Sub-GHz-resolution C-band Nyquist-filtering interleaver on a high-index-contrast photonic integrated circuit

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Abstract: Modern optical communications rely on high-resolution, high-bandwidth filtering to maximize the data-carrying capacity of fiber-optic networks. Such filtering typically requires high-speed, power-hungry digital processes in the electrical domain. Passive optical filters currently provide high bandwidths with low power consumption, but at the expense of resolution. Here, we present a passive filter chip that functions as an optical Nyquist-filtering interleaver featuring sub-GHz resolution and a near-rectangular passband with 8% roll-off. This performance is highly promising for high-spectral-efficiency Nyquist wavelength division multiplexed (N-WDM) optical super-channels. The chip provides a simple two-ring-resonator-assisted Mach-Zehnder interferometer, which has a sub-cm² footprint owing to the high-index-contrast Si₃N₄/SiO₂ waveguide, while manifests low wavelength-dependency enabling C-band (> 4 THz) coverage with more than 160 effective free spectral ranges of 25 GHz. This device is anticipated to be a critical building block for spectrally-efficient, chip-scale transceivers and ROADMs for N-WDM super-channels in next-generation optical communication networks.

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References and links

7. K. Sone, X. Wang, S. Oda, G. Nakagawa, Y. Aoki, I. Kim, P. Palacharla, T. Hoshida, M. Sekiya, and J. C. Rasmussen, “First demonstration of hitless spectrum defragmentation using real-time coherent receivers in...
1. Introduction

The constant growth in demand for high data-rate telecom services, coupled with the need for an increasingly flexible and versatile network, poses imminent challenges for next-generation...
optical fiber networks. These networks must be not only support large capacity transmission [1, 2], but also allow for flexible bandwidth resource management [3–7]. These requirements are often seen to be conflicting. In order to maximize the achievable data rate, optical super-channel transmission systems have been developed to fully utilize the available transmission bandwidth, by minimizing the unoccupied spectrum (i.e. guard-bands) between channels [2, 8–10]. The use of super-channels enables extremely high data carrying capacity in standard single-mode fibers (e.g. [1]). However, super-channels provide difficulties for flexible operation of optical networks. In fiber optic networks, the provisioning of data carrying capacity is often done through assigning wavelength channels. The resolution—which we define here as the 10%-90% roll-off—of currently deployed wavelength routing devices is, however, limited to ~10-GHz [11]. Such systems require guard-bands between wavelength channels, reserving spectrum that could otherwise be used to carry data. Therefore, to take full advantage of spectrally efficient super-channels in next-generation fiber networks, the development of sharper optical filters is required.

High performance filtering is also generally a key step in generating optical super-channels. In the digital domain, the required filters demand a high sampling rate to enable high bandwidth operation, and large number of filter taps to allow for high spectral resolution. As such, digital processing for optical super-channels is often power hungry and has a high computational overhead, which increases latency in communication systems. This has led to the investigation of hybrid electro-photonic systems for signal processing, off-loading some signal processing or filtering functions onto high-bandwidth photonic sub-systems. Transmitter [12–14] and receiver [15] systems have been demonstrated with operating bandwidths far in excess of those achievable with electronic-only methods. 'Nyquist' pulses with rectangular spectra have also gained interest [16, 17], focusing on applications to optical super-channel generation using Nyquist wavelength division multiplexing (N-WDM). N-WDM is a very promising candidate for implementing super-channel multiplexing [9, 18–20]. With N-WDM, channels are generally formed by passing a modulated signal through a rectangular-shaped filter for pulse shaping—a Nyquist filter. These Nyquist filters have typically very sharp frequency roll-off and a bandwidth matching the baud rate of the signal [2, 9, 18, 21]. The width of the filter necessarily requires high bandwidth processing, while the sharp roll-off requires a long response time for the filter. Although high bandwidth Nyquist filters can be produced using optical processes, it is often difficult to produce the long impulse responses needed to obtain the high spectral resolution desired for optical Nyquist filters. Breaking this resolution limitation while retaining high bandwidth operation would significantly expand the range of applications for photonic sub-systems.

