematic diagram of the experimental setup.TC :Tunable Coupler, TPS: Tunable Phase Shifter (Garrett *et al.*, 2023)

The issue of low-power, programmable microwave band-stop filters with sub-MHz precision is addressed in Fig.40. The researchers came up with a creative idea that uses RF phase engineering to make Brillouin-based band-stop MPFs that are wideband, reconfigurable, and programmable. This energy-efficient technique allows for seamless transition between bandpass and band-stop filters by means of straightforward phase modifications. The study showcased the effective implementation of a low-power (11.8 dBm total pump power), adaptable, and adjustable band-stop MPF with a suppression of over 15 dB, a form factor of less than 1.35, and the flexibility to reconfigure its bandwidth up to 1 GHz. The study has considerable importance in radar, signal processing, wireless communications, and defense systems. It provides solutions to the issues of power efficiency in traditional filters based on SBS. The strengths encompass an innovative methodology, prioritization of energy efficiency, empirical verification, and the possibility of seamless incorporation into contemporary microwave systems (Girish *et al.*, 2023).

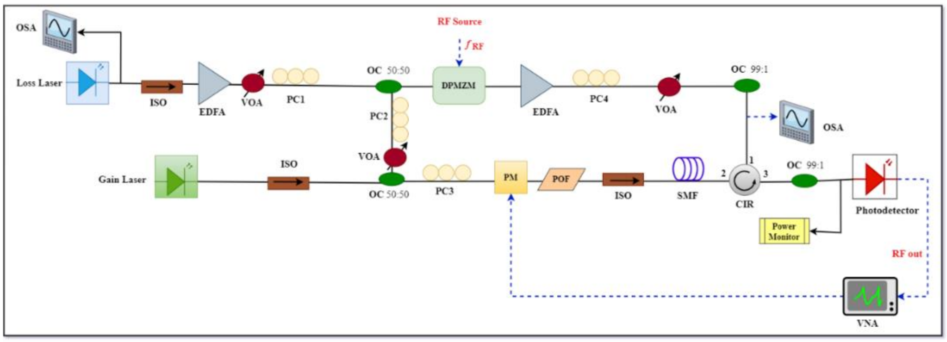

Fig. 40. The illustration of the experimental setup for the band-stop filter. POF: Programmable Optical Filter (Girish *et al.*, 2023)

An extremely small bandwidth and a wide tuning range in a single-passband MPF employing Brillouin fiber laser technology is achieved in Fig. 41. By integrating a Brillouin laser resonator, they developed a narrow-band MPF that can be adjusted to operate within a frequency range of 0–20 GHz. The filter also exhibits a high out-of-band rejection of 20 dB and a minimum 3 dB bandwidth of around 114 Hz. This work makes a substantial contribution to MWP technology by providing notable benefits in terms of high-frequency resolution, robust agility, and effective isolation filtering. The research has several notable strengths, including its innovative approach, real-world testing, and potential applications in generating high-purity spectra, conducting sensitive sensing, and enabling precise radar in MWP technology (Xu *et al.*, 2023).

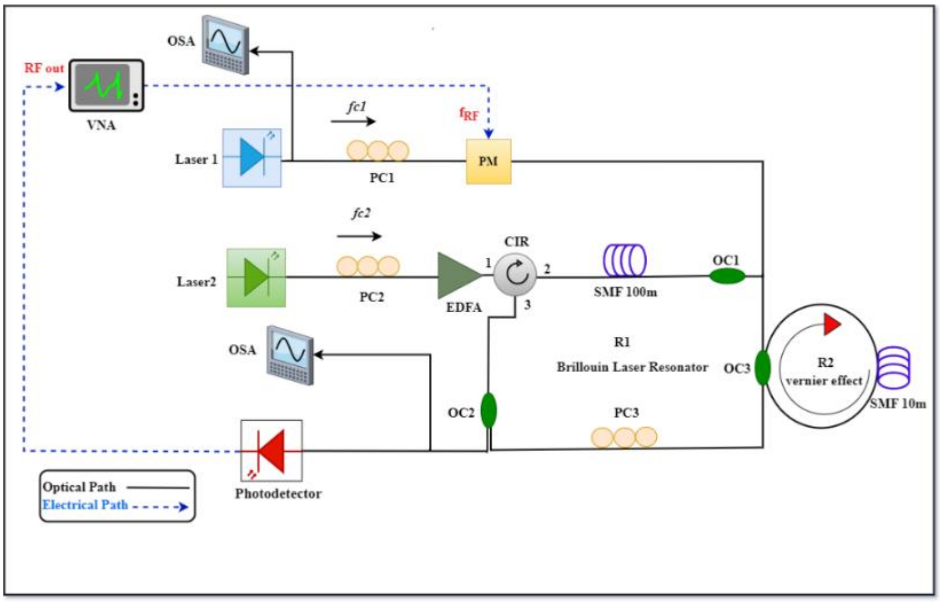

Fig. 41. Configuration for the MPF experiment (Xu *et al.*, 2023)

The proposed MPF of Fig.42 is verified the operation a tunable narrow-band filter that utilizing a Brillouin fiber laser that incorporates a parity-time symmetry (PT symmetry). The technique successfully attained an extremely narrow range of frequencies without the need for intricate optical filters. This was accomplished by integrating tiny linewidth Brillouin fiber laser resonators with PT-symmetric system mode selection. An impressive sub-kilohertz bandwidth, easy adjustment, a very narrow passband of 72 Hz, an impressive rejection ratio of over 18 dB for side modes, and a tuning range from 0 to 20 GHz were all shown. The research focuses on meeting the need for extremely narrow bandwidth and adjustable MPFs in applications such as high-precision radar imaging and MWP sensing. Notable strengths encompass a pioneering approach, empirical validation, and prospective influence on advanced wireless RF systems, making substantial contributions to MWP and signal processing technology (Hou *et al.*, 2023). The proposed tunable MPF in Fig.43 leverages the SBS effect in a Brillouin fiber laser to achieve a high-performance filter with a simplified tuning mechanism. By incorporating a cascaded ring Fabry–Pérot configuration, the filter can be continuously tuned across a wide frequency range of 0 to 20 GHz. The design uses a 100-meter-long main cavity and a 30-meter-long secondary cavity to reduce the Brillouin gain bandwidth and ensure stable single-frequency operation with effective side-mode suppression. This filter demonstrates a high rejection ratio of approximately 17.6 dB outside the band, making it highly effective for high-frequency applications such as radar imaging and MWP sensing. The system's performance was validated through simulations using OptiSystem software, supported by a mathematical model derived from fundamental equations. The results confirm the filter's capability to provide stable operation under varying conditions. The proposed MPF represents a significant advancement in MWP technology, offering a practical solution for RoF applications and modern high-frequency communication systems (AL-Zaidi and Sabbar, 2024).

