

Integrated microwave photonic filters for flexible satellite payloads: the achievements of THORMUX project from design to evaluation

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ABSTRACT

We propose and demonstrate an integrated microwave photonics four-channel demultiplexer filter for flexible satellite payloads. The demultiplexer allows for a fully reconfigurable passband bandwidth, ranging from 42 MHz to 1.5 GHz, and central frequency tunability spanning in the Ka (27.5–30 GHz), Q (37.5–42.5 GHz) and V (42.5–50 GHz) RF bands. The core filter of the demultiplexer is a photonic eight-ring coupled-resonator optical waveguide (CROW) structure with high selectivity, implemented in the ultra-low loss Si₃N₄/SiO₂ TriPleX[®] photonic integrated circuit (PIC) platform. Reconfigurability is achieved by using power efficient stress-optic lead zirconate titanate (PZT)-based actuators, allowing for a power consumption lower than 80 μ W per demultiplexed channel. The proposed device is anticipated to be key enabler of flexible, low-SWaP next-generation communication systems.

Keywords: integrated optics, microwave photonics, optical filters, optical signal processing, satellite payloads, silicon nitride

1. INTRODUCTION

As modern satellite telecommunication providers pursue higher data rates, a clear trend has emerged toward flexible payload architectures that incorporate high spectral selectivity filters and dynamic spectral resources allocation [1], [2]. Achieving this objective is highly nontrivial and remains the subject of research and development (R&D) efforts, as commercially available RF filters with desired flexibility are currently not available [3]. Integrated microwave photonics (iMWP) is an emerging technology that can overcome the fundamental limitations of the current electronics by processing RF signals in the optical domain using photonic integrated circuits (PICs), providing reduced size and weight [4]–[6]. These advantages make the technology a strong platform for developing compact, highly reconfigurable channel-selection and demultiplexing (DEMUX) filters. Several iMWP filters have been already demonstrated [7]–[11]. However, the existing iMWP filters have not yet been able to simultaneously achieve all key performance requirements, such as high selectivity, high stopband rejection, low insertion loss, flat-top passbands (PBs), and wide tuning range. Additionally, their tuning mechanisms typically rely on power-intensive thermal heaters, resulting in significant power consumption that scales poorly with the number of channels, limiting their suitability for power-constrained applications. Within this context, the ESA-funded THORMUX project (tunable photonic-RF demultiplexer) seeks to develop novel iMWP filters with high performance and attractive size, weight and power consumption (SWaP), enabling tuneable filtering and demultiplexing functionalities for flexible satellite payloads in the Ka-, Q- and V- RF bands [12].

This paper presents the design, realization and experimental evaluation of two PIC filter modules implemented in the ultra-low loss Si₃N₄/SiO₂ TriPleX[®] waveguide platform [13], enabling a four-channel DEMUX architecture for satellite payloads. The goal of this work is to provide certain signal processing concepts, as well as evaluating the measured performance versus the filter mask requirements and performance predictions. The first PIC filter module is based on a lattice configuration comprising five asymmetric Mach–Zehnder interferometers (AMZIs), and is used to enable single side band – suppressed carrier (SSB-SC) filtering by the rejection of all image frequencies at the output of the modulator (mixer) for RF input signals in any of the Ka (27.5–30 GHz), Q (37.5–42.5 GHz) and V (42.5–50 GHz) bands. The second PIC filter module consists of novel four-channel demultiplexer filter, based on the cascade of a coupled ring

resonator optical waveguide (CROW) and AMZI-lattice filters. It is designed to perform the channel-selection function of an input (de)multiplexer (IMUX) for flexible satellite payloads. The testing showed a reconfigurable CROW filter with a tunable PB bandwidth and central frequency. The reconfigurability is enabled by power-efficient ($< 1 \mu\text{W}$) stress-optic lead zirconate titanate (PZT) actuators [14], allowing for a power consumption of $< 80 \mu\text{W}$ per demultiplexed channel.

The evaluation demonstrates that the proposed filter satisfies all stringent channelization filtering requirements while maintaining extremely low power consumption. This breakthrough in integration of low-power stress-optic actuation in reconfigurable PICs paves the way for a broad range of advanced functionalities in PIC-based satellite payloads, including multi-channel beamformers or programmable photonic quantum processors.

2. MICROWAVE PHOTONICS DEMUX ARCHITECTURE

Figure 1 illustrates the proposed microwave photonic (MWP) architecture for implementing a four-channel demultiplexing (DEMUX) filter. The system comprises three Si_3N_4 TriPleX[®] PIC modules. PIC 1 incorporates the carrier-reference (CR) laser source, PIC 2 contains the SSB-SC filtering stages, and PIC 3 performs the four-channel DEMUX operation. PIC 1 initially generates an optical CR at a wavelength of 1550 nm (a), which is distributed by a 1-to-5 optical splitter. One branch of the carrier is applied to an external phase modulator (PM), where the input RF signal in the Ka, Q or V bands, is encoded onto the optical CR, generating a double-sideband full-carrier (DSB-FC) spectrum consisting of the lower sideband (LSB), CR, and upper sideband (USB) (b). The modulated optical signal is subsequently routed to SSB-SC Filter 1 in PIC 2, where the undesired CR and LSB are suppressed while the USB is transmitted with minimal distortion (c). Processing only a single sideband provides a key advantage: any operation performed on the USB in the optical domain is directly mapped onto the corresponding RF output signal. This one-to-one correspondence is preserved because the SSB-SC filter eliminates the LSB, thereby preventing spectral folding.

