Integrated Microwave Photonic Filters

Yang Liu,[1,2,*] Amol Choudhary,[3], David Marpaung,[4] and Benjamin J. Eggleton [1,2]

[1] *Institute of Photonics and Optical Science (IPOS), School of Physics, The University of Sydney, NSW 2006, Australia*
[2] *The University of Sydney Nano Institute (Sydney Nano), The University of Sydney, NSW 2006, Australia*
[3] *Ultra Fast Optical Communications and High-performance Integrated Photonics (UFO-CHIP), Department of Electrical Engineering, Indian Institute of Technology (IIT) Delhi, Hauz Khas, New Delhi 110016, India*
[4] *Faculty of Science and Technology, University of Twente, 7522 NB Enschede, Netherlands*
[*] *yang.liu@sydney.edu.au*

Abstract: Microwave signal filtering is a fundamental and central functionality in radio frequency systems. We review the principles, architectures, and superior performance of emerging integrated microwave photonic filters enabled by on-chip linear and nonlinear photonic devices. © 2021 The Author(s)

1. Introduction

Microwave filters are a basic and important building block in the front end of radio-frequency (RF) and microwave receivers, providing signal filtering functionality to separate signals of interest from the noise background and to mitigate unwanted interference to avoid RF amplifier saturation [1]. Microwave photonics (MWP) [2–4] is attractive technology for demanding filtering applications that require large instantaneous bandwidth, ultra-wideband frequency tuning, and low loss; these demanding requirements are severe limitations for traditional RF and microwave counterparts [5]. The photonic advantages are enabled by the RF-to-optical frequency up-conversion and flexible filtering in the optical domain, typically achieved using fiber-based devices [5].

Over the recent decade, the convergence of MWP and photonic integrated circuit (PIC) [6–8] technologies has enabled the rapid development of integrated microwave photonics (IMWP) [9–11]. Underpinned by advanced PIC technologies, IMWP filters have been implemented by incorporating key optical components of MWP filters onto a chip-scale platform. Compared to MWP filters using bulky fiber-based optical filters, IMWP filters using centimeter-scale photonic chips exhibit dramatically reduced size, weight, and power consumption as well as enhanced stability, which are critical requirements for modern wireless communications and avionic applications. IMWP filters also preserve the photonics-enabled advantages such as ultra-wideband frequency tunability, resulting from the ultra-wide fractional frequency range of the optical frequencies. Such wideband tuning capability overcomes the existing limitation of narrow frequency tunability in state-of-the-art electronic filters [12, 13]. Although wideband-tunable RF filters operating around 30 GHz have been reported, the realization of 5 GHz frequency tuning requires a very high control voltage, which limits their practical applications. Attractively, the tightly-confined optical fields in the integrated circuits can induce strong nonlinear optical effects, producing advanced and unique signal processing and filtering functionalities that were previously unachievable for traditional microwave devices.

To date, most of efforts in IMWP filters have been made to implement key optical filtering components in compact photonic circuits, enabling enhanced filtering functionalities and reduced system footprint. For the future development, the ultimate goal of IMWP filters is achieving fully-integrated filter systems that incorporates light sources, modulators, photonic filtering circuits and photodetectors in one photonic chip, leading to significantly enhanced compactness and system stability

2. Recent Progress of Integrated Microwave Photonic Filters

Key milestones in the development of IMWP filters are shown in Fig. 1. The early exploration of IMWP functionalities leveraged the development of the PIC technology, starting from the advent of integrated silicon photonics [31] and Indium Phosphide (InP) photonics [32]. The very early demonstrations of IMWP were carried out using multi-tap architectures for phased-array antennas and RF spectrum filtering in silicon chip in 1997 [14]. In 2009, the first IMWP filter using integrated low-loss silicon resonators was reported [15], followed by the demonstration using silicon sub-wavelength gratings [16]. Recent rapid development of IMWP technique has benefit from the massive progress in PICs technology, which has been driven by the investment and advancements in other fields such as data centres and telecommunications. Pioneering demonstrations of IMWP filters based on active InP photonic circuits, using cascaded Mach-Zehnder interferometers (MZIs) [17] and ring network were reported [33] in 2011. In the meantime, Si_3N_4 ring resonators were demonstrated as an advantageous candidate for IMWP filters due

