Electro-photonics: an emerging field for photonic integrated circuits

Leimeng Zhuang, Arthur J. Lowery

Leimeng Zhuang, Arthur J. Lowery, "Electro-photonics: an emerging field for photonic integrated circuits," Proc. SPIE 10536, Smart Photonic and Optoelectronic Integrated Circuits XX, 105361I (22 February 2018); doi: 10.1117/12.2289251

Event: SPIE OPTO, 2018, San Francisco, California, United States

Electro-Photonics: an emerging field for photonic integrated circuits

Leimeng Zhuang[a] and Arthur J. Lowery[a,b]
(*Invited*)
[a]Monash Electro-Photonics Laboratory, Dept. Electrical and Computer Systems Engineering, Monash University, Clayton, VIC3800, Australia; [b]ARC Centre of Excellency for Ultrahigh bandwidth Devices for Optical Systems (CUDOS), Monash University, Clayton, Australia.
leimeng.zhuang@monash.edu; arthur.lowery@monash.edu

ABSTRACT

Electro-Photonics combines the best of both electronics and optics to tackle the challenges of next generation optical communication networks in terms of capacity, flexibility, and energy efficiency. The optimal sharing of the processing work load between the electrical and optical domain brings considerable benefits to communication system complexity, performance, and construction as well as operational cost. As a key technology, photonic integrated circuits (PICs) play a critical role for the implementation of signal processing in the optical domain, serving for signal generation, switching, and acquisition. PICs point to advancing of network devices such as transmitters, receivers, and switches with desirable features of large bandwidth, high stability, precise control, easy tuning, and potential for low-cost fabrication by enabling miniaturization of complex optical systems on a chip scale. In this paper, we review the PIC research progress of the Monash Electro-Photonics Laboratory and its major contributions to the fields of optical communications and microwave photonics. We focus on applications in optical orthogonal frequency division multiplexing (O-OFDM), Nyquist wavelength division multiplexing (N-WDM), optical pulse manipulation, and programmable optical processors. The results of these works underline not only hardware fabrication capability and performance improvement for electro-photonics, but, more importantly, a new engineering paradigm that stimulates innovations in information and communication technologies.

Keywords: Photonic integrated circuits, integrated optics, optical signal processing, optical communications, microwave photonics, waveguide.

1. INTRODUCTION

The current focus of the *Electro-Photonics Laboratory* at Monash University, Australia, is to consider the best mix of optical and electronic technologies to produce optimal solutions for signal processing in optical communications and microwave photonics, introduced as electro-photonics. The motivation comes from two primary factors: one is the new challenges in terms of processing capacity, flexibility, and energy efficiency raised by the ever- and fast-increase demand on data traffic; the other is the fact that neither electronics or optics alone is sufficient to satisfy all the key functions and features that would be required by the applications in the next generation communication networks [1]. As far as the current technologies are concerned, the electronics is mature and supporting both analog and digital functions with easy access to memory, but hard to implement high data rates due to limited bandwidths; whereas optics provides a substantially larger processing bandwidth and higher energy efficiency, but inflexible and constrained to the real-time processing operations.

Figure 1 shows a conceptual framework for hybrid electronic-photonic signal processing and a diagram of general approach to allow processing tasks to be optimally shared by a combination of electronic and photonic processing. In this approach, photonic integrated circuits (PICs) [2–4] play an important role which miniaturize optical signal processing functions on the chip scale with very high stability and control precision. Such PIC implementations facilitate full integration of the optical signal processing functions, serving as embeddable modules with general practical features of small size, weight and power consumption, strong robustness and reliability, and potential for low-cost fabrication. Nowadays, the easy accessibility to a variety of waveguide materials [5] and functional building blocks [6] via the business model of generic foundry and multi-project-wafer run (e.g. www.jeppix.eu) have led to a strong surge of interest and effort worldwide in prototyping and developing PICs. This is because it enables fabless and cost-sensitive

Smart Photonic and Optoelectronic Integrated Circuits XX, edited by Sailing He, El-Hang Lee, Proc. of SPIE Vol. 10536, 105361I · © 2018 SPIE
CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2289251

units such as university research groups and small-, medium-sized enterprises to rapidly generate their own intellectual properties of PIC applications at affordable time and cost, instead of only relying on collaborations with large companies having exclusive fabrication capabilities. In addition, the constant improving of fabrication maturity is heading towards large-scale integration of thousands of functions with high performance, uniformity and repeatability [7].