Following this processing stage, the optical USB can be regarded as a wavelength-division multiplexed (WDM) signal carrying information from four independent channels (Ch. 1-4). This composite signal is then routed to the DEMUX filter implemented on PIC 3, where it is separated into four distinct optical channels (Ch.4-d.1 and Ch.1-d.2). The DEMUX filter serves as the primary signal-processing unit of the proposed architecture, performing the channel demultiplexing operation. A key feature of this filter is its ability to provide tunable center frequencies and adjustable PB widths, while preserving the required spectral response. Each extracted USB channel is subsequently combined with a reinjected unmodulated CR reference originating from one of the remaining outputs of the 1-to-5 splitter. The multiplexing process of the CR and USB is carried out by SSB-SC Filters 2–5 located on PIC 2 (e.1 and e.2), which operate effectively in cascade with SSB-SC Filter 1. Consequently, any residual modulated CR and LSB components undergo a second suppression stage, thereby enhancing the rejection of these unwanted spectral components. Finally, the processed optical channel signals are detected by an external photodetector array (PD1–PD4), where optical-to-electrical conversion is achieved through optical beating, yielding the corresponding RF outputs signals.

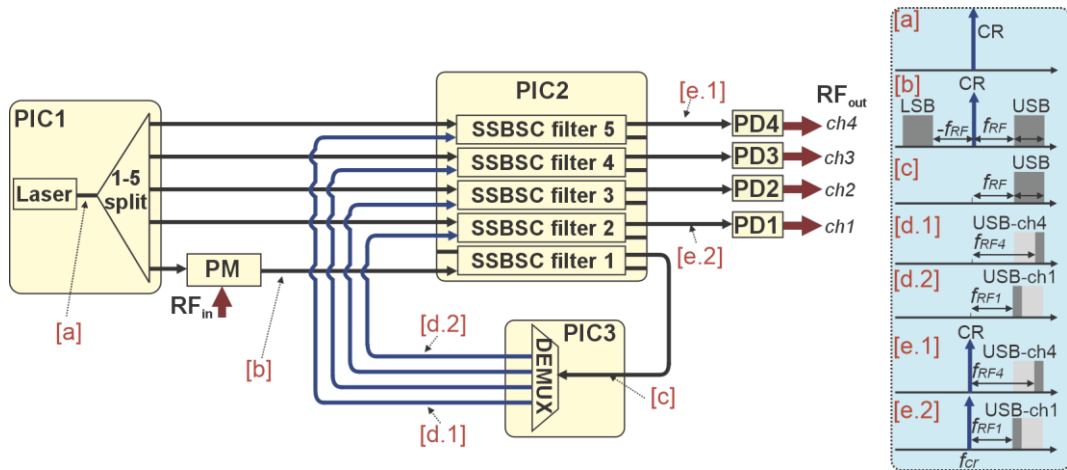


Figure 1. Microwave photonics DEMUX architecture (PIC = photonic integrated circuit, PM = phase modulator, LSB = lower sideband, CR = carrier reference, USB = upper sideband, f_{RF} = RF frequency, SSB-SC = single-sideband suppressed-carrier, PD = photodiode, DEMUX = demultiplexer, ch. = channel).

3. FILTER DESIGN

The filters investigated in this work are delay-line-based interferometric filters implemented using multi-stage AMZI lattice and CROW architectures, as illustrated in Figure 2 (a) and (b), respectively. In both architectures, optical signals are split and recombined through power couplers (κ s), while path-length differences in the arms of the AMZIs or the circumference of the ring resonators (RRs) generate the interference responsible for the spectral response [15]. By cascading multiple stages, a wide range of filter functions can be synthesized. However, increasing the number of stages also increases component count, design complexity, and fabrication cost. Therefore, a key design objective is to realize the required filter response using the minimum number of stages and lowest implementation complexity.

The key design parameters of a PIC filter include the number of stages, the free spectral range (FSR), waveguide propagation loss, the phase shifts (ϕ s) and the coupling coefficients (κ s) settings. Compared with AMZI lattice filters, CROW filters generally achieve steeper roll-off and higher out-of-band rejection with fewer stages, whereas AMZI filters inherently provide linear-phase (zero-dispersion) responses. The FSR and PB characteristics are determined by the interferometric path-length differences, with AMZI filters supporting larger FSR, whereas CROW filters enable narrower PBs and higher spectral selectivity. Waveguide propagation loss has a stronger impact on the performance of CROW than on AMZI lattice filters. The phase shifts (ϕ s), implemented using thermo-optic heaters or stress-optic PZT actuators, are used to align or tune the filter's center frequency. Similarly, the coupling coefficients (κ s) determine the filter's spectral shape, bandwidth, and rejection characteristics. In tunable implementations, the couplers can be realized as symmetric MZIs incorporating integrated heaters or PZT actuators, enabling dynamic adjustment of the coupling coefficients. Such tunable couplers enable bandwidth reconfiguration in CROW filters while providing additional flexibility for compensating fabrication tolerances in both AMZI lattice and CROW filters. Table 1 summarizes the key design considerations for the AMZI lattice and CROW filters.