Advances in photonic integration technology not only promise a path to mass production of photonic components for optical communications, but have also enabled improvements in the resolution and variety of optical filters (e.g. [22–29]). While effort is still needed to reach industrial maturity, photonic integration technologies have significantly improved over the past decade [30–36]. As a waveguide platform, direct-bandgap materials, e.g. indium phosphide, provide excellent properties for active functions [32]. However, silicon-based materials are compatible with CMOS fabrication equipment, which is seen as key to low-cost production, particularly for large-volume scenarios. For passive functions on silicon-based materials, high-index-contrast silicon-on-insulator and low-index-contrast silica waveguides are known to be able to offer desirable device compactness and performance, respectively—but not vice versa [22, 23, 25, 26, 30]. This tradeoff may limit further improvements to passive device performance on these platforms, particularly for optical filters where long impulse responses are required. Alternatively, high-index-contrast silicon nitride (Si3N4/SiO2) waveguides have shown both low loss and high device compactness simultaneously [37]. These waveguides also support device parameter tuning [24, 37, 38] (including post-fabrication circuit topology reconfigurability [39]) and hybrid integration with devices of other platforms [40–42]. These features are promising for improved passive functions, including optical filters.
In addition to integration platform considerations, the design methodology for chip-based filters can be modified to allow for performance improvements. Many chip-based passive optical filter architectures, e.g. arrayed waveguide gratings, implement moving-average (MA) filters [43], a class that is characterized by a finite-impulse response (FIR). MA filters use only feed-forward paths, requiring multiple optical delays to implement a filter circuit, with each delay tuned to keep the relative optical phase constant. Moreover, for these filters the required delay difference between the shortest and longest paths to ensure sharp roll-off can be one or two orders of magnitude different between (a 250 times difference in [22], 52 times in [23]). The large number of delays and phase tuning elements increases circuit complexity, loss, power consumption, crosstalk, and renders the circuit prone to failure due to limits in fabrication tolerance. This intrinsic trade-off between performance and complexity poses barriers to practical implementation of MA-type filters for use in N-WDM systems.

The performance-complexity trade-off can be broken by moving to designs based on autoregressive moving-average (ARMA) architectures, where feed-back paths are used to generate a large number of delays without requiring a large number of separate delay lines. Filter designs based on ARMA architectures can be implemented on-chip by incorporating ring-resonators to provide feedback, and can often be modeled as infinite-impulse response (IIR) filters [43]. The rings effectively provide a large number of different delays from the one component, reducing overall circuit complexity while maintaining high performance. ARMA designs have been previously used to provide optical filtering (e.g [44, 45]); however the fabrication processes used were not able to provide the performance desired for N-WDM systems, which is particularly challenging when delay lengths on the order of centimeters are required, which seems to limit pass bands around 100-GHz wide [44, 45]. Fine-grained ARMA filters for applications in microwave photonics have been shown, with a focus on providing a single filter [46]. We note that high performance optical filtering has also been shown using nonlinear processes, which tends to increase device complexity or power consumption to extreme levels [47, 48].

In this work, we present an on-chip Nyquist-filtering interleaver, achieving high performance with a significantly simplified circuit design. The circuit uses an ARMA architecture, implemented as a two-ring-resonator-assisted Mach-Zehnder interferometer (2RAMZI). This implementation shows a sub-cm² device footprint owing to the high-index-contrast Si₃N₄/SiO₂ waveguide, while manifests low wavelength-dependency enabling operation over the full C-band with sub-GHz frequency resolution. We show that our device is able to perform 12.5-GHz passband Nyquist filtering with a transition band sharpness equivalent to an 8% roll-off digital root-raised cosine (RRC) filter. The device covers over 160 times 25-GHz-wide free spectral ranges, with −25-dB adjacent channel extinction ratios measured over 4 THz. Further, we show that the Nyquist filtering function provided by our chip closely mimics an equivalent digital RRC filter when used for transmitter side pulse shaping, with only 0.1-dB penalty measured. Moreover, we use the 2RAMZI interleaver as part of a wavelength selective switch (WSS), demonstrating switching of 12.5-GHz N-WDM channels out of a super-channel, with add and drop functions showing < 1-dB penalty. These results show new possibilities for chip-scale realization of high-spectral efficiency N-WDM transceivers and ROADMs needed for next-generation, high-speed, elastic optical communication networks.