The remainder of this paper gives a brief review of the recent works on PIC implementations of optical signal processors at Monash Electro-Photonics Laboratory within the concept of electro-photonics, some snapshots of which is shown in Fig. 2. Section II presents the implementations of optical Fourier transforms for O-OFDM. Section III shows the generation and reception of N-WDM signals. Section IV gives a number of examples of on-chip manipulations of optical short pulses serving for optical sampling. Section V describes the concept of programmable optical signal processors and their potential for applications. Section VI concludes this paper with our visions of future developments in this area.

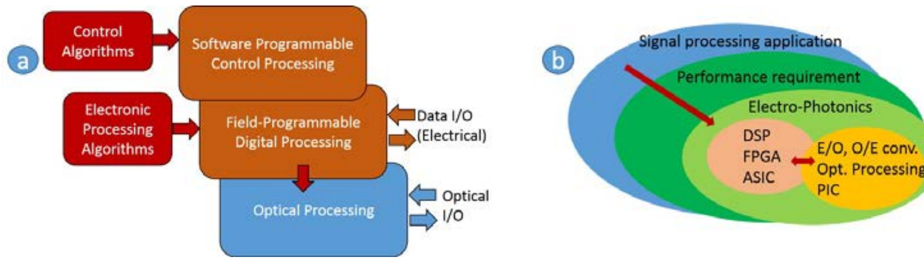

Figure 1. (a) Concept framework of electro-photonics. (b) General approach of hybrid electronics-photonics signal processing using PICs.

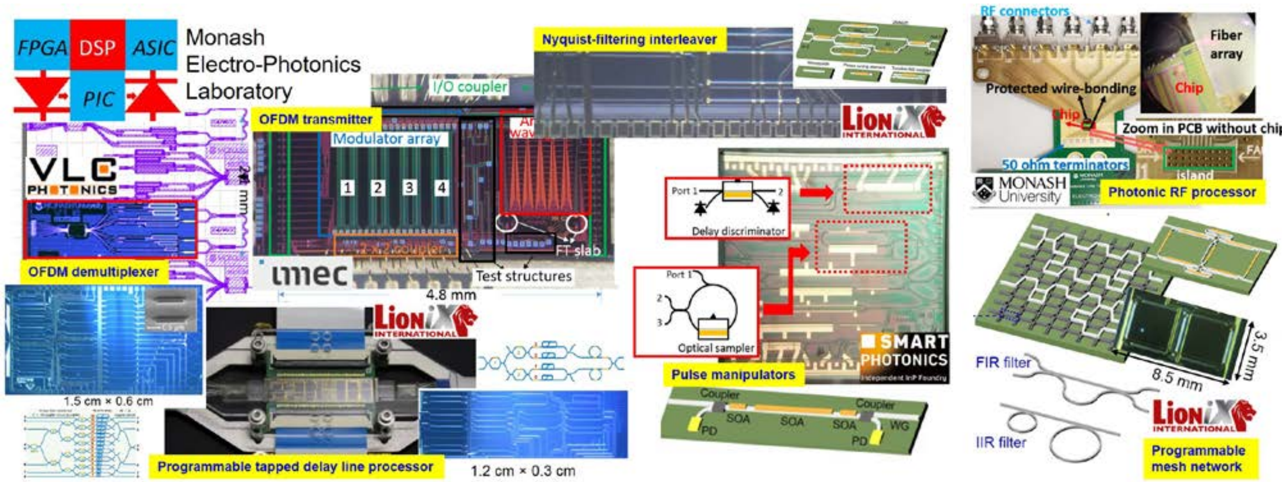

Figure 2. Snapshots of the optical signal processor PICs [15, 16, 19, 24, 26, 27, 31] designed and system-implemented by Monash Electro-Photonics Laboratory in the past few years via external foundry services.