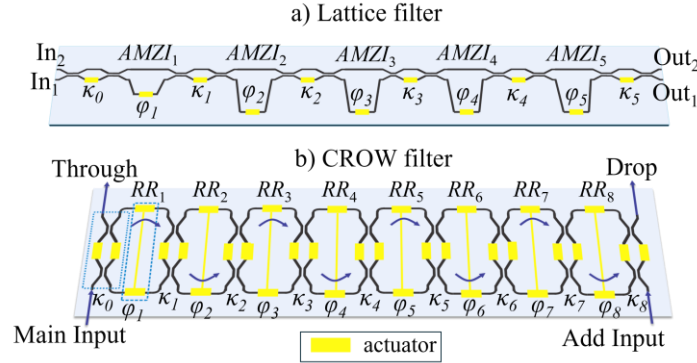


Figure 2. Functional schematics of the main filter types, employed in this work: a) AMZI Lattice filter, b) CROW filter.

Table 1. Selection of filter type based on application guidelines.

application requirement	preferred filter
Narrow bandwidth and high spectral selectivity	CROW
Linear-phase / zero-dispersion response	AMZI Lattice
Very large FSR	AMZI Lattice
Tunable bandwidth	CROW (with tunable couplers)
Tunable center frequency	Both
Fabrication-tolerant implementation	Both (with phase shifters and tunable couplers)

Considering the characteristics of multi-stage RR-based CROW and AMZI-based filters, we selected the configuration that best satisfies the requirements of the SSB-SC and channel-selection filtering functions.

3.1 SSB-SC filter

The SSB-SC filter must provide sufficient suppression of both the LSB and the CR across the Ka-, V-, and Q-band frequency ranges. This requirement renders RR-based implementations impractical, since the maximum FSR achievable with RRs with low-power consumption PZT actuators remains significantly smaller than the frequency span of the Q and V bands. Consequently, a multi-stage AMZI lattice filter represents the most suitable solution because of its large FSR,

as well as its wide PB and stopband (SB) bandwidths. Figure 2 (a) illustrates the architecture of the implemented SSB-SC lattice filter. The filter consists of five AMZIs stages, which is the minimum number required to satisfy the filter specifications. Six tunable couplers, with power coupling coefficients denoted by κ_0 to κ_5 , control the power transfer between adjacent AMZI stages. In addition, each AMZI stage incorporates a phase shifter (ϕ_1 – ϕ_5) for tuning the PB to the desired center frequency. To achieve a flat-top passband, two distinct differential path lengths are employed. The first stage (AMZI 1) has a path-length difference of 1.06 mm, corresponding to an FSR₁ of 160 GHz. The subsequent stages (AMZI 2–5) use twice this path-length difference, resulting in an FSR₂ of 80 GHz. Consequently, the overall filter's FSR is determined by the first stage, yielding an FSR of 160 GHz. The filter transfer function is formed by the superposition of a set of harmonically related sinusoidal responses with appropriately tailored amplitudes and phases [15]. By properly selecting the κ s and the ϕ s, the filter realizes a ninth-order spectral response with an optimized flat-top PB. The lattice architecture comprises two input ports (In 1 and In 2) and two output ports (Out 1 and Out 2). Assuming negligible waveguide loss, the transfer functions at the two output ports are complementary.

3.2 Channel selection DEMUX filter

The channel-selection filter must provide a highly selective PB response with reconfigurable bandwidth, strong suppression of adjacent-channel interference, and tunable center-frequency operation across the Ka-, Q-, and V-band frequency ranges. To satisfy these requirements, the channel-selector is implemented as a cascade of two complementary filtering stages. The first stage consists of a multi-RR CROW filter, which provides the channel-bandwidth control. Owing to its high spectral selectivity and excellent out-of-band rejection, the CROW filter is well suited for precise channel shaping. However, the FSR achievable with RRs is constrained by the minimum physical resonator circumference, restricting the center-frequency tuning to the Ka band. To overcome this limitation, a second post-filtering stage based on multi-stage AMZI lattice filters is employed. This stage extends the effective FSR of the channel selector, enabling center-frequency tuning across the Q and V bands by leveraging the inherently larger FSR of AMZI-based filters. Consequently, the combined architecture retains the high spectral selectivity of the CROW filter while providing the wide tuning range required for broadband operation. The number of stages in both the CROW and AMZI lattice filters was minimized while ensuring compliance with the specified filter-mask requirements.

Figure 3 shows the implemented four-channel selection DEMUX filter in PIC3. The architecture incorporates a 1-to-4 tunable optical power splitter, realized using PZT-actuated TCs enabling any splitting ratio between 0.25 and 1. Each splitter output is connected to an identical channel selector comprising a cascade of CROW and AMZI lattice filters. The CROW filter consists eight directly coupled RRs, as shown in Fig. 2 (b). Each RR has a circumference of 7.94 cm, corresponding to an FSR of 2.48 GHz. This FSR was selected to support a tunable PB bandwidth from 125 MHz to 1000 MHz. Nine TCs with power coupling coefficients denoted by κ_0 to κ_8 , control the optical power transfer between adjacent RRs. In addition, each RR incorporates a phase shifter (ϕ_1 – ϕ_8) for independent tuning of its resonance frequency. The tunable couplers enable dynamic reconfiguration of the PB bandwidth, whereas the phase shifters tuning of the filter center frequency. Reducing the coupling coefficients increases the resonant behavior of the rings, thereby improving the spectral selectivity. By appropriately adjusting the phase shifters, the resonators of all the rings can be aligned to the same center frequency. Each TC incorporates two PZT actuators. Although only one actuator is required for normal operation, the second provides redundancy, thereby improving the robustness and reliability of the overall system.