2. Device description

Figure 1(a) depicts a schematic of the Nyquist-filtering interleaver circuit. It comprises a 2RAMZI, which is a 2 × 2 asymmetric Mach-Zehnder interferometer (MZI) with two ring resonators coupled to each of its arms. The ring resonators have an optical roundtrip path twice as long as the path difference between the MZI arms ΔL, and the corresponding time delay determines the free spectral range (FSR) of the circuit [43]. Mach-Zehnder (MZ) couplers are used throughout the circuit, allowing phase and coupling control with 7 chromium resistor-based heaters. Figures 1(b) and 1(c) show the circuit mask layout and a photograph of a demonstrator chip, respectively. The chip is fabricated in a commercial high-
index-contrast Si$_3$N$_4$/SiO$_2$ waveguide technology platform (TriPleX [24, 33, 37], see Appendix). The waveguide circuit is designed with a FSR of 25 GHz and a chip footprint area of $1 \times 0.4$ cm$^2$. The chip operates with end-face coupling, optimized for TE-polarization. Using fiber coupling, the total insertion loss of the chip measures to be about 9 dB, which is dominated by the coupling losses of about 4 dB/facet. However, a recent work has shown that the coupling loss between Si$_3$N$_4$/SiO$_2$ waveguide and waveguides in other materials can be lowered to less than 1 dB/facet when using a proper waveguide facet design [42].

Figure 1(d) depicts the measured passband power response and dispersion, showing a good agreement with theory (see Appendix). The near-rectangular passband is characterized by a flat top, a $-3$-dB bandwidth of 12.5 GHz, and a $-25$-dB bandwidth of 13.5 GHz. In terms of Nyquist multiplexing, this means a $-25$-dB inter-channel isolation at 8% of the Nyquist frequency. In terms of the 10%-90% ($-0.5$ to $-10$-dB) resolution figure used by [22], we observe close to 0.5-GHz resolution. Figure 1(e) depicts the measured bar- and cross-port power responses with excellent passband repeatability and frequency periodicity, showing no significant differences between their passbands. This is a result of good waveguide uniformity and low wavelength dependency of the material properties. Figure 1(f) depicts a passband measurement from 191.5 THz to 196 THz, showing the full C-band coverage of the device. The power fluctuation over the measured passbands is an artifact of the measurement method.
(see Appendix). The device operates with a passband-stopband extinction of 25 dB throughout a bandwidth of over 4 THz, equivalent to more than 160 FSRs of 25 GHz. The device features low wavelength-dependency, giving a FSR deviation about 0.02% over a span of 10 FSRs, equivalent to a passband central frequency deviation about 0.1% of the FSR (see Appendix). These results prove the viability of creating high-performance optical processing functions on chip with compact circuits.

3. Nyquist-filtering and multiplexing for N-WDM transmitters

Using the demonstrator chip as a Nyquist-filtering interleaver, we experimentally demonstrated all-optical Nyquist filtering and multiplexing for N-WDM transmitters. There are two major approaches for generating optical signals over a broad bandwidth, i.e. by using phase-locked or independent optical carriers. In standard dense wavelength division multiplexed (DWDM) systems, uncorrelated optical carriers (e.g from independent lasers) are separately modulated, which provides sinc-like spectra around each laser line. In this system, the 2RAMZI can allow the aggregation of signals from independent transceivers into a Nyquist-spaced super-channel. In addition to this, phase-locked frequency combs have been show by several groups to provide a novel method to generate broad bandwidth all-optical orthogonal frequency division multiplexed signals (e.g [49, 50]). These frequency combs provide a ‘white’ spectrum when modulated [51]. Here, the 2RAMZI may be effectively used to combine outputs from several modulators on single transceiver chip, fed by a mode-locked laser. The Nyquist-filtering interleaver circuit is shown here to enable Nyquist-spaced super-channels from signals generated by either method.