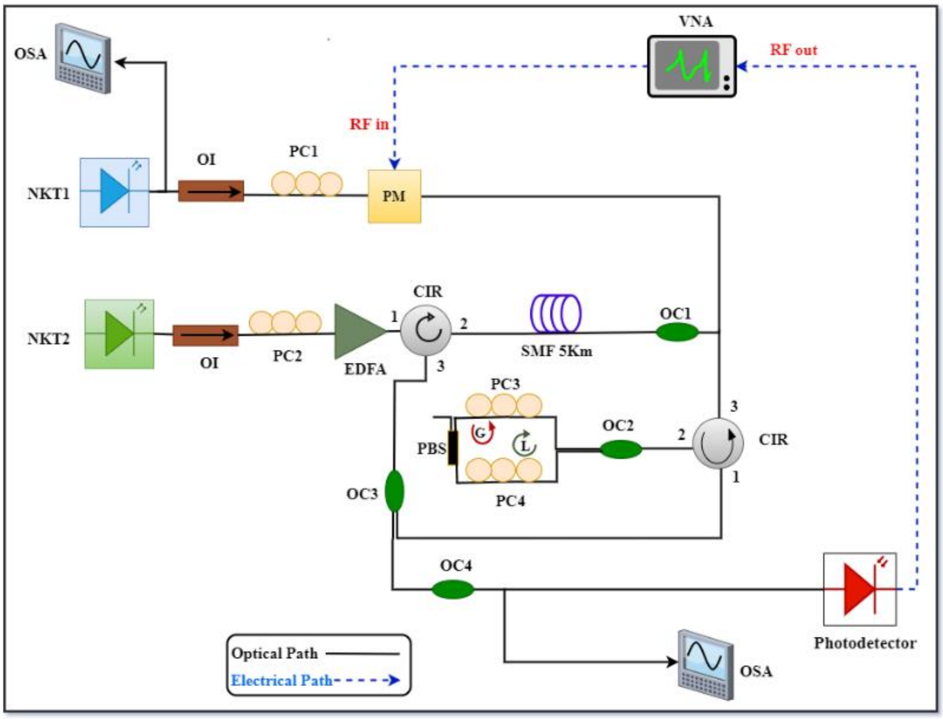

Fig. 42. Apparatus for MPF experiments. A ring resonator with a cascaded PT-symmetric system is represented by the light blue area indicated. NKT: the narrow linewidth laser (Hou *et al.*, 2023)

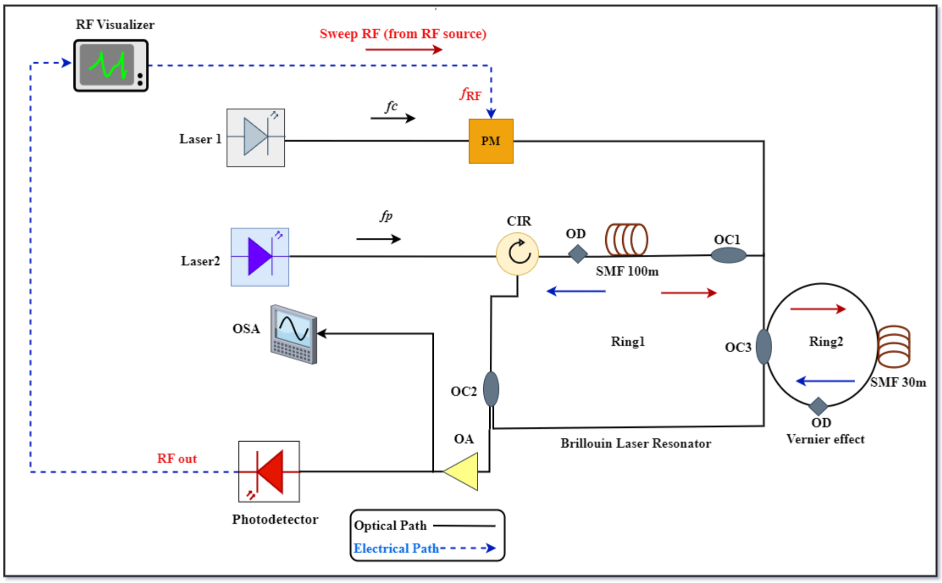

Fig. 43. Illustrates the proposed setup of the MPF. OD: Optical Delay, SMF: Bidirectional Single Mode Fiber, OA: Optical Amplifier (AL-Zaidi and Sabbar, 2024)

Table 1 presents a summary of the most recent research on MPFs. This overview encompasses works published within the past three years, offering insights into the methods used for filter fabrication and highlighting key findings. During this period, efforts have continued to enhance the work in microwave photonic filter research by expanding the scope of filter synthesis and adapting the bandwidth to suit specific applications. This has allowed for more tailored and efficient filter designs, further advancing the practical utility of MPFs across various domains.

Table 1. Summary of literature review

Ref. No. Year	Problem	Method	Pros and Cons	Result
(Gong et al., 2021) 2021	Improving the tuning range of the MPF while reducing passband fluctuation.	Vector modulation technology and frequency shifter based on CS-SSB modulation.	Pros: -Precision control. -Wide tuning range. -Adaptability. Cons: Complex setup.	- 3 dB Bandwidth: 20 MHz to 500 MHz. - Passband Fluctuation: As low as 0.49 dB. - Wide-Band Tuning Range: From 1 GHz to 20 GHz. - High Out-of-Band Rejection: Exceeds 40 dB. - SNR: Measured at 33.7 dB. - EVM: Measured at 2.1%.
(Ali, Haxha and Flint, 2022) 2022	High-speed wireless communication systems are having trouble with more noise and less effective filters.	SBS in an innovative configuration to achieve enhanced gain and bandwidth control in a tunable MPF.	Pros: -High gain. -Bandwidth control. -Wide tuneability. -Thermal stability. Cons: -Complex experimental setup. -Environmental sensitivity. - Bias control challenges.	- Maximum Gain: 70 dBm, suitable for high-gain applications. - Changeable Bandwidth: Offers fine control over bandwidth, meeting requirements for applications needing precise bandwidth adjustment. - Improvements in Modulation Methods: Substantial enhancements observed across several modulation methods. - Remarkable Adjustability: Demonstrates adjustability at 32 GHz in the RF domain and 40 GHz in the optical domain, showcasing its versatility. - Bandwidth Modification: Employed RF mixing with a tunable laser to adjust the filter bandwidth, achieving a range from 20 MHz to 40 MHz.

Ref. No. Year	Problem	Method	Pros and Cons	Result
(Gertler et al., 2022) 2022	Analyze limitations of current MPFs in terms of spectral resolution, rejection capabilities, and frequency tunability.	Brillouin interactions within a multi-port photonic-phononic emitter-receiver (PPER) device.	Pros: -High spectral resolution. -Wide frequency tunability. -CMOS-compatible fabrication. Cons: -Complex Fabrication Process. -Environmental Sensitivity. - High power requirements.	- Ultra-narrowband (2.7 MHz) notch filters. - High rejection (57 dB). - Frequency tunability across a broad spectral band (6 GHz).
(Raj et al., 2022) 2022	The current Brillouin-based bandpass MPFs suffer from restricted bandwidth and excessive power consumption.	RF interferometry and advanced phase engineering.	Pros: -Energy efficiency. -High selectivity and flat passband. -Wide frequency tunability. -Low power requirement. Cons: -Phase and amplitude control. -Complex experimental setup. - Integration challenges.	- Bandwidth: Realized 700 MHz. - Selectivity: Greater than 20 dB. - Peak SBS Gain: Just 8 dB. - Frequency Adjustability: Demonstrated adjustability up to 22 GHz. - Free of additional Brillouin noise in the passband. - Phase Response: Showed a flat and very linear phase response. - Group Delay: Leading to zero group delay.
(Xu et al., 2022) 2022	The constraints of traditional MPFs include a narrow frequency tuning range and a limited selection of passbands.	Dual-polarization dual-parallel Mach-Zehnder modulator (DPol-DPMZM).	Pros: -Extended frequency tuning range. -Enhanced energy efficiency. -Versatility in operating modes. -Compact structure. Cons: -Dispersion effects. -Environmental sensitivity. - Precise control requirements.	- Tuning Range: Achieved a tuning range of 1.43–19.43 GHz using a single-tone RF carrier range (DC–9 GHz). - Passband Magnitude Issue: Fixed varying passband magnitudes by adjusting the DC bias of the lower DPMZM, creating a dual-passband MPF. - Dual-Passband Creation: Obtained a dual-passband MPF with identical magnitudes and a 2 GHz frequency interval by manipulating the RF carrier frequency of a single-tone signal.