2. OPTICAL OFDM

Telecommunication systems desire high spectral occupation rate in order to accommodate higher capacity within a defined transmission bandwidth. Pulse shaping at the transmitter is a common technique to limit the channel bandwidth and therewith minimize the interchannel crosstalks. Such technique is also applied at the receiver for noise shaping, e.g. matched filters. Electrical shaping at high baud rates requires fast digital signal processing (DSP) and digital to analog conversion (DAC), the implementation of which are typically expensive and power hungry. In contrast, optical shaping using PICs provide an effective path to overcome those issues, together with the practical features of integrated optics.

Optical OFDM transmitters [8] have sinc-shaped spectrum for each subcarrier and in principle allow inter-subcarrier spacing equal to the baud rate without being affected by the spectral overlaps. However, this makes it difficult to demultiplex a particular subcarrier without specially designed optical filters, and thus can be an obstacle to wavelength routing. According to the OFDM principles, the subcarrier shaping and (de)multiplexing are performed by means of the Fourier transform (FT). In terms of PIC implementations, one approach is to use a combination of couplers and delay lines. A number of demonstrations have been reported to prove the concept with the FT operation up to 8 points [9]. Although featuring high flexibility for circuit topology design, this approach has a tradeoff with the circuit and control complexity, as its number of couplers increases with the number of FT points, together with the risk in performance due to the increased number of waveguide crossings. An alternative approach is to use the arrayed waveguide grating router (AWGR) [10], which can be designed to be a close approximation of FT. As explained in ref. [10], an AWGR comprises of two 'free-space' coupling slabs connected together with an array of waveguides [11]. In this illustration, the first slab coupler plays the role of an optical splitter, the arrayed waveguides provides incremental delays, ΔT, for the parallel-to-serial conversion, and the second slab coupler performs the FT where the phase shift from input waveguide n to output m is designed approximately proportional to the product $n \times m$. These operations are equivalent to the discrete sum of phase-weighted samples in a FT. However, a good approximation of FT without any amplitude weighting/windowing requires the waveguide path losses across the whole device to be identical for any value of m, which in practice needs particular designs to compensate for two major effects: one is uneven output powers along the slab coupler outputs due to far-field beam pattern, the other is the loss difference between the arrayed waveguides.

An O-OFDM transmitter requires an inverse FT, which is simply the forward FT with the inputs and outputs swapped. A practical design is described in ref. [12], including an extra slab coupler at the input, which splits pulses from a mode-locked laser to a bank of modulators, and then feed an FT followed by a parallel-serial converter to produce a time domain waveform. An additional waveguide is used in the AWGR design to provide a cyclic extension to the output waveform [13]; in this case it is a cyclic post-fix as it has a greater delay then the original waveguides. The OFDM symbol rate (the data baud rate) should be decreased relative to the subcarrier spacing to accommodate the cyclic prefix. A practical OFDM receiver design is shown in ref. [12], where the AWGR is a reversed version with respect to the transmitter case, except that the modulators are replaced by samplers, and the outputs of the receivers must be fed into individual receivers [10]. If a CP has been added at the receiver, its waveguide must be left out of the receiver design. This means that the CP is discarded at the receiver, as in conventional OFDM designs.

For on-chip implementations [14], some designs use a binary-tree of 1×2 splitters instead of the slab coupler-based splitter to even out the waveguide powers, while performing FT with a slab coupler. Fig. 3(a) shows an O-OFDM demultiplexer design using silicon-on-insulator waveguides, developed by Monash University and VLC-Photonics (Spain), which has been demonstrated in a transmission system experiment [15]. An O-OFDM transmitter design is shown in Fig 3(b), together with the component characterizations [16]. This design is fabricated using IMEC iSIPP25G silicon platform enabling integration of modulators and an AWGR.