The two corresponding experimental setups are depicted in Figs. 2(a) and 2(b) respectively, both generating Nyquist-spaced super-channels comprising seven 12.5-Gbaud QPSK-modulated sub-bands, using two independent data streams for simplicity. As the interleaver chip is optimized to operate in a single polarization, polarization management was performed throughout the setup to guarantee a uniform, single polarization state for all sub-bands. Figures 2(c) and 2(e) depict the spectra of a single sub-band based on the two different light sources. Note that, because the modulated spectrum is wider than twice the sub-band bandwidth, the spectrum of the \( n \)th channel overlaps with the \( n+/-2 \) channels of the interleaver, which results in strong inter-sub-band crosstalk for super-channel generation. This issue can be avoided by pre-filtering the odd and even channels before combining them at the interleaver, e.g. using two conventional WDM multiplexers or WSSs to restrict the per-channel spectrum within the bandwidth of two times the baud rate [52]. Comparing Figs. 2(c) and 2(e), the frequency comb-based approach results in sub-bands with flattened tops, unlike the CW laser-based approach. As such, the comb-based approach provides a closer approximation to ideal Nyquist channels and is therefore expected to offer better system performance. Figures 2(d) and 2(f) depict the measured spectra of 7-sub-band Nyquist-spaced super-channels generated as illustrated in Figs. 2(a) and 2(b), respectively. For the sake of simplicity, in the CW-laser case, we implemented the spectrum-restricting pre-filtering in the digital domain before modulation, while in the frequency-comb case, the pre-filtering was skipped, as the white spectrum intrinsically provides the desired two-data-stream interleaved super-channel.
We performed back-to-back (B2B) transmission experiments to verify the performance of the signals depicted in Figs. 2(c)-2(f). Figure 2(g) shows the measured signal quality factor ($Q$) versus optical signal-to-noise ratio (OSNR) for the case of single sub-band transmission. Figure 2(h) is for the case of 7-sub-band super-channel transmission, with the center sub-band being received. To compare with traditional electrical-domain Nyquist-filtering methods, we separately generated a CW laser-based super-channel with the sub-bands defined before modulation, using a digital RRC filter with a roll-off factor of 0.08 and electrical pre-emphasis to flatten the spectrum. For all signal generation schemes, the digital receiver used a single-polarization constant modulus algorithm to converge to a matched filter solution [53], followed by differential Viterbi-Viterbi frequency offset estimation and Viterbi-Viterbi phase estimation algorithms to recover the signals [54]. In Figs. 2(g) and 2(h), the measured $Q$ values of the optical approaches show good agreement with their digital counterparts, having an OSNR penalty difference of $< 0.1$ dB at $Q = 8.53$ dB—the error-free threshold for common 7% hard-decision forward-error-correction codes (7% FEC). This means that optical Nyquist-filtering using 2RAMZI is able to provide comparable performance to digital RRC filtering with a roll-off factor of 0.08. Figure 2(g) also shows a 7% FEC-threshold OSNR penalty of 0.5 dB, compared to the unfiltered QPSK transmission. This penalty is attributed to the passband dispersion (as shown in Fig. 1(d)) introducing inter-symbol interference.
2(h), the two optical approaches show similar performance. Penalties due to the unflattened sub-band spectral shape of the CW laser-based approach are only noticeable for OSNR > 15 dB. Compared with the single sub-band case in Fig. 2(g), the super-channels in Fig. 2(h) have an extra OSNR penalty of < 1 dB at the 7% FEC threshold, due to crosstalk between the sub-bands. A further reduction of the crosstalk will require an interleaver passband shape with sharper transitions (< 8%) and stronger out-of-band suppression (> −25-dB). Some recent studies have shown the possibility for achieving these performance improvements in such a device [45, 55]. The results above verify that the Nyquist-filtering and multiplexing functions of the interleaver chip are viable replacements for the conventional implementations, and the successful generation of Nyquist-spacing super-channels shows the feasibility of our all-optical approaches for practical applications in N-WDM systems.

4. Sub-GHz-resolution WSS for N-WDM super-channels

Further, we demonstrate that by using our interleaver chip as a fine-resolution pre-filter preceding a commercial WSS, an enhanced WSS (EWSS) with sub-GHz resolution can be created. This then enables add/drop multiplexing of sub-bands within an N-WDM super-channel. As illustrated in Fig. 3(a), due to the slow roll-off of the conventional WSS, dropping one sub-band from a super-channel causes severe inter-sub-band interference; however, with the interleaver preceding the WSS, the even and odd sub-bands will be first deinterleaved and can then be selectively dropped without such a problem.

![Diagrams](image)

Fig. 3. (a) Concept of sub-GHz-resolution N-WDM demultiplexing. (b) Experiment setup for demonstrating key N-WDM ROADM functionality, including the EWSS (AWG: Arbitrary waveform generator, CMZM: complex I/Q modulator, OBF: optical band-pass filter, LO: local oscillator, DSP: digital signal processing). Insets (i-v) correspond to signal spectra at different points within the EWSS.
In addition to this ‘drop’ functionality, the experiment also includes the emulation of an ‘add’ operation, in order to fully demonstrate the viability of simultaneous, reconfigurable ‘add’ and ‘drop’ functions in a ROADM architecture using our EWSS. After the drop operation, a replacement sub-band can then be added back with the ‘continue’ stream by means of passive coupling, where the added sub-band is obtained by filtering and is polarization-aligned with the ‘continue’ stream.