Ref. No. Year	Problem	Method	Pros and Cons	Result
(Varun and Pant, 2022) **2022**	The dispersion impairs Brillouin-based Bandpass MPFs.	Double-sideband intensity modulation and controlling the phase dependent on bias using a z-cut intensity modulator.	Pros: - Effective dispersion mitigation. - Improved out-of-band rejection. - Consistent filter performance. - Dynamic and compatible with integrated systems. Cons: - Complex experimental setup. - Environmental sensitivity. - Need for precise bias control. - Dispersion effects on phase response.	- Bias Voltage Manipulation: Adjusting the bias voltage on a z-cut intensity modulator enhances performance. - DSB-IM Based MPF: Shows excellent out-of-band rejection (> 40 dB) and consistent performance across various dispersion conditions. - DSB-PM Based MPF: Experiences reduced frequency rejection or dispersion with increasing values. - Intensity Modulators: Could be utilized for dispersion adjustment in integrated MWP systems.
(Zhang et al., 2022) **2022**	Overcoming the issue of obtaining MPF with a limited bandwidth and high-quality factor.	Using SBS, a high-quality narrow bandpass filter can be generated.	Pros: - Narrow bandwidth and high Q-factor. - High gain response. - Phase and gain control. - Mathematical formulation and experimental validation. Cons: - Complexity of implementation. - Sensitivity to environmental conditions. - Power requirements. - Scalability issues.	- Short bandwidth of 7.8 MHz. - Gain response of 24 dB. - High-quality factor of 2412. - Variation trend of the filter bandwidth and gain response provides insights into the general discipline of this technology.
(Garrett et al., 2023) **2023**	Making a fully integrated photonic circuit that has all the necessary electro-optic parts and the megahertz-level spectral resolution for RF	Integrating waveguides, onto a silicon photonic chip made in a CMOS foundry, incorporated integrated modulators and photodetectors.	Pros: - High spectral resolution. - Significant out-of-band rejection. - Compact and integrable design. - Innovative use of heterogeneous integration. Cons: - Propagation losses. - Insertion losses. - Need for improved RF link gain. - Design optimization	- Spectrum resolution of 37 MHz. - The MWP filter demonstrated a remarkable out-of-band rejection of 51 dB. - a compact 3-dB bandwidth of 37 MHz. - The ability to adjust the central frequencies of the notches throughout a range of 15 GHz.

Ref. No. Year	Problem	Method	Pros and Cons	Result
	applications.		required.	
(Girish et al., 2023) 2023	Adjust the microwave band-stop filters low-power reconfigurability, and tunability with sub-MHz precision and the ability to block interference signals across a wide frequency range.	SBS-based MPF can be achieved with great resolution using modern RF phase engineering to tune the upper sideband and RF interference to make a microwave band-stop filter.	Pros: -Low power consumption. -Wide bandwidth reconfigurability. -High suppression. -Flexibility in filter topologies. Cons: -Phase manipulation requirements. -Limited by SBS gain and loss responses. - Environmental sensitivity. - Complex experimental setup.	- Form factor of less than 1.35, can be configured to operate up to 1 GHz. - Exceptional shape factor of 1.2. - Suppression is more than 15 dB. - By adjusting the phase, the filter can be transformed from band-pass to band-stop.
(Xu et al., 2023) 2023	With a wide tuning range, resolve the issue of achieving ultra-narrow filter bandwidth and high frequency selectivity in MPF.	Utilize a Brillouin laser resonator to attain an extremely narrow filter bandwidth and exceptional frequency selectivity in the MPF.	Pros: -Ultra-narrow bandwidth. -Large tuning range. -High out-of-band rejection. -Vernier effect utilization. -Stability and flexibility. Cons: -Complex setup. -Sensitivity to environmental factors. - Limited pump power efficiency. - Dependency on Optical Components.	- Steady tuning of the MPF within the frequency range of 0–20 GHz while maintaining an out-of-band rejection ratio of around 20 dB. - Minimum 3-dB bandwidth of around 114 Hz.
(Hou et al., 2023) 2023	The main problem that had to be solved was the need for MPFs with very narrow bandwidths and wide	Constructed an ultra-narrow bandwidth MPF using a single Brillouin fiber laser with longitudinal mode parity time symmetry.	Pros: -Ultra-narrow bandwidth. -Large tuning range. -High side mode rejection ratio. -Simple and agile tuning performance. -Integration potential. -Innovation in filter design.	- Ultra-narrow bandwidth MPF is created. - The experimental findings demonstrate that the MPF achieves a narrow single-pass band of 72 Hz and a side-mode rejection ratio of 18 dB. - Center frequency tuning range spanning from 0 to 20 GHz.

Ref. No. Year	Problem	Method	Pros and Cons	Result
	tuning ranges.		Cons: -High pump power requirements. -Sensitivity to environmental factors. - Complex experimental Setup. - Tuning resolution.	
(AL-Zaidi and Sabbar, 2024) 2024	Developing a tunable MPF for high-frequency and high-bandwidth applications with simplified tuning and stability.	SBS based MPF with a cascaded ring Fabry–Pérot configuration using a Brillouin laser resonator.	Pros: - High tunability (0-20 GHz). - Stable performance. - High out-of-band rejection. - Simple tuning mechanism. Cons: - Potential challenges in practical deployment due to environmental factors.	- Tunable across 0-20 GHz. - Out-of-band rejection ratio 17.6 dB. - System shows stable operation in simulations. - Potential use in advanced RoF systems and high-frequency communication.
(Parihar et al., 2024) 2024	Achieving a 100 dB MPF with high passband-to-stopband extinction and improving stability in communication systems	Utilizing single laser system with SBS to create an Electromagnetically Induced Transparency like response.	Pros: - High rejection ratio (100 dB). - Tunability and efficiency with low power (13 dBm). - Stability achieved with single-laser system. Cons: - Complex setup requiring precise phase control.	- Achieved 100 dB rejection between passband and stopband. - Demonstrated a stable system with tunability across 10.8 GHz to 22.8 GHz. - Maximum delay achieved: 50 ns with RF signal suppression at 14.875 GHz.
(Zhang et al., 2024) 2024	Achieving a tunable MPF with ultra-narrow passband and high out-of-band rejection.	Utilizing vector composite SBS to superimpose two Brillouin loss spectra on a central Brillouin gain, narrowing the MPF's bandwidth and improving out-of-band rejection.	Pros: - Ultra-narrow passband. - High out-of-band rejection. - Tunable frequency range. Cons: - Reduced SBS gain due to superimposed losses. - Complex setup requiring precise control of polarization and power.	- 3-dB bandwidth: 5.5 MHz. - 20-dB bandwidth: 14.4 MHz. - Out-of-band rejection: 55 dB. - Frequency tuning: 11 GHz to 20 GHz. - Interference suppression: 56 dB. - Signal loss: 0.3 dB.

Ref. No. Year	Problem	Method	Pros and Cons	Result
(You et al., 2024) 2024	Developing a flexible, tunable MPF with a dual ultra-narrow passband and high selectivity.	Using a dual-wavelength Brillouin laser resonator with a dual-ring cavity structure to generate dual ultra-narrow passbands.	Pros: - Ultra-narrow passband. - High out-of-band suppression. - Wide tunability of center frequency and passband intervals. Cons: - Complex experimental setup with precise control requirements.	- 3-dB bandwidth: 83 Hz. - Out-of-band suppression: 28.3 dB, 29 dB. - Tuning range: 300 kHz to 20 GHz. - Passband interval: 2-18 GHz.