3. NYQUIST WDM

Nyquist-WDM has its WDM channels featuring Nyquist bandwidth, or equivalently a bandwidth equal to the baud rate. This feature means ultimate spectral efficiency which can be implemented by tightly filtering each WDM channel and then packing the channels with little or no guard band [17]. In this context, optical filtering can be used to perform wavelength routing. The channel filtering can be performed using optical filters. A good example using free-space optics is a high-resolution photonic processors based on an AWGR combined with a Liquid-Crystal on Silicon spatial light modulator [18]. For on-chip solutions, we have recently demonstrated N-WDM-like superchannel generation (filtering + multiplexing) and demultiplexing using a ring-assisted Mach-Zehnder interferometer (RAMZI) [19] as a Nyquist-filtering interleaver, where both data-modulated mode-locked laser pulses and CW wavelengths are used. The chip was fabricated using TriPleX Si_3N_4/SiO_2 waveguide [3]. Figure 4(a) shows the circuit schematic, chip photo, and filter shape. The use of ring resonators considerably reduced circuit and control complexity, compared to the tapped-delay-line topologies [4]. This is because ring resonators allows its optical loop path to be used multiple times to generate a large number of taps instead of each tap requiring an independent delay line. It is worth mentioning that our experiment shows successful operations on channel bandwidth of 12.5 GHz, a factor of 4 smaller than the standard 50-GHz DWDM grid, the concept of which is of great interest for high-granularity WDM for next generation elastic communication networks.

As another key point, such filters enables easy implementation of ROADMs for N-WDM superchannels. Commercial ROADMs do not have sufficiently sharp pass-to-stop-band transitions to support such functions [20]. To avoid spectral overlapping between the sub-bands in the superchannels, a common approach is to use wide guard-bands to reduce the inter-sub-band crosstalks, while sacrificing spectral efficiency. We have demonstrated that the resolution of a commercial ROADM can be improved by using a RAMZI interleaver as a pre-processor to split 'odd' and 'even' channels to separate ROADM inputs [21]. This approach enables add-drop functionality of zero-guard-band N-WDM channels using commercial wavelength-selective switches (WSS) that use LCoS technology [22]. In further investigations, we have extended such a RAMZI circuit with additional capabilities, i.e. multi-port multiplexing [23] and filtering with variable passband-stopband ratio (variable free spectral range/FSR) [24].

4. OPTICAL PULSE MANIPULATION

For high-capacity transmission systems, optical sampling is an important technique, such as O-OFDM and optical time division multiplexing (OTDM) [25]. It allows a data tributary to be reproduced without interference from other data tributaries (i.e. inter-carrier-interference in OFDM signals or inter-symbol-interference in OTDM signals). As a benefit, performing optical sampling lowers the required receiver electrical bandwidth. When without it, this bandwidth has to exceed the combined baud rate of many data tributaries. A general architectural design of an optical sampling receiver using active PIC is shown in ref. [26] (Chapter 14). This design comprises two major functions, i.e. a pulse timing discriminator for detecting the timing difference between two pulse sequences (e.g. OTDM signal and clock signal) and an optical mixer for temporally selecting the output signal in accordance to a clock signal/control pulse train. For on-chip implementation, we have demonstrated these two functions using semiconductor optical amplifier (SOA)-based circuits for proof of concept [27, 28].

A design of a pulse timing discriminator is explained in ref. [27], which uses a cascade of three SOAs in a dedicated indium phosphide (InP) circuit. We counter-propagate optical pulses within a SOA where the first pulse to enter the amplifier gets the most gain and the second pulse sees the depleted gain due to the first pulse. Thus, by measuring the relative intensities of the output pulse trains on a certain timescale, their relative timing can be determined. In our experiment, we showed the timing detection of GHz-rate optical pulses with kHz-rate electrical output. Our implementation of an optical mixer is explained in ref. [28], which uses an InP nonlinear optical loop mirror (NOLM) comprising a SOA incorporated in a Sagnac loop. In the NOLM, the SOA converts the intensity variation of a clock signal to phase variation of the input signal via nonlinear cross-phase effect; the clockwise-travelling and counter-clockwise-travelling signals receive different amount of phase variations in the Sagnac loop, depending on their interaction window time with the clock signal in the SOA. Eventually, by means of interference, the output coupler of the Sagnac loop translates this phase variation difference into an amplitude time gate that performs the sampling. Our experiment showed a sampling rate of 10 GHz. While this concept has been well discussed, the implementation on a very compact optical chip points out the possibility of integrating the entire optical sampler receiver as one device.