Figure 3(b) depicts the experiment setup. Here, the input optical signal to the EWSS is a CW laser-based Nyquist-spaced super-channel comprising 14 × 12.5-Gband sub-bands on a 12.5-GHz grid over a bandwidth of 175 GHz (with the left-most sub-band, ‘S1’, at 193.0125 THz). The sub-bands are generated with a two-stream-interleaving pattern using a serrodyne frequency-shifter [56] from 7 CW lasers, where Nyquist filtering is implemented using digital RRC filtering with a roll-off factor of 0.08 and electrical pre-emphasis in order to provide a sub-band spectral shape similar to the optically generated one (see Fig. 2(f)). Figure 3(b) also shows the measured optical signal spectra at different positions within the EWSS, when the sub-band at 193.1 THz is dropped. After the EWSS, the remaining odd and even sub-bands are de-correlated, polarization-aligned, and recombined into the ‘continue’ stream of the EWSS (point (v) in Fig. 3(b)). A differential delay of close to 10 ns is used for the de-correlation, which emulates a worst-case scenario where each sub-band experiences the maximum degradation from crosstalk.

Figure 4(a) shows system performance with all sub-bands set to ‘continue’. Signal $Q$ versus OSNR of three neighboring sub-bands is plotted with and without the EWSS included. Without the EWSS and noise loading, all three sub-bands show a $Q\approx16$ dB, which is limited by the inter-sub-band crosstalk. When the EWSS is included, the three sub-bands show an OSNR penalty < 0.5 dB at the 7% FEC threshold compared to the case without EWSS. This penalty is due to splitting and re-combining the odd and even sub-bands. Figure 4(b) shows system performance when the EWSS is set to drop 1 or 2 sub-bands.

The performance for the dropped (‘S8’ at 193.1 THz and ‘S7’ at 193.0875 THz) and neighboring ‘continue’ sub-bands (‘S9’ at 193.1125 THz and ‘S6’ at 193.075 THz) is plotted.
against OSNR. The dropped and continued sub-bands have similar performance at the 7% FEC threshold, showing a required OSNR variation < 0.5 dB. Figure 4(c) shows the band-to-band performance comparison at a fixed OSNR of 11.5 dB. Here, similar $Q$s are observed, with a $Q$ variation of 0.7 dB for the case without the EWSS, and 1 dB for the case with the EWSS included and set to ‘continue’ for all sub-bands. Figure 4(d) demonstrates that the EWSS can demultiplex each of the 14 sub-bands to a drop port, where the band-to-band performance variation is only 0.7 dB for a fixed OSNR of 11.5 dB. Figure 4(e) shows the potential for simultaneous ‘add’ and ‘drop’ functions in the system. The constellations and extracted $Q$ values of the dropped, the passively added, and the nearest-neighbor ‘continue’ sub-bands are shown. In this result, there is no additional noise loading, and the $Q$ of the ‘continue’ and passive ‘add’ sub-bands are within 0.5 dB of 15.4 dB, with the ‘drop’ sub-band at 17 dB. This shows that the ‘continue’ and passive ‘add’ sub-bands all experience similar cross-talk. The ‘drop’ sub-band is isolated from the super-channel before combination, so is not distorted by inter-channel interference, as seen in its higher $Q$. The results in Fig. 4 show the feasibility of the desired ‘drop’ and ‘add’ functions using the proposed EWSS, and so prove the potential of the interleaver chip for enabling key ROADM technologies for N-WDM super-channels.

5. Discussion and conclusion

The demonstrator interleaver chip in this work operates with a WDM grid of 12.5 GHz. This can be changed in the circuit FSR design according to the bandwidth arrangement requirements of different applications. For the circuit design, additional ring resonators can be used in the RAMZI circuit to further improve the passband shape [45, 54]. However, the use of ring resonators means that the circuit introduces dispersion to the signal [43]. Previously, this has been considered as a road-block to the use of such filter designs in optical communication systems. However, with the advent of digital dispersion compensation, this dispersion has little effect on the system performance, as observed in our experiments. Notably, the low circuit complexity of RAMZIs will benefit system construction greatly in terms of device yield, implementation of control and power efficiency compared to common MA filter designs. Like many other applications of photonic integrated circuits, chip temperature stabilization is required during operation to guarantee the accuracy of circuit parameters. Depending on the used waveguide technologies, electro-optical tuning elements could be used to replace the thermo-optical ones [38], which will bring clear benefits for the power consumption and compactness of the associated temperature control system. Further, a polarization-diverse design would allow dual-polarization operation. Regarding photonic integration, chip-level integration of RAMZI circuits and electro-optics such as lasers, modulators and photodetectors will be highly promising for the development of N-WDM transceivers in terms of device compactness and packaging cost. For the realization of this, both monolithic integration and chip-to-chip micro-assembly technologies have shown clear potential in their current status of progress [31, 32, 40–42].