Figures below illustrate some results of research published in 2024 on tunable MPFs with narrow passbands and high out-of-band rejection are analyzed. Figures showcasing key results, such as bandwidth, rejection ratio, and tunability, have been included to highlight recent advancements.

The tunable MPF was able to achieve precise center frequency tuning within a range of 0 to 20 GHz by adjusting the pump light wavelength, as shown in Fig.44. The results demonstrated stable tuning performance, with an out-of-band rejection ratio of approximately 17.6 dB, confirming the filter's effectiveness in handling high-frequency signals in modern communication applications (AL-Zaidi and Sabbar, 2024).

The filter achieved high rejection of up to 100 dB using an asymmetrical Electromagnetically Induced Transparency (EIT) technique, as shown in Fig.45. The results demonstrated precise tuning of the filter at a center frequency of 14.875 GHz, with stable performance in eliminating nearby interfering signals, making it highly effective for high-frequency communication applications (Parihar *et al.*, 2024).

The results presented in Fig.46 (A) demonstrate the ability of the proposed MPF to achieve ultra-narrow passbands by adjusting parameters such as frequency separation (d) and the loss-to-gain ratio (m). The MPF attained a 3-dB bandwidth of 5.5 MHz and a 20-dB bandwidth of 14.4 MHz, highlighting its high selectivity. Fig.46 (B) shows the MPF's tunability across a frequency range of 11 GHz to 20 GHz, with a stable out-of-band rejection of 55 dB, confirming its adaptability for wide-range applications. Fig.46 (C) further emphasizes the MPF's effectiveness, demonstrating interference suppression of 56 dB with minimal signal loss of 0.37 dB, making it highly suitable for handling interference in high-frequency communication systems while maintaining signal integrity (Zhang *et al.*, 2024).

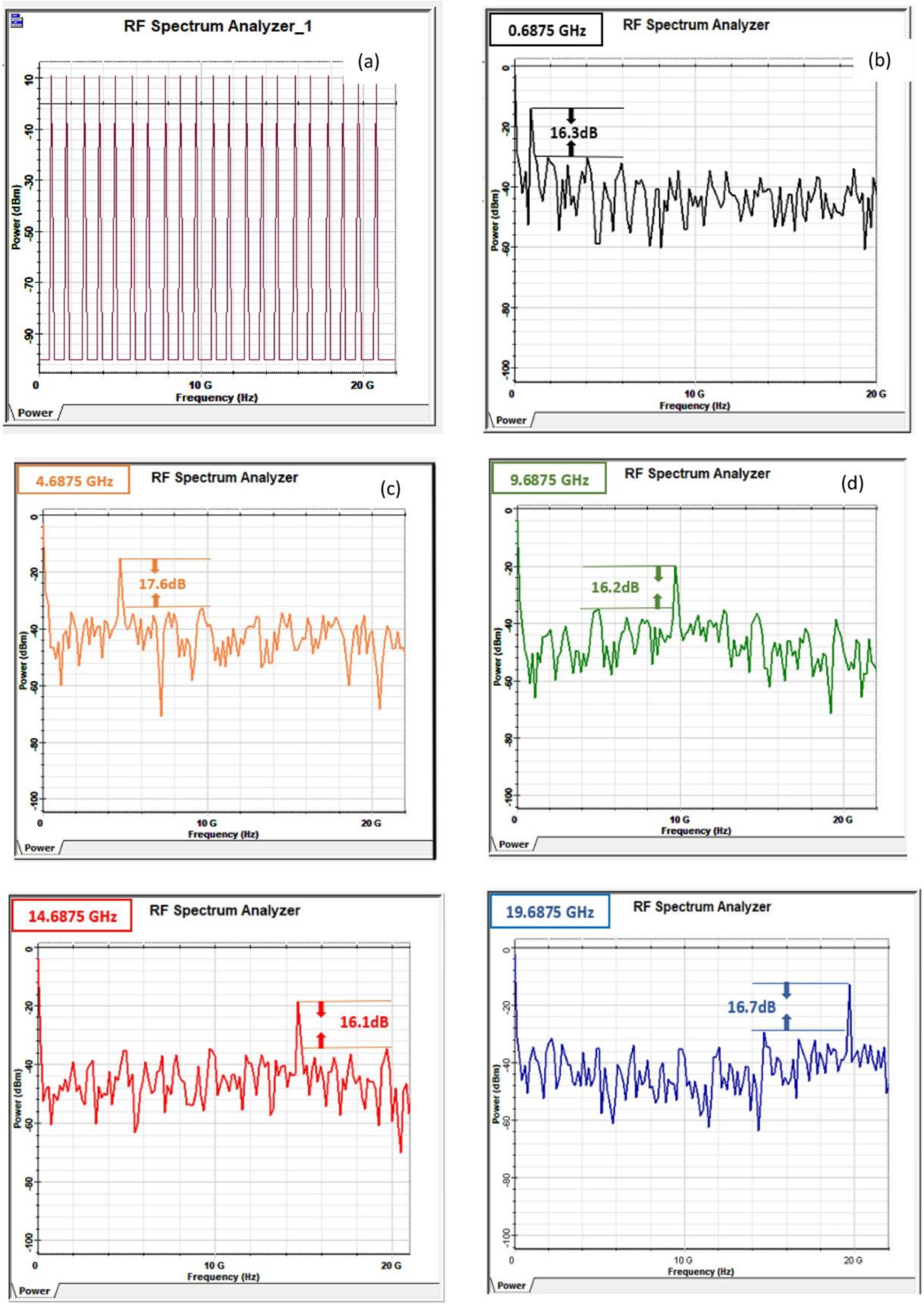

Fig. 44. (a) shows the input RF signal, while (b–g) display the center frequency response of the tunable MPF as the pump light wavelength is varied (AL-Zaidi and Sabbar, 2024)