5. PROGRAMMABLE OPTICAL PROCESSOR

To date, a large number of signal processor chips have been reported on a variety of waveguide platforms [29]. A number of works utilizing the nonlinear optical properties such as stimulated Brillouin scattering and four-wave mixing [30], the on-chip implementations of which require particular waveguide materials. In contrast, on-chip processing using linear interferometric filters [6] features high transparency to different waveguide platforms and allows for easy implementation of on-chip control as well as integration of multiple functional building blocks to enable complex systems on a chip. The great design freedom of interferometric filters allow for synthesis of arbitrary amplitude and phase responses. In terms of impulse response characteristics, such filters can be divided into two kinds, i.e. finite impulse response (FIR) filters and infinite impulse response (IIR) filters. Their design process is interchangeable with that of digital filters, and therefore benefits greatly from the well-developed digital signal processing algorithms. For the on-chip implementation, FIR and IIR filters are typically constructed using tapped delay line and ring resonator topologies, respectively, with both kinds comprising a combination of couplers and delay lines. This implies that when a circuit comprises a 2-dimensional lattice mesh network of basic building blocks and each basic building block can be varied to perform either a coupler or a delay line, one can then in principle implement multiple and arbitrary FIR and IIR filter topologies by simply programming those basic building blocks, assuming that the lattice mesh network has a sufficient size. Moreover, when those basic building blocks also allows for amplitude and phase control, one can implement variations of filter shape and frequency.

A conceptual design and an experimental demonstration of such a mesh network has been reported in ref. [31], where the square lattice is used for the mesh geometry. The basic building block comprises a Mach-Zehnder interferometer (MZI) coupler whose coupling coefficient and overall phase shift can in principle change in the range from 0 to 1 and from 0 to 2π, respectively, by controlling the phase shifts on both arms [3]. This tuning mechanism of the MZI coupler facilitates the full programmability of the lattice mesh network. The proof-of-concept device comprises a 2×1 mesh network fabricated in a TriPleX Si_3N_4/SiO_2 waveguide and using electrical resistor-based heaters as phase tuning elements [3]. The experimental verification shows the programmablility of four different functions (not limited), i.e. a one-coupler ring resonator, a two-coupler ring resonator, a serial cascade of two independent ring resonators, or a pair of mutually-coupled ring resonators. In a further study of the mesh geometry [32], Pérez et al. made a thorough comparison between the triangular, square, and hexagonal lattices, and found that the hexagonal mesh is the most suitable option for implementation in terms of circuit complexity and fabrication challenges although the square mesh offers highest routing flexibility of optical paths. To inspire further advance, we recently published a review article on this topic covering the design principle, worldwide development, and potential applications of such processors chips [29]. Alongside, a collaboration between Polytechnic University of Valencia and University of Southampton has led to a successful demonstration of a silicon processor chip comprising six hexagonal mesh cells and its programmability for a multitude of signal processing and switching functions [33, 34].

6. CONCLUSION

Electro-photonics benefits from considering optimal mix of electronic and photonic technologies to address new challenges in generating, processing and receiving high-capacity communications systems. PICs are a key technology for implementing optical signal processing functions with practical device features that are important for commercial adoption. As examples for promising applications, we have discussed on-chip optical processing using AWGR-based circuits for O-OFDM and RAMZI circuits for N-WDM. The demonstrated functions cover channel spectrum filtering/shaping, superchannel multiplexing and demultiplexing. These demonstrations show the advantage of optical signal processing with extremely wide bandwidths and low power consumption. A perceived limitation is the filtering resolution; however, this can be mitigated by increasing baud rates of modulators. In fact, our works addressed superchannel transmission systems with sub-band grids in the order of 10 GHz, which is of high interest for enabling next generation high-grannularity elastic communication networks. We also showed proof-of-concept devices for on-chip optical pulse manipulation, i.e. a delay/timing discriminator and an optical mixer, both working with pulse rates in the order of 10 GHz. These functions point a path towards a fully integrated optical sampler receiver which is very useful for OTDM and O-OFDM systems.