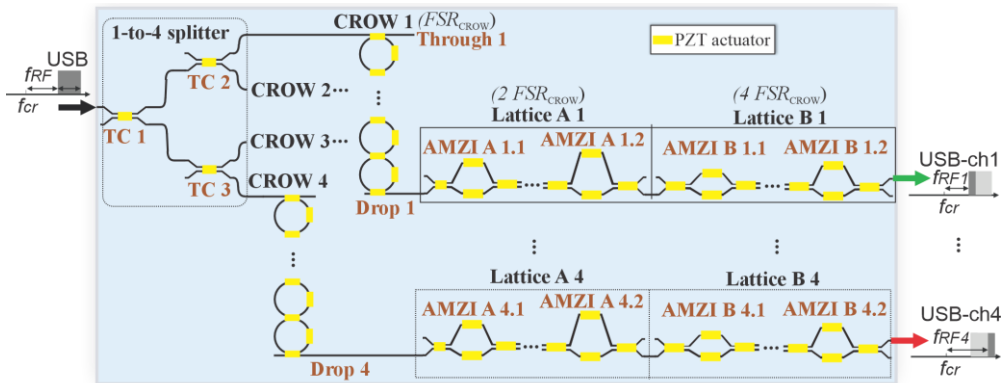


Figure 3. Functional schematic of the 4-channel DEMUX filter in PIC 3, where each channel includes a cascade of an 8-RR CROW filter, two 3-AMZI Lattice Filters A and two 2-AMZI Lattice Filters B.

The CROW filter comprises four ports: an Input port, an Add port, a Drop port, and a Through port. The desired channel is extracted at the Drop port, which exhibits the highly selective passband response of the filter. The Through port provides the complementary transfer function by suppressing the selected channel and thereby exhibiting a notch filter response. The Add port enables insertion of an optical signal into the resonator chain, providing add/drop multiplexing functionality.

The AMZI post-filtering stage is composed of two cascaded fifth-order and two cascaded third-order AMZI lattice filters, extending the effective FSR of the channel selector to 9.92 GHz. Lattice Filter A consists of three AMZI stages and provides an FSR of 4.96 GHz, corresponding to twice the FSR of the CROW filter. Its primary function is to suppress the first and third unwanted passband replicas generated by the CROW filter. Lattice Filter B comprises two AMZI stages and exhibits an FSR of 9.92 GHz, corresponding to four times the CROW FSR. It is designed to suppress the second unwanted passband replica. Because this replica is located farther from the desired channel, the required transition-band performance is less stringent, allowing Lattice Filter B to employ one fewer AMZI stage than Lattice Filter A. The lattice filters are equipped with TCs to set their spectral shape and phase shifts to set their central frequency. To achieve the required out-of-band rejection, two instances of Lattice Filter A and two instances of Lattice Filter B are cascaded within each channel-selection path. This configuration ensures more than 40 dB suppression of all unwanted passband replicas.

4. REALIZED PIC MODULES

The proposed MWP architecture, introduced in Section 2, is realized using the three PIC modules shown in Figure 4. PIC 1 (Fig. 4(a)) integrates five hybrid lasers and is responsible for optical carrier generation. The gain sections are realized in InP, while the RR-based mirror filters are implemented on the high-index-contrast (HIC) Si_3N_4 platform [13]. Two gain sections are combined with a 2-RR mirror filter to form the high-power main laser, which is externally modulated by the RF input signal, while the remaining gain sections provide local-oscillator (LO) lasers for frequency-conversion functionality. The module incorporates 43 thermo-optic actuators for laser-frequency tuning and optical power distribution. PIC 1 has dimensions of $52 \text{ mm} \times 74 \text{ mm} \times 5 \text{ mm}$, a weight of 150 g, and is described in detail in [16]. PIC 2 (Fig. 4(b)) contains six identical SSB-SC filters fabricated on the same waveguide platform. The module incorporates 78 thermo-optic heater actuators, measures $52 \text{ mm} \times 52 \text{ mm} \times 5 \text{ mm}$, and weighs 150 g. For both PIC 1 and PIC 2, the waveguide propagation loss is approximately 0.05 dB/cm. PIC 3 (Fig. 4(c)) implements the four-channel DEMUX filter. It is fabricated on a low-index-contrast (LIC) Si_3N_4 platform, providing ultra-low propagation loss ($<1 \text{ dB/m}$) and enabling resonators with quality factors up to 4×10^6 . The module includes 318 PZT tuning elements, each consuming less than $1 \mu\text{W}$ in quasi-static operation, resulting in a total tuning power below $320 \mu\text{W}$. PIC 3 measures $129 \text{ mm} \times 135 \text{ mm} \times 5 \text{ mm}$ and weighs 700 g.

All modules operate in the 1550-nm wavelength band and are interconnected using polarization-maintaining single-mode fiber arrays. The fiber-to-chip coupling loss is 0.75 dB per interface for PICs 1 and 2 and 1.1 dB for PIC 3. The higher coupling loss of the SS PIC 3 is attributed to its unpolished chip facets. The tuning electrodes are wire-bonded to custom PCBs, which provide electrical interfacing to the control electronics. The PICs, PCBs, and fiber-array interfaces are mounted on gold-plated copper carriers that provide both mechanical support and efficient thermal management.