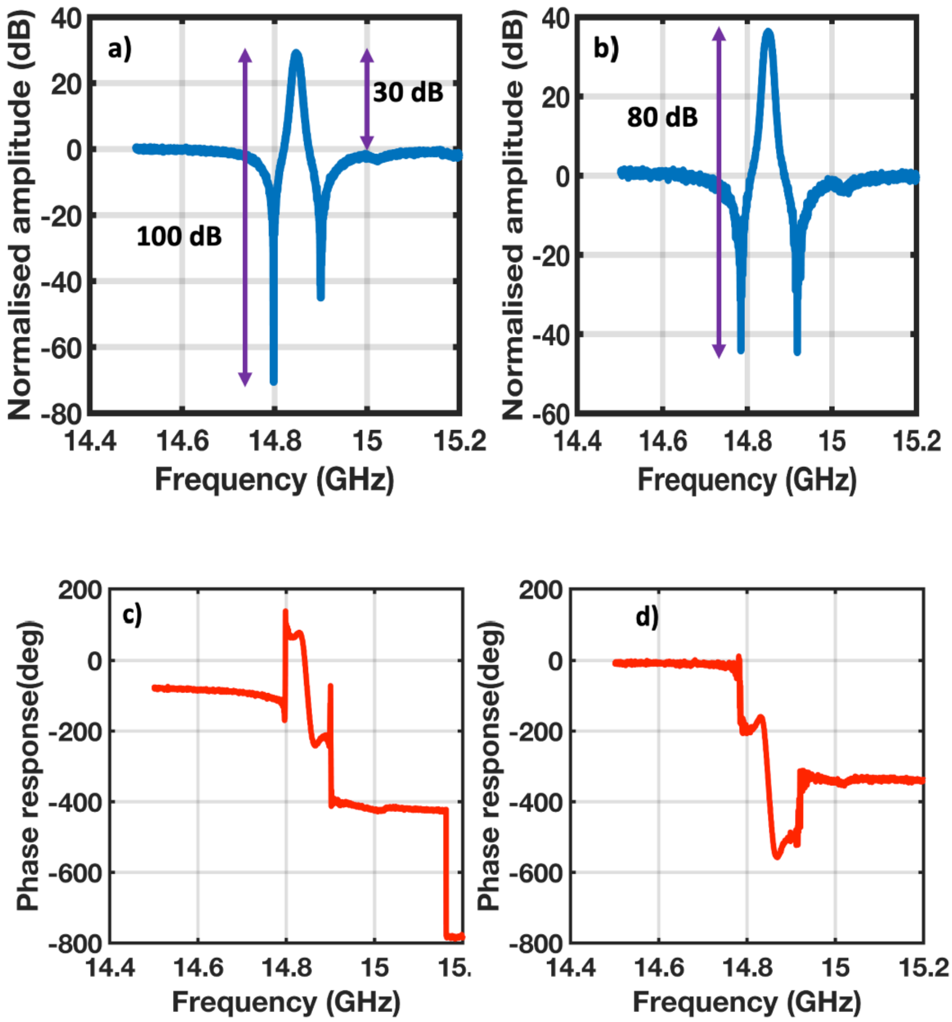

Fig. 45. (a) Asymmetrical EIT response showing 100 dB rejection, (b) Symmetrical EIT response at 14.875 GHz with 80 dB rejection, achieved using 10 dB lower sideband suppression, (c) Phase response corresponding to the asymmetrical EIT, and (d) Phase response corresponding to the symmetrical EIT (Parihar *et al.*, 2024)

Fig.47 (A) compares the dual passband responses between single-ring and double-ring Brillouin laser resonators. The double-ring resonator achieves better sideband suppression, with out-of-band rejection ratios of 28.3 dB and 29 dB, compared to 7.7 dB and 7.8 dB for the single-ring setup, highlighting the enhanced performance of the dual-ring structure due to the Vernier effect. Fig. 47 (B) shows the center frequency tuning of the MPF by varying the wavelength of the SBS pump light, demonstrating wide tunability from 300 kHz to 20 GHz. The ability to precisely control the passband center frequency over a large range underscores the MPF's flexibility. Fig.47 (C) illustrates the tuning performance of the dual passband interval, which can be adjusted from 2 GHz to 18 GHz by modifying the microwave source frequency, making the MPF adaptable for applications requiring multi-band filtering (You *et al.*, 2024).

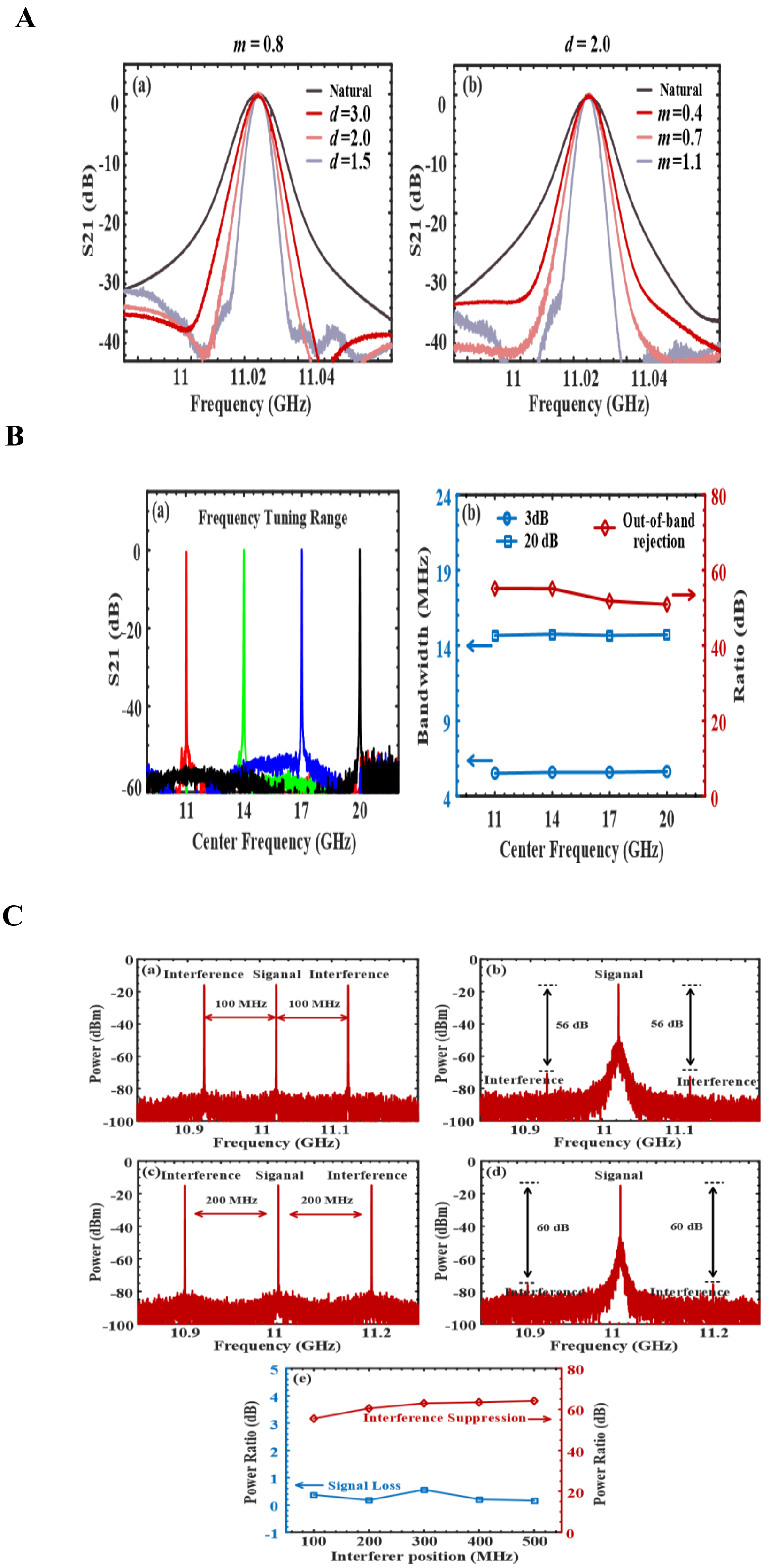

Fig. 46. (A) The experiment confirms the effectiveness of the proposed MPF in achieving a narrow passband and explores how the parameters d and m influence its shape, (B) the experimental results demonstrate the tunability of the center frequency and (C) a comparison between the RF signal before and after passing through the MPF (Zhang *et al.*, 2024)