Furthermore, we introduced the concept of programmable optical processor chips. These are meant to break the chip design paradigm of one particular function per chip, and instead, enable implementations of many different functions on the same chip via software programming. Following a similar path to microelectronics, this concept provides an effective way to significantly reduce the cost and time of developing PICs and increase the potential applications as well as the pace of fabrication optimization of a chip design. Driven by the need of miniaturizing optical subsystems, PIC foundries worldwide have been in constant growing in terms of scale and maturity, making great effort to enable technologies for commercial pluggable optical modules with bright future for a thriving industry.

REFERENCES

[1] Gerstal, O., Jino, M., Lord, A., Yoo, S. J. B., “Elastic optical networking: a new design dawn for the optical layer?,” IEEE Communication Magazine, P. S12 (2012).

[2] Smit, M., van der Tol, J. & Hill, M., “Moore’s law in photonics,” Laser & Photo. Rev. 6, 1-13 (2012).

[3] Roeloffzen, C. G. H., Zhuang, L., Taddei, C., Leinse, A., Heideman, R. G., van Dijk, P. W. L., Oldenbeuving, R. M., Marpaung, D. A. I., Burla, M. and Boller, K.-J., “Silicon Nitride microwave photonic circuits,” Opt. Express, 21(19), 22937-22961 (2013).

[4] Goh, T., Itoh, M., Yamazaki, H., Saida, T., and Hashimoto, T., “Optical Nyquist-filtering multi/demultiplexer with PLC for 1-Tb/s class super-channel transceiver,” Proc. OFC2015, LA, USA, Tu3A.5 (2015).

[5] Bower, J. E., “Evolution of photonic integrated circuits,” 75th Annual Device Research Conference, South Bend, (2015).

[6] Madsen, C. K. & Zhao, J. H. Optical filter design and analysis: a signal processing approach, Wiley, NY, (1999).

[7] Heck, M. J. R., “Hybrid and heterogeneous photonic integrated circuits for high-performance applications,” SPIE OPTO, Proc. 9365, Integrated Optics: Devices, Materials, and Technologies XIX; 936503 (2015).

[8] Lowery, A. J., and Armstrong J., "Orthogonal frequency division multiplexing for dispersion compensation of long-haul optical systems," Opt. Express 14, 2079-2084 (2006).

[9] Takiguchi, K., Oguma, M., Takahashi, H., and Mori, A., "PLC-based eight-channel OFDM demultiplexer and its demonstration with 160 Gbit/s signal reception," in Optical Fiber Communications (OFC), San Diego, OThB4 (2010).

[10] A. J. Lowery, "Design of arrayed-waveguide grating routers for use as optical OFDM demultiplexers," Opt. Express 18, 14129-14143 (2010).

[11] Dragone, C., "An N*N optical multiplexer using a planar arrangement of two star couplers," IEEE Photon. Technol. Letts. 3, 812-815 (1991).

[12] Lowery, A. J., Zhuang, L., Corcoran, B., Zhu, C., and Xie, Y., “Photonic circuit topologies for optical OFDM and Nyquist WDM,” J. Lightwave Technol. 35, 781-791 (2017).

[13] Lowery, A. J., "Inserting a cyclic prefix using arrayed-waveguide grating routers in all-optical OFDM transmitters," Opt. Express 20, 9742-9754 (2012).

[14] Takiguchi, K., Kitoh, T., Mori, A., Oguma, M., and Takahashi, H., "Integrated-optic OFDM demultiplexer using slab star coupler-based optical DFT circuit," in European Conf. on Opt. Commun (ECOC), Torino, Postdeadline 1-4 (2010).

[15] Zhuang, L., Zhu, C., Corcoran, B., and Lowery, A. J., "All-optical coherent OFDM transmission of 8x40 Gb/s using and on-chip AWGR-FT 1x8 decoder circuit," in Optical Fiber Communications (OFC), LA, USA, W3C.2 (2015).

[16] Xie, Y., Zhuang, L., Broek, R., Wang, Q., Song, B., Geng, Z., and Lowery, A. J., “Compact 4×5 Gb/s silicon-on-insulator OFDM transmitter,” Optical Fiber Communication Conference, LA, USA, W2A.9 (2017).