In conclusion, we have reported a compact optical Nyquist-filtering interleaver in high-index-contrast Si$_3$N$_4$ waveguide. The device features sub-GHz resolution, a near-rectangular passband with 8% transition band, and full C-band coverage with more than 160 effective free spectral ranges of 25 GHz across a bandwidth over 4 THz. In terms of system performance, the small penalties measured (0.1 dB in generation and < 1 dB in the EWSS) show that RAMZI devices provide a promising platform for optical filtering in N-WDM systems. By combining high-performance optical Nyquist-filtering and interleaving functions, we anticipate that the reported device will open a new path towards compact, high-spectral-efficiency MUX and DEMUX devices for N-WDM transceiver and ROADM technologies that will play a key role in the next-generation, high-speed elastic networks.
Appendix

Demonstrator chip

The demonstrator chip described in this paper was fabricated using a Si$_3$N$_4$/SiO$_2$ waveguide technology (TriPleX, proprietary to LioniX B.V., The Netherlands) using a CMOS-equipment-compatible process. This waveguide platform allows modification of the waveguide dispersion and polarization properties by changing the cross-section. The waveguides can be optimized to provide extremely low losses, around 0.1 dB/cm at C-band wavelengths [24, 37]. The chip in this work uses “two-strip-geometry” design of the TriPleX waveguide [37]. The two Si$_3$N$_4$ strips, each having a width of 1.5 μm and a layer thickness of 170 μm, are vertically stapled with a 500-nm thick SiO$_2$ intermediate layer between them. A waveguide bend radius of 125 μm was used, resulting in a chip footprint of 1 × 0.4 cm$^2$. A smaller footprint may be achieved by further reducing the bend radius; however, this will incur a higher chip insertion loss [37]. The waveguide group index and its wavelength-dependency are about 1.72 and 2 × 10$^{-5}$/nm, respectively, in the C band. In the chip, the ring resonators and the MZI inter-arm delay line are designed to be 1.4 cm and 0.7 cm, respectively, resulting in an interleaver FSR of 25 GHz with a FSR deviation less than 0.02% over a span of 10 FSRs. The employed Mach-Zehnder couplers have a length of 3450 μm (including a heater section of 2100 μm and two 3-dB directional couplers of 675 μm).

Tapered waveguide facets can be provided to reduce coupling loss to lower than 1 dB/facet [40]. Thermo-optical tuning elements were implemented using chromium heaters and gold leads, with an average power consumption of about 150 mW/heater and a tuning speed in the order of milliseconds. A recent study has shown implementation of power-efficient stress-optical tuning elements on the TriPleX platform, which reduce the power consumption by multiple orders of magnitude and reduce the tuning speed to the order of microseconds [38].

Interleaver transfer function

The transfer matrix of 2RAMZI, $H$, can be given in z-transform [43]:

$$H = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix}$$

$$= \eta \begin{bmatrix} \sqrt{1 - \kappa_R} & -j\sqrt{\kappa_L} \\ -j\sqrt{\kappa_R} & \sqrt{1 - \kappa_R} \end{bmatrix} \begin{bmatrix} A_1(z) & 0 \\ 0 & A_1(z) \end{bmatrix} \begin{bmatrix} \sqrt{1 - \kappa_L} & -j\sqrt{\kappa_L} \\ -j\sqrt{\kappa_L} & \sqrt{1 - \kappa_L} \end{bmatrix}$$

$$A_1(z) = \frac{\sqrt{1 - \kappa_L} - t^2 z^2 e^{j\phi}}{1 - \sqrt{1 - \kappa_L} t^2 z^2 e^{j\phi}}$$