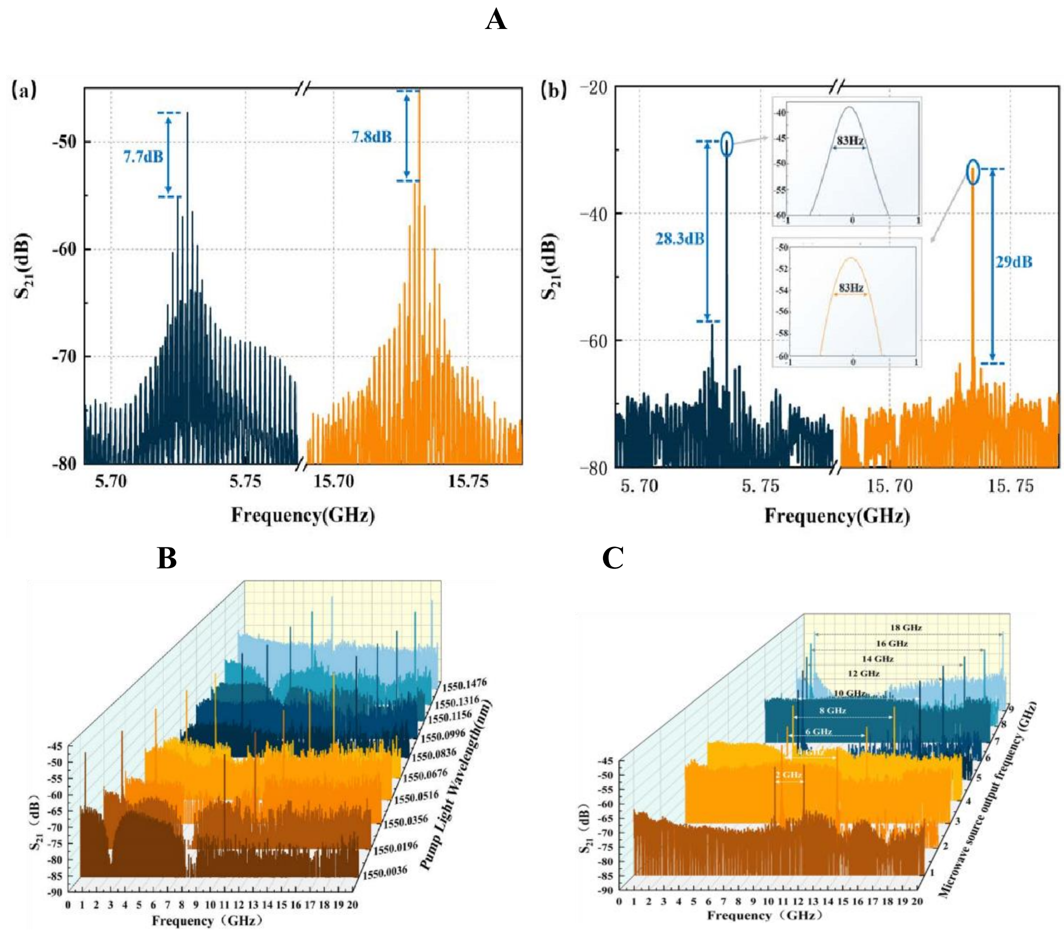

Fig. 47. (A) a comparison of the dual passband responses between the single-ring (R1) and double-ring (R1+R2) Brillouin laser resonators, (B) the center frequency response of the MPF as the pump light wavelength shifts from 1550.0036 nm to 1550.1636 nm and (C) The adjustable tuning performance of the dual passband interval by varying the frequency of a microwave source output signal from 1 GHz to 9 GHz (You *et al.*, 2024)

Future research in the field of MPFs could explore innovative techniques to enhance control over frequency ranges and expand bandwidth, utilizing SBS. This exploration could also involve integrating artificial intelligence applications and machine learning algorithms to optimize filter performance and integration into wireless communication systems. Concurrently, there is a need to develop methodologies to improve energy efficiency and mitigate noise levels in these filters to meet the evolving demands of satellite communication applications. Moreover, investigating the applicability of SBS-based MPFs in high-speed airborne communication technologies offers an exciting avenue for further research.

Additionally, future directions could focus on advanced signal processing techniques to enhance the performance and versatility of these filters, possibly through the integration of emerging technologies like quantum computing or photonics integrated circuits. Exploring potential applications in fields such as quantum communication or terahertz communication systems could also be fruitful. Efforts to develop compact and cost-effective implementations for practical deployment in next-generation networks and sensor systems are essential for advancing these filters' capabilities.

Furthermore, optimizing the energy efficiency of MPFs based on SBS remains a crucial area for future research. This could involve exploring novel materials and structures to enhance performance while reducing power consumption. Additionally, integrating these filters into emerging technologies such as Internet of Things devices and 5G/6G communication systems could broaden their practical applications. Addressing scalability and manufacturability concerns could further accelerate their adoption across various industries. Collectively, these research endeavors aim to advance the capabilities and applications of SBS-based MPFs in diverse technological domains.

3. CONCLUSION

The analysis concludes by pointing out the several microwave systems that could benefit from MPFs that use SBS. The review papers showcase the innovative methods, experimental proofs, and customized passband properties of SBS-based MPFs. Researchers have created new types of MPFs to address important problems and limitations in older ones. These include frequency-tuning-range-extended MPFs, high-selectivity rectangular filters, switchable MPFs, and MPFs that can change their bandwidth. Also, photonic technology in MWP makes it possible to process wideband, high-frequency microwave signals that have passband characteristics that can be changed and a high level of stability and selectivity. These MPFs have a wide range of possible uses in many different industries, including but not limited to: optical wireless communication, optical signal processing, satellite communications, optical sensors, and instrumentation. The review paper highlights the importance of MWP technology and the role that MPFs with SBS play in its advancement, as well as its potential impact on civil and industrial applications. Thorough analysis of research publications, experimental validations, and theoretical underpinnings offered in the review support the continuous development and application of MPFs in microwave systems. Highlighting the developments, possible uses, and importance of this technology in MWP, this conclusion summarizes the main points and contributions of the review article on MPFs with SBS.

4. REFERENCES

AL-Zaidi, Z. and Sabbar, A. (2024) ‘Tunable microwave photonic filters based on stimulated Brillouin scattering for radio over fiber applications’, Journal of Optics [Preprint]. Available at: https://doi.org/10.1007/s12596-024-02245-7.

Ali, M., Haxha, S. and Flint, I. (2022) 'Tuneable Microwave Photonics Filter Based on Stimulated Brillouin Scattering with Enhanced Gain and Bandwidth Control', Journal of Lightwave Technology, 40(2), pp. 423–431. Available at: https://doi.org/10.1109/JLT.2021.3118315.

Alrubei, M.A.T. and Dmitrievich, P.A. (2023) 'AN APPROACH FOR SINGLE-TONE FREQUENCY ESTIMATION USING DFT INTERPOLATION WITH PARZEN WINDOWING', Kufa Journal of Engineering, 14(3), pp. 93–104.

Aryanfar, I. et al. (2016) 'Reconfigurable microwave bandstop filter based on stimulated Brillouin scattering in a photonic chip', Optics InfoBase Conference Papers, 1(I), pp. 1–2.

Bao, X. and Chen, L. (2012) 'Recent progress in distributed fiber optic sensors', sensors, 12(7), pp. 8601–8639.

Borges, R.M., Muniz, A.L.M. and Sodre Junior, A.C. (2017) 'Development and performance analysis of a photonics-assisted RF converter for 5G applications', Fiber and Integrated Optics, 36(1–2), pp. 25–37.

Boyd, R.W. (2007) 'Nonlinear optics third ed'. Academic Press.

Brignon, A. and Huignard, J.-P. (2004) 'Phase conjugate laser optics'.

Brilliant, N.A. (2002) 'Stimulated Brillouin scattering in a dual-clad fiber amplifier', JOSA B, 19(11), pp. 2551–2557.

Capmany, J., Ortega, B., et al. (2005) 'Discrete-time optical processing of microwave signals', Journal of Lightwave Technology, 23(2), pp. 702–723.

Capmany, J., Member, S., et al. (2005) 'Discrete-Time Optical Processing of Microwave Signals', Journal of Lightwave Technology, pp. 702–723.

Capmany, J. and Novak, D. (2007) 'Microwave photonics combines two worlds', Nature Photonics, 1(6), pp. 319–330. Available at: https://doi.org/10.1038/nphoton.2007.89.