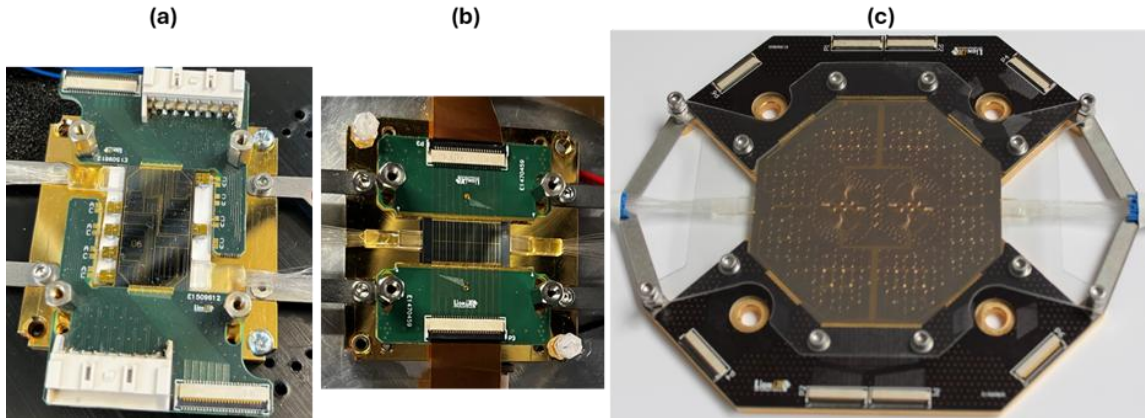


Figure 4. Realized PIC devices: (a) laser PIC 1, (b) SSB-SC filters PIC 2 and (c) DEMUX filter PIC 3.

5. EXPERIMENTAL VERIFICATION OF THE FILTERS

This section presents the experimental validation of the SSB-SC lattice filter (PIC 2) and DEMUX channel selection filter (PIC 3). All obtained spectra are plotted as a function of the offset frequency, which is defined as the frequency difference with respect to the optical CR frequency corresponding to a wavelength of 1550 nm (193.414 THz).

5.1 SSB-SC filter PIC 2

The experimental characterization of the AMZI lattice filter, providing the SSB-SC functionality, is presented in Figure 5. Owing to its architecture comprising a five-stage AMZI lattice layout with TCs, the filter can be configured to realize first-, third-, fifth-, seventh-, and ninth-order filter responses, as shown in Figure 5 (a). The filter order is selected by setting the TCs to the appropriate combination of coupling coefficients, with the optimal values listed in Table 2. As the filter order increases, the response progressively approaches the desired rectangular spectral shape. Specifically, both the PB and SB bandwidths increase, while the transition band (TB) becomes steeper, resulting in improved filtering performance. The FSR and insertion loss (IL) remain essentially unchanged across all filter orders, with measured values of 160 GHz and 1.5 dB, respectively. The insertion loss is dominated by the 2 fiber-to-chip interfaces, which together contribute approximately 1.5 dB of loss.

The filter achieves its optimum performance when configured for the highest achievable order, which in this work corresponds to a ninth-order response. Figure 5 (b) shows the measured optical power transfer of two individual lattice filters tuned to exhibit ninth-order flat-top passband characteristics, with their passbands aligned in frequency. The intended spectral locations of the LSB, USB, and optical CR relative to the filter response are indicated in the figure. For RF signals within the Ka (27.5–30 GHz), Q (37.5–42.5 GHz), and V (42.5–50 GHz) bands, optical modulation generates sidebands that are positioned at frequency offsets of $[-50, -27.5]$ GHz (LSB) and $[27.5, 50]$ GHz (USB) with respect to the optical CR. As demonstrated in Figure 5 (b), the response of the SSB-SC filter provides the desired single-sideband filtering functionality: the LSB and CR are suppressed by more than 20 dB through the stopband of the filter, while the USB is transmitted through the flat-top passband with an insertion loss of only 1.5 dB.

Figure 5(b) also presents the response of Filter 2 when excited through its complementary input, resulting in the complementary spectral transfer function denoted as Filter 2 CRI. This configuration is employed for carrier reinsertion