and

$$A_1(z) = \frac{\sqrt{1 - \kappa_L} - t^2 z^2 e^{j\phi}}{1 - \sqrt{1 - \kappa_L} t^2 z^2 e^{j\phi}}$$

where $z = \exp(-j\nu)$ with $\nu = [-\pi, \pi]$ representing the angular frequency normalized to the free spectral range (FSR) of the device ($\Delta f_{FSR} = 1/\Delta T = c/(\Delta L n_g)$ with $\Delta T$ the delay time for an optical path of $\Delta L$, $c$ the vacuum speed of light and $n_g$ group index of the waveguide); $t$ is the amplitude transmission coefficient for an optical path of $\Delta L$ (determined by the waveguide loss); $\eta$ is a complex coefficient which accounts for the general insertion loss and phase shift introduced by the MZI; parameters $\kappa$ and $\phi$ express the power coupling coefficient of the MZ coupler and phase shift, which are controlled via the heaters on our demonstrator chip. In terms of signal processing, the parameters in Table 1 configure the chip to be an infinite
impulse response system that has its frequency responses $H_{mn}$ ($m, n = [1, 2]$) synthesizing a 5th-order Chebyshev Type II filter [43]. The filter characteristic is determined by 4 poles and 5 zeros, featuring flat passband, equal-ripple stopband, and sharp transition. The interleaver function as shown in Fig. 2(d) owes to the filter feature that the passband-stopband bandwidth ratio is close to 1 within a FSR.

<table>
<thead>
<tr>
<th>Circuit parameter</th>
<th>Definition:</th>
<th>Control heater:</th>
<th>Parameter value for interleaver function:</th>
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<tr>
<td>$\kappa_L$</td>
<td>Input coupler</td>
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<td>0.5</td>
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<tr>
<td>$\kappa_R$</td>
<td>Output coupler</td>
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<td>Ring resonator phase in the upper MZI arm</td>
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<td>$\kappa_2$</td>
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<td>$\phi_2$</td>
<td>Ring resonator phase in the lower MZI arm</td>
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<td>$\phi_D$</td>
<td>MZI lower arm phase</td>
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</table>

**Experiment setup**

The frequency response of the photonic chip was characterized by means of wideband noise spectrum measurement. The wideband noise source uses the amplified spontaneous emission of erbium-doped fiber amplifier. The spectrum measurement was performed using a high-resolution spectrometer (Agilent 83453). Due to the lack of a noise source with sufficient bandwidth, the C-band response in Fig. 1(f) was obtained by means of measuring the responses of multiple 80-GHz-wide sections separately. These measurements for Fig. 1(f) used a “white” spectrum was generated using 7 equal-spaced tunable CW lasers modulated at a symbol rate equal to their spacing as the test source input to the chip. Due to the laser power fluctuation at different frequencies and wavelength dependency of the modulator, the measured passbands exhibit power fluctuations across the C band, however, this did not affect the passband-stopband extinction measurement. The chip was temperature-stabilized using a dedicated Peltier element-based cooling system. Calibration and control of the tuning elements were conducted using multiple variable voltage supplies (HAMEG HM7042-5). The voltage-phase relation of the tuning elements was characterized using the dedicated test devices fabricated on the same wafer. The voltages applied for achieving the interleaver function were calculated using a custom-designed frequency-response simulation program. The CW lasers used in the experiments were narrow linewidth tunable lasers (AlnairLabs TLG-300M). The frequency comb was generated by overdriving a low-bias MZ modulator (Covega 20-GHz MZ modulator) and optical filtering (Finisar WaveShaper). The data generation and digital pre-filtering were implemented using a 65GSa/s arbitrary waveform generator (Keysight M8195A). Complex 20-GHz bandwidth MZ modulators (Sumitomo DQPSK modulator) were used for QPSK modulation and serrodyne operation. A coherent receiver (u2t CPRV1220A) was used for signal reception. Before coherent detection, the optical signal is amplified and optically filtered (40-GHz bandwidth using Finisar WaveShaper), and noise-loaded with amplified spontaneous emission from erbium-doped fiber amplifier. The receiver output is digitized with a real-time, 80 GSa/s, 33-GHz bandwidth oscilloscope (Agilent DSO-X 928041), and offline processed. The digital signal processing flow resamples to 2 Sa/symb, applies spectrum-based frequency offset compensation, then matched filtering. A constant-modulus algorithm based adaptive equalizer and a Viterbi-Viterbi phase estimator are used before bit-error rate calculation.

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