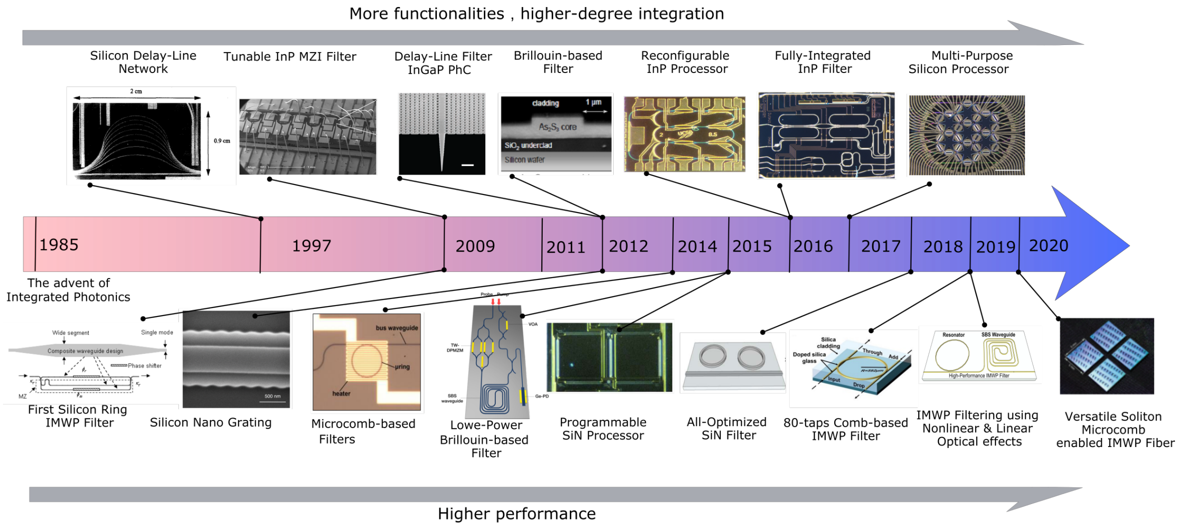

Fig. 1. Timeline of major advancements in integrated microwave photonic filters, showing the milestones in architectures, platforms and performance. Figures are reprinted from [14–30].

to the ultra-low optical losses. In 2012, an ultra-compact transverse IMWP filter, for the first time, was achieved using an InGaP photonic crystal waveguide that provides frequency-dependent time delay for each tap [18]. Recently, the emerging concept of programmable photonic circuits was extensively studied in Si_3N_4 circuits [23] in 2015, active InP photonic circuits [24] in 2016, and in silicon circuits [27] in 2017, respectively, enabling multiple IMWP filtering functionalities using the same photonic circuit. A recent breakthrough has been made to implement a fully-integrated MWP filter, achieving for the first time the 100% degree of photonic integration of an IMWP filter [25].

On-chip nonlinear optical effects, as an active optical process, started to gain great interest for implementing IMWP filters in 2012, when on-chip stimulated Brillouin scattering (SBS) induced by strong photon-phonon interactions, was harnessed as the basis of a tunable single-bandpass RF filter with a record-narrow spectral resolution of 30 MHz [19]. An IMWP notch filter with ultrahigh selectivity was subsequently achieved using on-chip SBS with significantly reduced optical pump power [22]. On-chip optical frequency combs via optical Kerr effect, were introduced as an unprecedentedly compact laser array, providing numerous delay taps for delay-line-based IMWP filters [20, 29, 30]. A novel class of IMWP filter based on the simultaneous use of on-chip linear and nonlinear optical effects was recently demonstrated, achieving the synergy of optimal filter functionalities and high RF performance [28].

3. Technical Challenges and Outlook

We review the recent progress on achieving high-RF-performance integrated microwave photonic filters, which made important steps towards meeting the demanding performance requirements of practical RF and microwave applications. Future research and development of integrated microwave photonic filters is expected to target the simultaneous synergy of optimal filtering schemes, novel photonic processing approaches using both linear and nonlinear optical devices, and advanced photonic integration technologies.

4. References

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