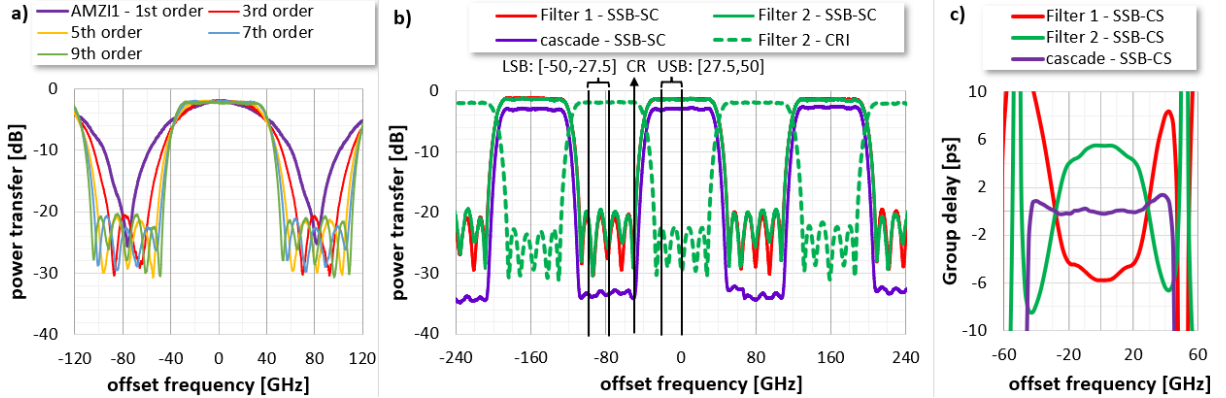


Figure 5. Experimental characterization of single side band – carrier suppression – carrier re-injection (SSB – CS – CRI) filters in PIC 2: a) power transfer of a single filter tuned to different orders. b) Power transfers of the single 9th order lattice filter 1 and 2 and their cascade, as well as power transfer of filter's 2 complementary output. c) Group delay response of the single 9th order lattice filter 1 and 2 and their cascade.

Table 2. Targeted coupling coefficient values (κ s), derived from the lattice filters theory [15] to obtain a: 1st, 3rd, 5th, 7th and 9th order filter spectral response.

filter order	κ_0	κ_1	κ_2	κ_3	κ_4	κ_5
1	0.5	0.5	0	0	0	0
3	0.5	0.714	0.075	0	0	0
5	0.5	0.794	0.195	0.02	0	0
7	0.5	0.812	0.261	0.059	0.009	0
9	0.5	0.845	0.331	0.101	0.024	0.004

(CRI), enabling the optical carrier generated by the laser to be multiplexed with the filtered USB at the filter output. Figure 5 (b) further shows the optical power transfer obtained by cascading the two ninth-order lattice filters. The filters are tuned to exhibit identical amplitude responses but complementary group-delay characteristics. In the cascaded configuration, the stopband rejection is improved by approximately 10 dB, reaching a total suppression level of 30 dB. The corresponding group-delay responses are presented in Figure 5 (c), with the analysis focused on the passband region. Filters 1 and 2 exhibit complementary group-delay characteristics, with a group-delay variation (GDV) of approximately ± 7.5 ps across the passband. Consequently, cascading the two filters effectively compensates the group-delay distortion, reducing the residual passband GDV to less than 0.5 ps, as indicated by the purple curve.

5.2 Channel selection DEMUX filter PIC 3

Bandwidth reconfigurability

Using the CROW filter, we demonstrate passband bandwidth (1-dB BW) reconfigurability from 42 MHz to 1500 MHz, as shown in Figure 6. The passband BW is adjusted by tuning the power coupling coefficients (κ s) of the nine PZT TCs of the CROW. Bandwidth tuning is performed by starting from simulation-based coupling values and applying manual fine adjustments to meet the desired filter specifications. As the PB bandwidth increases, the fiber–chip–fiber insertion loss decreases, from 7.4 dB (42 MHz) and 5.8 dB (175 MHz) to 2.8 dB for bandwidths of 444 MHz and above, as shown in Figure 6 (a). This behavior is expected because narrower PBs require stronger resonances, causing light to make more round trips within the ring resonators and therefore accumulate higher propagation losses. As examples, the TC settings corresponding to filter bandwidths of 175 MHz and 940 MHz are provided in Table 3. Of the total loss, 2.2 dB originates from the fiber-to-chip interfaces, while the filter itself contributes 5.2 dB, 3.6 dB, and 0.6 dB for bandwidths of 42 MHz, 175 MHz, and ≥ 444 MHz, respectively. For all demonstrated PB bandwidths the measured GDV remains lower than 2.5 ns, as shown in Figure 6 (b). It should be noted that, in Figure 6 (a), the apparent stopband rejection is limited by the dynamic range of the equipment rather than by the intrinsic filter performance.

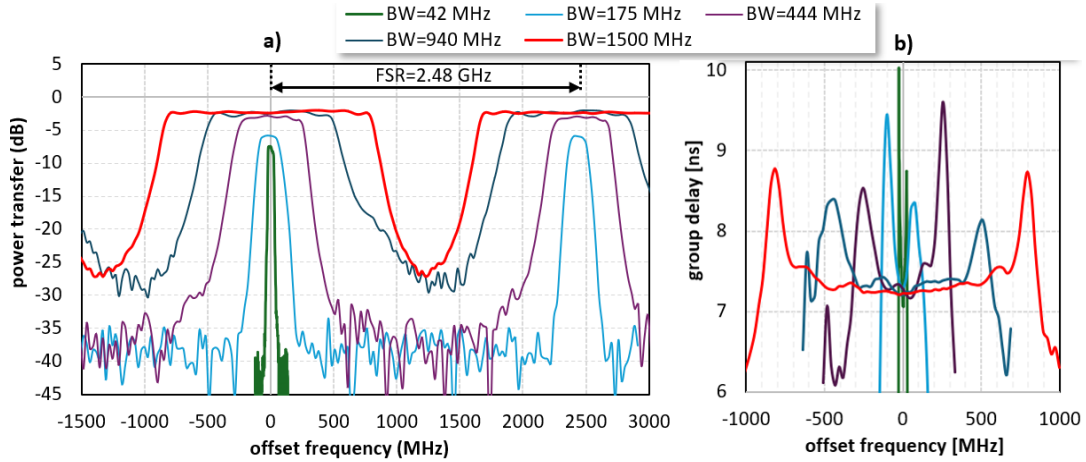


Figure 6. Experimental demonstration of CROW tunable passband bandwidth including a) power transfer and b) group delay transfer.