Casas-Bedoya, A. et al. (2015) 'Tunable narrowband microwave photonic filter created by stimulated Brillouin scattering from a silicon nanowire', Optics Letters, 40(17), p. 4154. Available at: https://doi.org/10.1364/ol.40.004154.

Choudhary, A. et al. (2016) 'Reconfigurable and frequency-agile on-chip microwave photonic bandpass and bandstop filters using stimulated Brillouin scattering', Photonic Fiber and Crystal

Devices: Advances in Materials and Innovations in Device Applications X, 9958, p. 99580E. Available at: https://doi.org/10.1117/12.2235672.

Feng, C., Preussler, S. and Schneider, T. (2017) ‘Transparent Microwave Photonic Filter Based on Brillouin Losses in Optical Fiber’, JOURNAL OF LIGHTWAVE TECHNOLOGY, X(X), pp. 1–4. Available at: http://arxiv.org/abs/1709.07055.

Feng, C., Preussler, S. and Schneider, T. (2018) ‘The influence of dispersion on stimulated-brillouin-scattering-based microwave photonic notch filters’, Journal of Lightwave Technology, 36(22), pp. 5145–5151. Available at: https://doi.org/10.1109/JLT.2018.2871037.

Fisher, R.A. (2012) Optical phase conjugation. Academic press.

Garrett, M. et al. (2023) ‘Integrated microwave photonic notch fi lter using a heterogeneously integrated Brillouin and active-silicon photonic circuit’, Nature Communications, pp. 1–9. Available at: https://doi.org/10.1038/s41467-023-43404-x.

Gertler, S. et al. (2022) ‘Narrowband microwave-photonic notch filters using Brillouin-based signal transduction in silicon’, Nature Communications, 13(1). Available at: https://doi.org/10.1038/s41467-022-29590-0.

Girish, K. et al. (2023) ‘Low-Power, Reconfigurable Brillouin RF Photonic Bandstop Filters’, IEEE Photonics Technology Letters, 35(6), pp. 305–308. Available at: https://doi.org/10.1109/LPT.2023.3241322.

Gong, J. et al. (2021) ‘Bandwidth-reconfigurable microwave photonic filter based on stimulated Brillouin scattering effect spreading by vector modulation technology’, Microwave and Optical Technology Letters, 63(12), pp. 2985–2990. Available at: https://doi.org/10.1002/mop.33015.

Gong, J. wen et al. (2019) ‘Bandwidth-reconfigurable single-passband microwave photonic filter based on stimulated Brillouin scattering’, Optoelectronics Letters, 15(1), pp. 11–15. Available at: https://doi.org/10.1007/s11801-019-8115-4.

Gu, J. et al. (2019) ‘Polarization dependence of stimulated Brillouin scattering-based switchable microwave photonic filter’, Optica Applicata, 49(1), pp. 5–11. Available at: https://doi.org/10.5277/oa190101.

Guo, Y. et al. (2016) ‘Distortion analysis of a stimulated Brillouin scattering-based microwave photonic bandpass filter’, 2015 International Conference on Optoelectronics and Microelectronics, ICOM 2015, pp. 142–147. Available at: https://doi.org/10.1109/ICoOM.2015.7398791.

H. Tang et al. (2019) ‘Flat-top microwave photonic bandpass filter with tunable bandwidth based on SBS and FWM’, IEEE, 2, pp. 5–7.

Hameed, A. (2019) ‘Rayleigh fading-shadowing of outdoor channels analysis based on SNR-PDF model’, Kufa Journal of Engineering, 10(2), pp. 114–125.

Hon, D.T. (1982) ‘Applications of wavefront reversal by stimulated Brillouin scattering’, Optical Engineering, 21(2), pp. 252–256.

Hou, J. et al. (2023) ‘Ultra-Narrow Bandwidth Microwave Photonic Filter Implemented by Single Longitudinal Mode Parity Time Symmetry Brillouin Fiber Laser’, Micromachines, 14(7). Available at: https://doi.org/10.3390/mi14071322.

Hu, S. et al. (2017) ‘Tunable dual-passband microwave photonic filter based on stimulated Brillouin scattering’, IEEE Photonics Technology Letters, 29(3), pp. 330–333. Available at: https://doi.org/10.1109/LPT.2017.2647968.

Jiang, F. et al. (2013) ‘An optically tunable wideband optoelectronic oscillator based on a bandpass microwave photonic filter’, Optics express, 21(14), pp. 16381–16389.

Jiang, H. et al. (2016) ‘Wide-range, high-precision multiple microwave frequency measurement using a chip-based photonic Brillouin filter’, Optica, 3(1), p. 30. Available at: https://doi.org/10.1364/optica.3.000030.

Kovalev, V.I. and Harrison, R.G. (2006) ‘Suppression of stimulated Brillouin scattering in high-power single-frequency fiber amplifiers’, Optics letters, 31(2), pp. 161–163.

Lee, H. and Agrawal, G.P. (2003) ‘Suppression of stimulated Brillouin scattering in optical fibers using fiber Bragg gratings’, Optics Express, 11(25), pp. 3467–3472.

Li, J. qi et al. (2016) ‘Dual-band bandpass tunable microwave photonic filter based on stimulated Brillouin scattering’, Optoelectronics Letters, 12(4), pp. 276–279. Available at: https://doi.org/10.1007/s11801-016-6109-z.

Li, M. and Zhu, N. (2016) ‘Recent advances in microwave photonics’, Frontiers of Optoelectronics, pp. 160–185. Available at: https://doi.org/10.1007/s12200-016-0633-0.

Liao, S. et al. (2014) ‘Integrated programmable photonic filter on the silicon-on-insulator platform’, Optics Express, 22(26), pp. 31993–31998.

Lilin Yi, Wei Wei, Y.J. and W.H. (2015) ‘Ideal Rectangular Microwave Photonic Filter With High Selectivity Based on Stimulated Brillouin Scattering’, OSA, pp. 6–8.

Liu, L. et al. (2015) ‘Photonic measurement of microwave frequency using a silicon microdisk resonator’, Optics Communications, 335, pp. 266–270.

Mahendra, A. et al. (2018) ‘High link performance of Brillouin-loss based microwave bandpass photonic filters’, OSA Continuum, 1(4), p. 1287. Available at: https://doi.org/10.1364/osac.1.001287.

Marpaung, D. et al. (2015) ‘Low-power, chip-based stimulated Brillouin scattering microwave photonic filter with ultrahigh selectivity’, Optica, 2(2), p. 76. Available at: https://doi.org/10.1364/optica.2.000076.

Marpaung, D., Yao, J. and Capmany, J. (2019) ‘Integrated microwave photonics’, Nature photonics, 13(2), pp. 80–90.

Omatsu, T. et al. (2012) ‘The current trends in SBS and phase conjugation’, Laser and Particle Beams, 30(1), pp. 117–174.

Parihar, R. et al. (2024) ‘100 dB Microwave Photonic Filter for Communications and RF Sensing Applications’, Journal of Lightwave Technology [Preprint].

Perkins, L.J. et al. (2009) ‘Shock ignition: A new approach to high gain inertial confinement fusion on the national ignition facility’, Physical review letters, 103(4), p. 45004.

Preussler, S. et al. (2016) ‘Microwave-photonic filters’, GeMiC 2016 - 2016 German Microwave Conference, pp. 61–64. Available at: https://doi.org/10.1109/GEMIC.2016.7461556.