[17] Curri, V., Carena, A., Bosco, G., Poggiolini, P., and Forghieri, F., "Optimization of DSP-based Nyquist-WDM PM-16QAM transmitter," in European Conf. on Opt. Commun. (ECOC), Amsterdam, Tu.4.A.5 (2012).

[18] Rudnick, R., Tolmachev, A., Sinefeld, D., Golani, O., Ben Ezra, S., Nazarathy, M., et al., "Sub-banded/single-sub-carrier drop-demux and flexible spectral shaping with a fine resolution photonic processor," in European Conf. on Opt. Commun (ECOC), ed. Cannes, France, PD4.1 (2014).

[19] Zhuang, L., Zhu, C., Corcoran, B., Burla, M., Roeloffzen, C. G. H., Leinse, A., et al., "Sub-GHz-resolution C-band Nyquist-filtering interleaver on a high-index-contrast photonic integrated circuit," Opt. Express, 24, 5715-5727 (2016).

[20] Zhu C., Corcoran, B., Zhuang, L., and Lowery, A. J., "Doubling the ROADM sites using pairwise coding for 4%-guard-band superchannels," in Optical Fiber Communications (OFC), Anaheim, CA, Th1D.1 (2016).

[21] Corcoran, B., Zhu, C., Schröder, J., Zhuang, L., Foo, B., Burla, B., et al., "Multipass performance of a chip-enhanced WSS for Nyquist-WDM sub-band switching," J. Lightwave Technol. 34, 1824-1830 (2016).

[22] Schröder, J., Roelens, M. A. F., Du, L. B., Lowery, A. J., Frisken, S., and Eggleton, B. J., "An optical FPGA: Reconfigurable simultaneous multi-output spectral pulse-shaping for linear optical processing," Opt. Express 21, 690-697 (2013).

[23] Zhuang, L., Zhu, C., Xie, Y., Burla, M., Roeloffzen, C. G. H., Hoekman, M., et al., "Nyquist-filtering (de)multiplexer using a ring resonator assisted interferometer circuit," J. Lightwave Technol. 34, 1732-1738 (2016).

[24] Xie, Y., Geng, Z., Kong, D., Zhuang, L., and Lowery, A. J., “FSR-variable 10-GHz-granularity WDM superchannel filter in a photonic integrated circuit,” J. Lightwave Technol., under review (2018).

[25] Saruwatari, M., et al., “All-optical signal processing for terabit/second optical transmission,” IEEE J. Select. Topics Quantum Electron. 6, 1363 (2000).

[26] Lowery, A. J., “Active photonic integrated circuits,” In Optoelectronic Devices, Springer, NY, 427-448 (2005).

[27] Lowery, A. J., and Zhuang, L., “Photonic integrated circuit as a picosecond pulse timing discriminator,” Opt. Express 24, 8776 (2016).

[28] Zhuang, L., Zhu, C., Corcoran, B., Geng, Z., Song, B., and Lowery, A. J., “On-chip optical sampling using an integrated SOA-based nonlinear optical loop mirror,” In 42nd European Conference on Optical Communication (ECOC), W4. P1 (2016).

[29] Xie, Y., et al., “Programmable optical processor chips: toward photonic RF filters with DSP-level flexibility and MHz-band selectivity,” Nanophotonics, doi: 10.1515, nanoph-2017-0077 (2017).

[30] Pant, R., et al., “On-chip stimulated Brillouin scattering for microwave signal processing and generation,” Laser Photon. Rev. 8, 653 (2014).

[31] Zhuang, L., Roeloffzen, C. G. H., Hoekman, M., Boller, K.-J., Lowery, A. J., “Programmable photonic signal processor chip for radiofrequency applications,” Optica 2, 854–859 (2015).

[32] Pérez, D., Gasulla, I., Capmany, J., Soref, R. A., "Reconfigurable lattice mesh designs for programmable photonic processors," Opt Express 24, 12093–12106 (2016).
[33] Pérez, D., Gasulla, I., Crudgington, L., et al., "Multipurpose silicon photonics signal processor core," Nat. Commun. 8, 636 (2017).
[34] Pérez, D., Gasulla, I., Javier Fraile, F., et al., "Silicon photonics rectangular universal interferometer," Laser Photo Rev 11, 1700219 (2017).