Table 3. Targeted coupling coefficients (κ s) values for all tunable couplers of a CROW filter, so as to achieve a maximally flattened CROW filter with passband bandwidth equal to 175 MHz and 940 MHz.

Passband bandwidth	κ_0	κ_1	κ_2	κ_3	κ_4	κ_5	κ_6	κ_7	κ_8
175 MHz	0.35	0.0315	0.016	0.015	0.0095	0.015	0.016	0.0315	0.35
940 MHz	0.918	0.585	0.387	0.33	0.32	0.33	0.387	0.585	0.918

Central frequency tunability

The central frequency tunability of the CROW filter is also demonstrated and presented in Figure 7. By tuning the phase shifters of the RRs, the passband of the CROW filter is shifted to two different frequencies with respect to the initial central frequency.

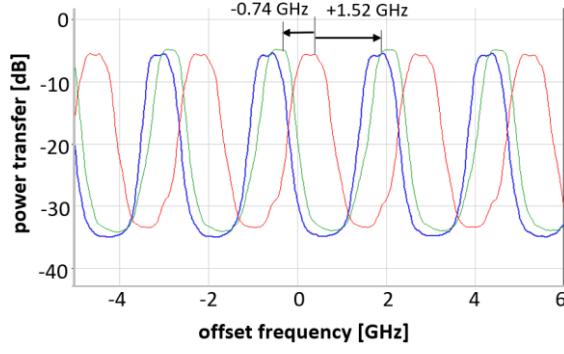


Figure 7. Experimental demonstration of central frequency tunability of the CROW passband.

Rejection level

Figure 8 (a) demonstrates the actual rejection level of the CROW filter, obtained using an alternative high-sensitivity experimental setup. As can be seen in Figure 8 (a), the rejection level was measured equal to 55 dB.

Channel selection filters cascade with extended FSR

Figure 8 presents the measured power transfer responses of all filters comprising the channel-selector cascade. Specifically, Figure 8(a) shows the response of the CROW filter, Figure 8(b) the responses of the two AMZI lattice filters A and their cascade, Figure 8(c) the responses of the two AMZI lattice filters B and their cascade, and Figure 8 (d)

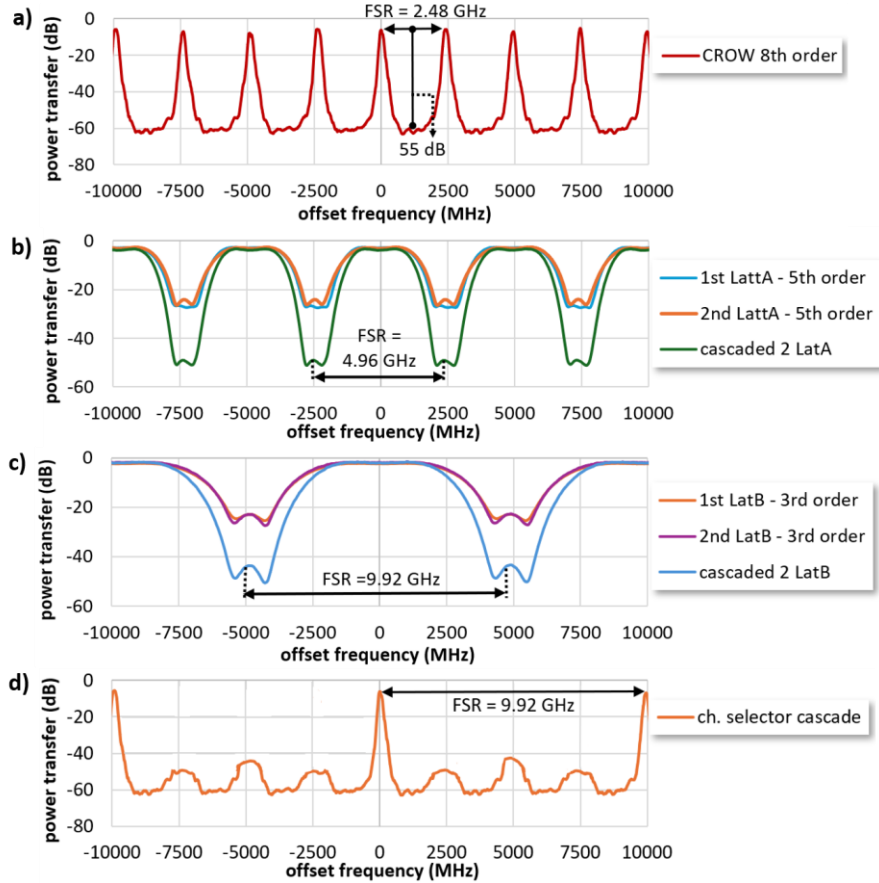


Figure 8. Experimental demonstration of CROW's high rejection level and FSR extension in PIC 3. Power transfers of: a) 8th order CROW, b) 5th order AMZI Lattices A and their expected cascade response, b) 3rd order AMZI Lattices B and their expected cascade response, and d) expected channel selector response with all filters cascaded.