Raj, P. et al. (2022) ‘Energy-efficient bandwidth enhancement of Brillouin microwave photonic bandpass filters’, Optics InfoBase Conference Papers, 30(17), pp. 30739–30749. Available at: https://doi.org/10.1364/fio.2022.fm4d.3.

Samaniego, D. and Vidal, B. (2016) ‘Photonic Microwave Filter with Steep Skirt Selectivity Based on Stimulated Brillouin Scattering’, IEEE Photonics Journal, 8(6), pp. 1–7. Available at: https://doi.org/10.1109/JPHOT.2016.2634782.

Samaniego, D. and Vidal, B. (2019) ‘Brillouin Microwave Filter with Enhanced Skirt Selectivity Using a Birefringent Fiber’, IEEE Photonics Technology Letters, 31(6), pp. 431–434. Available at: https://doi.org/10.1109/LPT.2019.2897398.

Schmitt, A.J. et al. (2010) ‘Shock ignition target design for inertial fusion energy’, Physics of Plasmas, 17(4).

Seeds, A.J. and Williams, K.J. (2006) 'Microwave photonics', Journal of Lightwave Technology, 24(12), pp. 4628–4641. Available at: https://doi.org/10.1109/JLT.2006.885787.

Shi, M. et al. (2017) 'Microwave photonic filter with variable selectivity and shape by SBS and dispersion-induced phase mismatching', 2017 Opto-Electronics and Communications Conference, OECC 2017 and Photonics Global Conference, PGC 2017, 2017–Novem, pp. 1–3. Available at: https://doi.org/10.1109/OECC.2017.8114828.

Shimizu, K. et al. (1993) 'Coherent self-heterodyne detection of spontaneously Brillouin-scattered light waves in a single-mode fiber', Optics letters, 18(3), pp. 185–187.

Smith, R.G. (1972) 'Optical power handling capacity of low loss optical fibers as determined by stimulated Raman and Brillouin scattering', Applied optics, 11(11), pp. 2489–2494.

Tang, H. et al. (2017) 'Analysis of performance optimization for a microwave photonic filter based on stimulated brillouin scattering', Journal of Lightwave Technology, 35(20), pp. 4375–4383. Available at: https://doi.org/10.1109/JLT.2017.2740948.

Varun, M.K. and Pant, R. (2022) 'Mitigation of Dispersion Induced Impairments in Brillouin-based Microwave Photonic Bandpass Filter', TechRxiv, pp. 0–7. Available at: https://doi.org/10.36227/techrxiv.21780236.v1.

Wang, S. et al. (2007) 'Investigation of serial coherent laser beam combination based on Brillouin amplification', Laser and Particle Beams, 25(1), pp. 79–83.

Wang, W.T. et al. (2014) 'Widely tunable single bandpass microwave photonic filter based on Brillouin-assisted optical carrier recovery', Optics Express, 22(24), p. 29304. Available at: https://doi.org/10.1364/oe.22.029304.

Wang, W.T. et al. (2015) 'Microwave photonic filter with complex coefficient based on optical carrier phase shift utilizing two stimulated brillouin scattering pumps', IEEE Photonics Journal, 7(1), pp. 1–8. Available at: https://doi.org/10.1109/JPHOT.2015.2390150.

Wang, Y.L. et al. (2009) 'Investigation on efficiency of non-collinear serial laser beam combination based on Brillouin amplification', Laser and Particle Beams, 27(4), pp. 651–655.

Waterhouse, R. and Novack, D. (2015) 'Realizing 5G: Microwave photonics for 5g mobile wireless systems', IEEE Microwave Magazine, pp. 84–92. Available at: https://doi.org/10.1109/MMM.2015.2441593.

Wei, W. et al. (2017) 'Arbitrary-shaped Brillouin microwave photonic filter by manipulating a directly modulated pump', Optics Letters, 42(20), p. 4083. Available at: https://doi.org/10.1364/ol.42.004083.

Wen, H.S. et al. (2018) 'Ultrahigh-Q and tunable single-passband microwave photonic filter based on stimulated Brillouin scattering and a fiber ring resonator', Optics Letters, 43(19), p. 4659. Available at: https://doi.org/10.1364/ol.43.004659.

Xiao, Y. et al. (2015) 'Bandwidth reconfigurable microwave photonic filter based on stimulated Brillouin scattering', Optical Fiber Technology, 21, pp. 187–192. Available at: https://doi.org/10.1016/j.yofte.2014.11.002.

Xie, Y. et al. (2019) 'System-Level Performance of Chip-Based Brillouin Microwave Photonic Bandpass Filters', Journal of Lightwave Technology, 37(20), pp. 5246–5258. Available at: https://doi.org/10.1109/JLT.2019.2931077.

Xu, E. et al. (2022) 'Brillouin-assisted frequency-tuning-range-extended and passband-selected microwave photonic filter based on DPol-DPMZM', Journal of Modern Optics, 69(1), pp. 34–40. Available at: https://doi.org/10.1080/09500340.2021.1993365.

Xu, X. et al. (2023) 'Ultra-narrow bandwidth and large tuning range single-passband microwave photonic filter based on Brillouin fiber laser', Optics and Laser Technology, 157. Available at: https://doi.org/10.1016/j.optlastec.2022.108735.

Yan, J. et al. (2019) 'Widely tunable single bandpass microwave photonic filter based on dual-fiber stimulated Brillouin scattering', Microwave and Optical Technology Letters, 61(4), pp. 954–958. Available at: https://doi.org/10.1002/mop.31655.

Yao, J. (2009) 'Microwave photonics', Journal of lightwave technology, 27(3), pp. 314–335.

Yao, J. (2022) 'Microwave photonic systems', Journal of Lightwave Technology, 40(20), pp. 6595–6607.

Yi, L. et al. (2016) 'Polarization-Independent Rectangular Microwave Photonic Filter Based on Stimulated Brillouin Scattering', Journal of Lightwave Technology, 34(2), pp. 669–675. Available at: https://doi.org/10.1109/JLT.2015.2475297.

You, Y. et al. (2024) 'Flexible tunable microwave photonic filter with a dual ultra-narrow passband based on a dual-wavelength Brillouin laser', Optics Express, 32(19), pp. 33904–33916.

Yu, Y. et al. (2010) 'Switchable microwave photonic filter between high Q bandpass filter and notch filter with flat passband based on phase modulation', Optics Express, 18(24), p. 25271. Available at: https://doi.org/10.1364/oe.18.025271.

Zeng, Z. et al. (2019) 'Freely Tunable Dual-Passband Microwave Photonic Filter Based on Phase-to-Intensity Modulation Conversion by Stimulated Brillouin Scattering', IEEE Photonics Journal, 11(1), pp. 1–9. Available at: https://doi.org/10.1109/JPHOT.2019.2897593.

Zhang, K. et al. (2017) 'High-input dynamic range and selectivity stimulated Brillouin scattering-based microwave photonic filter utilizing a dual-stage scheme', Optics Letters, 42(17), p. 3287. Available at: https://doi.org/10.1364/ol.42.003287.

Zhang, Q. et al. (2018) 'Reconfigurable and switchable microwave photonic filter based on stimulated Brillouin scattering', Optical Engineering, 57(5), p. 1. Available at: https://doi.org/10.1117/1.oe.57.5.055102.

Zhang, Q. et al. (2022) 'Stimulated Brillouin Scattering-Based Microwave Photonic Filter with a Narrow and High Selective Passband', IEEE Photonics Journal, 14(4), pp. 1–7. Available at: https://doi.org/10.1109/JPHOT.2022.3184761.

Zhang, R. et al. (2024) 'Tunable Microwave Photonic Filter with Ultra-Narrow Passband and High Out-of-Band Rejection', Journal of Lightwave Technology [Preprint].