the overall response obtained by cascading all filters. The frequency axes are aligned to clearly illustrate the proposed FSR extension scheme. The cascade responses were obtained through offline processing of the experimentally measured transfer functions of the individual filters. As observed, the CROW filter exhibits an FSR of 2.48 GHz, while lattice filters A and B provide doubled and quadrupled FSRs of 4.96 GHz and 9.92 GHz, respectively. The FSR-extension strategy relies on aligning the passbands of all filters at the 0-MHz frequency offset. The stopbands of lattice filters A are configured to suppress the first and third repetitions of the CROW passband, whereas the stopbands of lattice filters B suppress the second repetition, achieving a rejection level of at least 40 dB. The suppression of the repeated CROW passbands can be clearly observed by comparing the responses in Figure 8 (a) and Figure 8 (d). Consequently, cascading all channel-selector filters extends the overall FSR to 9.92 GHz, increasing the central-frequency tuning range from 2.48 GHz to 9.92 GHz.

The IL of the complete filter cascade varies between 8.6 dB and 3.4 dB as the 1-dB bandwidth increases from 42 MHz to 1500 MHz. These values include the 2.2 dB loss associated with the fiber-chip-fiber interfaces. The out-of-band rejection ranges from 55 dB in spectral regions suppressed by the CROW filter to 40 dB in regions suppressed by the lattice filters. The rejection level by the lattice filter could reach the same level as the CROW by cascade an extra lattice filter A and B. The cascade of the two AMZI lattice-filter stages does not introduce any additional GDV. Therefore, the overall channel-selector filter exhibits the same GDV as the CROW filter, remaining below 2.5 ns across all operating conditions. The passband characteristics of the channel selector were evaluated for all realized bandwidth configurations and compared against the target specifications provided by the European Space Agency (ESA) for the intended satellite communication payload. For all measured bandwidths, the channel selection filter cascade meets the required performance metrics, as summarized in Table 4.

Table 4. Exhibited performance of the channel selection DEMUX filter cascade and respective requirements from the European Space Agency.

Parameter	unit	exhibited performance	ESA requirement
passband bandwidth	MHz	42 – 1500	125 – 1000
insertion loss at passband f_c	dB	8.6 – 3.4	≤ 10
power ripple in passband ($f_c \pm 0.5$ BW)	dB	0.8 - 1	≤ 1
channel isolation at :		:	:
$f_c \pm 0.9$ BW	dB	20	≤ 20
$f_c \pm 1.5$ BW		40 - 55	≤ 40
Free spectral range	GHz	9.92	≥ 7.5
Group delay variation in passband ($f_c \pm 0.5$ BW)	ns	≤ 2.5	≤ 14

*The insertion losses include the fiber-to-chip coupling loss of 2.2 dB.

6. OUTLOOK

The demonstrated Si_3N_4 channel-selection filter highlights the potential of ultra-low-loss photonic integrated circuits for advanced microwave-photonic signal processing. A natural next step is the heterogeneous integration of active indium phosphide (InP) devices, including tunable lasers, semiconductor optical amplifiers, modulators, and photodetectors, with the Si_3N_4 filtering platform. Such an approach would enable highly iMWP subsystems with substantially reduced SWaP, while simultaneously improving performance and functionality. By combining the ultra-low-loss Si_3N_4 passive circuits with the active functionality of InP components, fully integrated and programmable microwave-photonic filters could be realized to meet the demanding requirements of next-generation space and wireless communication systems.

Beyond channel selection, the proposed architecture can be extended to support additional microwave-photonic functionalities, including optical beamforming, frequency conversion, and signal switching/routing on the same photonic integrated circuit. Such multifunctional integration is particularly attractive for emerging 6G and satellite communication systems, where compactness, reconfigurability, and low power consumption are critical. A representative example is the European Horizon TERA-6G project [17], which investigates hybrid photonic integration technologies for reconfigurable terahertz transceivers, beamforming networks, and fiber-over-the-air architectures targeting future ultra-high-capacity wireless systems.

Integrating the proposed Si_3N_4 filtering technology into such heterogeneous photonic platforms could provide compact, highly selective, and reconfigurable signal-processing functions, further enhancing system performance, flexibility and scalability.

7. CONCLUSION

This work demonstrated two photonic integrated filter modules implemented on the ultra-low-loss TriPleX[®] Si₃N₄ platform for flexible satellite payloads. An AMZI lattice filter was used to realize SSB-SC filtering by suppressing image frequencies generated during optical frequency conversion in the Ka-, Q-, and V-bands, while a reconfigurable channel selector based on a CROW filter and cascaded AMZI lattice filters enabled programmable channelization. Experimental results showed tunable 1-dB bandwidths from 42 MHz to 1500 MHz and an effective FSR extension from 2.48 GHz to 9.92 GHz. The filter further achieved out-of-band rejection of exceeding 55 dB and group delay variation below 2.5 ns.

The achieved performance is enabled by the combination of the ultra-low-loss silicon nitride platform and highly power-efficient stress-optic PZT actuators. This unique combination of high-performance filtering, wide reconfigurability, and extremely low power consumption makes the proposed architecture particularly attractive for satellite communication payloads subject to stringent SWaP constraints. The measured results satisfy the ESA filtering requirements and demonstrate the strong potential of programmable silicon nitride PICs for future flexible microwave-photonic payloads.

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